Some Contributions to Smart Assistive Technologies

by

Eduardo Carrasco Alonso

Submitted to the department of Computer Science and Artificial Intelligence in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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2015

Aita eta Amari, beti oroimenean.

Iñigo, Danel eta Martarentzat.

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Abstract

This doctoral dissertation is built upon a number of scientific contributions conducted during the last decade with the general aim of producing a new generation of smart, personalized and pervasive assistive systems. The research relevant to this Thesis spans through three different but interrelated technological domains.

The first domain is Universal Accessibility, where the focus was the design, implementation and validation of architectures for the provision of universal access to local devices and online services, specifically for digital TV.

The second domain is Decision Support where we have designed, implemented and validated architectures that *(i)* are enriched semantically, *(ii)* are able to learn from experience, and *(iii)* show high adaptivity to capture, learn, reuse and evolve the experience of the decision makers, with a special emphasis on Clinical Decision Support systems.

The third domain is Assistive Technologies, where we have tackled interactivity challenges for people with different types of disabilities, studying how to achieve natural interaction in Ambient Assisted Living environments, engaging virtual environments for telerehabilitation, and outdoors assisted navigation for visually impaired people.

All these developments have been carried out in the context of projects leading to practical demonstrations, which include *(i)* assisted living for the elderly people, *(ii)* diagnosis, treatment and follow up of diseases such as Alzheimer's Disease and Breast Cancer, *(iii)* telerehabilitation of people with brain stroke, and *(iv)* assisted outdoors navigation of visually impaired people. We argue that these domains, and hence our contributions, are highly complementary, paving the way to the advent of a new generation of Smart Assistive Technologies which unobtrusively and seamlessly will support the end users in the daily living activities.

“Knowing others is intelligence; knowing yourself is true wisdom. Mastering others is strength; mastering yourself is true power. If you realize that you have enough, you are truly rich.” — Lao Tzu, Tao Te Ching

Acknowledgements – Agradecimientos

En primer lugar deseo agradecer al Prof. Manuel Graña y al Dr. Carlos Toro por el apoyo incondicional que me han prestado durante la realización de la Tesis. Su motivación y guiado experto han sido fundamentales en la realización del presente trabajo.

En segundo lugar, deseo agradecer expresamente a Dr. Gorka Epelde y a Dra. Eider Sanchez por su compañerismo y colaboración durante todos estos años de trabajo. El trabajo en equipo con vosotros ha sido enormemente enriquecedor tanto en lo profesional como en lo personal.

A continuación, agradecer al director del departamento de eSalud y Aplicaciones Biomédicas, Dr. Iván Macía, y la dirección de Vicomtech-IK4 formada por Dr. Julián Flórez, Dr. Jorge Posada y Dra. Edurne Loyarte, por darme la posibilidad de realizar esta Tesis fruto del trabajo diario, y por crear en Vicomtech-IK4 un espacio especial de creatividad, libertad e innovación.

Finalmente, agradecer a todos mis compañeros de Vicomtech-IK4, tanto del área como del resto de departamentos, por acompañarme día a día en esta aventura que es la vida, y por crear un entorno de amistad, profesionalidad y compañerismo en el que es un placer trabajar.

Prefacio de Manuel Graña

La presente tesis, presentada para su defensa por Eduardo Carrasco, se enmarca en una larga y noble tradición anglosajona de reconocer académicamente el mérito de una trayectoria de trabajo en la industria. En este caso, el doctorando ha realizado durante más de diez años trabajos de investigación en Vicomtech-IK4, trabajos que abarcan desde la realización de prototipos hasta la dirección de proyectos con fuerte responsabilidad. Simultáneamente, el candidato ha conseguido mantener un tono de publicaciones académicas en revistas que tienen un mérito adicional si consideramos las presiones a las que se encuentran sujetos los investigadores aplicados en un ambiente altamente competitivo. Ambas condiciones cumplidas, la experiencia aplicada y la publicación académica, el candidato cumple, desde mi humilde punto de vista, las condiciones para reconocer su trayectoria como equivalente a una tesis doctoral.

Una vez constatada la idoneidad del candidato, el problema que se nos planteó al trío de codirectores y candidato fue el siguiente: ¿en qué forma presentar los trabajos del candidato para que aproximen lo más posible al modelo de una tesis doctoral convencional? La forma más apropiada inmediatamente la identificamos en la presentación como una colección de artículos. Nuestro siguiente problema fue la selección de un núcleo de publicaciones sobre el cual desarrollar el argumento de la tesis, tarea no fácil dada la cantidad y diversidad de trabajos y publicaciones desarrolladas por el candidato. Finalmente, la estructura de la tesis que surge tiene dos partes: la primera es una parte discursiva estructurada en capítulos, que describe los trabajos y aportaciones seleccionados, la segunda es la colección de artículos seleccionados como contribuciones que soportan la candidatura al grado de doctor en Informática. De esta forma pretendemos ofrecer una presentación académicamente correcta y estéticamente cercana a la tesis convencional.

Manuel Graña

San Sebastián, Noviembre 2014.

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Chapter 1

Introduction and Overview

Assistive Technologies are gaining momentum rapidly in our society. Originally intended for increasing, maintaining, or improving the functional capabilities of people with disabilities, nowadays are expanding to a wide spectrum of sectors, activities and users at very fast pace. Health applications are one of those quick adopters that are taking the most of their benefits. Thanks to recent progress in related fields such as Universal Accessibility, Human-Computer Interaction and Decision Support Systems, in the following years it is expected that a new generation of Smart Assistive Technologies will emerge, which seamlessly and unobtrusively span across the everyday life of many citizen, increasing their quality of life and supporting them to realize their full potential.

This chapter provides a general introduction to this Thesis, presenting an overview of the contents, main publications and structure. Section 1.1 presents the motivations for this Thesis; Section 1.2 enumerates the publications achieved along this Thesis, which endorse it; and finally, Section 1.3 details the structure of the Thesis.

1.1 Thesis motivation

This Thesis covers research activities carried out along the last ten years in three related knowledge domains: *(i)* Universal Accessibility, *(ii)* Decision Support and *(iii)* Assistive Technologies. The environment of the development of the Thesis is an applied research center, Vicomtech-IK4, where research must be funded either by private company or by public funding obtained in competitive calls. This environment imposes working conditions which are quite different from the conventional academic environment where doctoral students carry their research activity.

Universal Accessibility is defined as the provision of accessibility and usability of current information and telecommunications technologies for anyone, at any place and at any time, and at in any living context in the Information Society ([Stephanidis 1997], [Nicolle 2001], [Abascal 2013]). It aims to enable equitable access and active participation of potentially all people in existing and emerging computer-mediated human activities, by developing universally accessible and usable products and services and suitable support functionalities in the environment. It should not be confused with an effort to impose a unique interaction solution to everybody, but as the provision of appropriate interoperability architectures, middleware, specifications and standards, that allow the provision of user-centered and personalized user interfaces to address the wide range of human abilities, skills, requirements, and preferences.

In this direction, a significant commitment to create a Barrier-Free Europe has been reached by the European Commission [European Commission 2010]. As a result, a significant amount of research and development on platforms for providing universal access to the Information Society has been carried out in recent years ([Faberger 2010], [openURC2014], [GPII 2014]). Despite these relevant efforts, those platforms have not yet arrived to the market in most of the cases. Several contributions of this Thesis have been centered on the improved usability of digital Television, through the implementation of standards for Universal Remote Controllers, which enhance usability and provide device independence to access the services arising in the new paradigm of digital TV.

Decision Support Systems (DSS) are computer systems providing valuable advice or recommendations for decision making in difficult situations, where the amount of information and the complexity of its analysis may overwhelm the human decision maker. Research on DSS started on the late 50's and, since then, they have been applied to a wide spectrum of applications ([Keen 1980], [Eom 2006]). Currently, DSS are a hot topic in many areas, especially in health care systems, where there is a great demand of such systems in order to support clinicians in the main tasks of their work such as diagnosis, prognosis, and in the treatment selection, in particular for those diseases that are complex or still fully unknown, lead to death, and that have a big impact in our society such as Alzheimer or Cancer.

The stronger technical challenges faced by DSS developers are: *(i)* its seamlessly integration in the hosting organization everyday workflow, *(ii)* its maintainability, extensibility, and scalability, *iii)* providing real-time answers to decision makers, (*iv)* the identification of new knowledge, and finally, *(v)* sharing and reuse of the components and knowledge obtained [Sanchez 2014b]. Among the broad spectrum of technologies proposed for DSS [Berner, 2007], in this Thesis we have followed the paradigm proposed by innovative semantic technologies such as SOEKS [Sanin 2009a] and DDNA [Sanin 2009b], as recently proposed by ([Toro 2012], [Sanchez 2013], [Sanchez 2014a]).

Assistive Technologies are defined as "any product (including devices, equipment, instruments, technology and software) specifically produced or generally available, for preventing, compensating for, monitoring, relieving or neutralizing impairments, activity limitations and participation restrictions. Assistive Technologies are used by individuals with disabilities in order to perform functions that might be difficult or impossible otherwise" [ISO 2007]. Thus, Assistive technologies include mobility devices such as walkers and wheelchairs, as well as hardware, software, online services and virtually any kind of peripherals that assist people with disabilities in accessing computers or other information technologies. Therefore, Accessibility and Usability research efforts can be clearly casted in the framework of Assistive Technologies. Hence, research conducted in this Thesis can be viewed as a transition from a very specific domain (digital TV) to the more general domain of Assistive Technologies which encompass a greater variety of devices and methods.

The potential number of Assistive Technologies users is currently very high and, furthermore, it is expected to continue growing during the years to come. As an example, there are currently approximately 45 million people in Europe who are suffering from a long standing health problem or disability [Eurostat 2011]. Furthermore, population aging implies that more people will have to live with some sort of chronic disability in the future. Due to this general situation, there is an enormous demand of Assistive Technologies with excellent customization and adaptation of the user interfaces to fit to the particular needs of a wide spectrum of users.

Figure 1.1 depicts how these three different technologies converge in what we call Smart Assistive Technologies, which is a good definition of the broad field where this thesis has been developed. The motivation for this PhD work has been to contribute to the state of the art on these three aspects of Smart Assistive Technologies in order to improve the quality of life of the end users, and to support them to realize their full potential in the Information Society, regardless of limitations in their abilities, skills, requirements, or preferences. As discussed in Chapter 5 “Conclusions and further work”, we believe that thanks to the contributions described in this Thesis a new generation of Smart Assistive Products could be developed in the future.

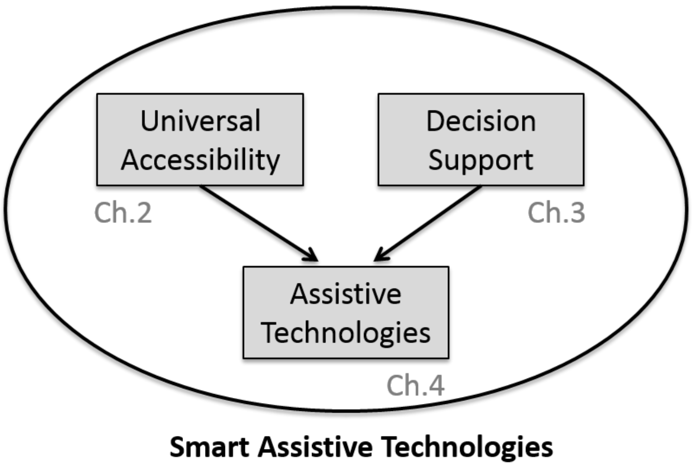

Figure 1.1. Smart Assistive Technologies as the general framework of the Thesis.

1.2 Publications

We have specifically selected, from the overall academic production achieved during the Thesis duration, the following publications as the main endorsement for the presentation of the Thesis:

[1] E. Carrasco, E. Sanchez, A. Artetxe, C. Toro, M. Graña, F. Guijarro, J.M. Susperregui, and A. Aguirre, “Hygehos Home: an innovative remote follow-up system for chronic patients”, in *Proceedings of the International Conference on Innovation In Medicine and Healthcare, InMed 2014*, San Sebastián, 2014.

[2] E. Sanchez, W. Peng, C. Toro, C. Sanin, M. Graña, E. Szczerbicki, E. Carrasco, F. Guijarro, and L. Brualla, "Decisional DNA for modeling and reuse of experiential clinical assessments in breast cancer diagnosis and treatment," in *Neurocomputing*, vol. 146, pp. 308-318, Elsevier, 2014. IF=2.005 (2013).

[3] E. Sanchez, C. Toro, A. Artetxe, M. Graña, C. Sanin, E. Szczerbicki, E. Carrasco, and F. Guijarro, "Bridging challenges of clinical decision support systems with a semantic approach. A case study on breast cancer," in *Pattern Recognition Letters*, vol. 34, pp. 1758-1768, Elsevier, 2013. IF=1.062**.**

[4] E. Sanchez, C. Toro, A. Artetxe, M. Graña, E. Carrasco, and F. Guijarro, “A semantic clinical decision support system: Conceptual architecture and implementation guidelines”, in *Proceedings of the 16th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems, KES 2012*, FAIA vol. 243, pp. 1390-1399, IOS Press, 2012.

[5] E. Sanchez, C. Toro, E. Carrasco, G. Bueno, C. Parra, P. Bonachela, M. Graña and F. Guijarro, “An architecture for the semantic enhancement of clinical decision support systems”, in *Proceedings of the 15th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems, KES 2011*, LNAI vol. 6882, pp. 611-620, Springer, 2011.

[6] C. Toro, E. Sanchez, E. Carrasco, L. Mancilla-Amaya, C. Sanin, E. Szczerbicki, M. Graña, P. Bonachela, C. Parra, G. Bueno and F. Guijarro, "Using set of Experience Knowledge Structure to extend a rule set of clinical decision support system for alzheimer's disease diagnosis," in *Cybernetics and Systems: An International Journal*, vol. 43, pp. 81-95, Taylor & Francis Inc., 2012. IF=0.973.

1.3 Structure of the Thesis

The research conducted in this Thesis was carried out under the framework of several relevant research and development projects in which the author participated. Those R&D project are presented and summarized in Appendix 1. From those projects several publications have been produced, endorsing the value of this Thesis from the academic point of view. The general structure of this Thesis is depicted in Figure 1.2.

Chapters have a common structure, consisting of an introduction, the description of a general conceptual framework, the identification of the main challenges addressed by the research, and the contributions achieved, ending with a conclusions section. The remainder of this Thesis is structured as follows:

- Chapter 2 presents the research done on the field of the Universal Accessibility. The main contributions in this chapter refer to applications in the digital TV domain, proposing architectures enhancing usability and accessibility.

- Chapter 3 is devoted to advances on Decision Support Systems, where the author has collaborated in the development of semantically enhanced systems, as well as in the development of decision systems able to learn from experience to enhance decision recommendations.

- Chapter 4 describes the contributions obtained in the field of Assistive Technologies, covering several applications which are a sample of the field covering Ambient Assisted Living, rehabilitation, and assisted navigation for visually impaired people.
- Chapter 5 discusses the overall contributions in the context of Smart Assistive Technologies, assessing the impact of the conducted research and providing some lines for future work.
- Appendix 1 contains the summary description of the relevant projects that supported this Thesis. As said in the introduction, the working environment is one of competitive applied research, so that achieving the completion of these research projects may be seen as an additional endorsement of the Thesis.
- Appendix 2 contains the brief descriptions of the papers that endorse the Thesis, as well as the actual copies of the published papers.

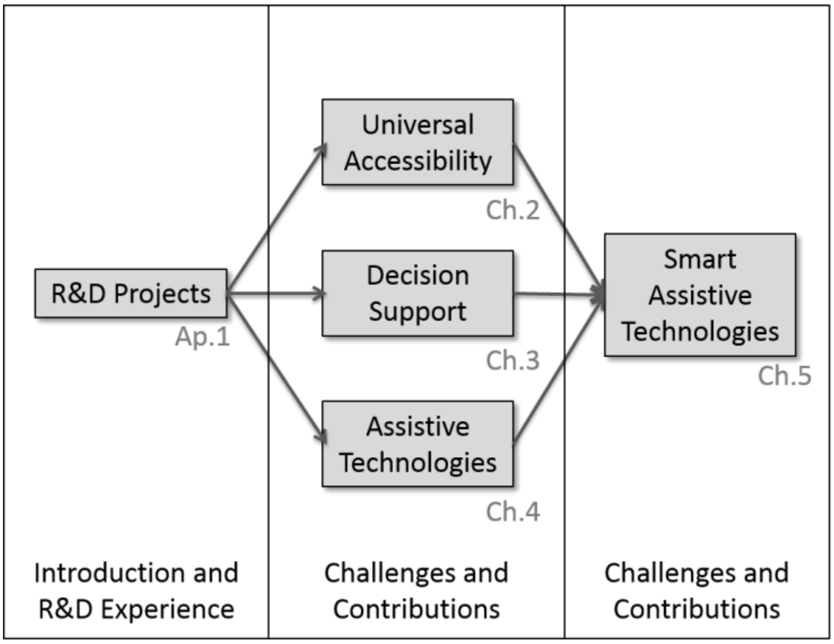

Figure 1.2. Structure of the Thesis.

Chapter 2

Universal Accessibility

This Chapter describes the research conducted in the field of Universal Accessibility. The focus of the research has been in the development of architectures to provide multi-context universal access to devices and services available in the current Information Society. Proposed contributions make use of established international standard “ISO/IEC Universal Remote Console URC” [ISO/IEC 2008] in order to extend the impact of the described results. Furthermore, the concept has been validated in a digital TV scenario. The obtained results show that the solution can be deployed on most devices and services available nowadays, such as mobile devices, self-service machines, internet services or home automation devices, to mention a few.

In this chapter, we focus in three challenges tackled during this Thesis.

1. First, we face the provision of universally accessible remote controls for any given target device.
2. Following, we tackle the provision of universal access to interactive online services.
3. Finally, we research on the provision of multi-context universal access to interactive online services.

This Chapter is structured as follows: Section 2.1 introduces the Universal Accessibility concept; Section 2.2 describes the state of the art in the field; Section 2.3 presents the general technological framework of the Chapter; Section 2.4 introduces the challenges tackled by the author and his research team; Section 2.5 describes the main contributions achieved. Finally, Section 2.6 presents a discussion of the results reported in this chapter, describing future work.

2.1 Universal Accessibility

Universal Accessibility is a recent term in literature, which sets its foundations in two previous concepts: Design for All and User-Centered Design ([Stephanidis 1997], [Abascal 2013]).

Design for All has been understood as the conscious and systematic effort to proactively apply principles, methods and tools to promote universal design in computer-related technologies, including internet-based technologies, thus avoiding the need for a posteriori adaptations, or specialized design [Stephanidis 2001]. Design for All was also described as design for human diversity, social inclusion and equality as stated in the EIDD Stockholm Declaration [Klironomos 2005]. It should not be conceived as an effort to advance a single solution for everybody, but as a User-Centered approach providing products that can automatically address the possible range of human abilities, skills, requirements, and preferences.

User-Centered Design is an approach to interactive systems development that aims to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors / ergonomics, and usability knowledge and techniques. This approach enhances effectiveness and efficiency improves human well-being, user satisfaction, accessibility and sustainability; and counteracts possible adverse effects on human health, safety and performance. User-Centered design can be characterized as a multi-stage problem solving process that not only requires designers to analyze and foresee how users are likely to use a product, but also to test the validity of their assumptions regarding user behavior in real world tests with actual users. Such testing is necessary as it is often very difficult for the designers of a product to understand intuitively the experiences of a first-time user of their design, and to predict each user's learning curve ([ISO 2010], [Cooper 2004]).

On the top of Design for All and User-Centered Design, Universal Accessibility implies the accessibility and usability of information and telecommunications technologies by anyone at any place, and at any time, and their inclusion in any living context [Stephanidis 1997]. It aims to enable equitable access and active participation of all people in existing and emerging computer-mediated human activities, by developing universally accessible and usable products / services and suitable support functionalities in the environment. These products / services must be capable of accommodating individual user requirements in different contexts of use, independent of location, target machine, or runtime environment. Due to the aforementioned facts, current standards and technologies supporting Universal Accessibility are under revision nowadays in order to find innovative ways to meet the expectations of the citizens of any country including those under development ([Nicolle 2001], [Abascal 2013]).

2.2 State of the art

In this section, the most relevant activities found in literature regarding the advance of Universal Accessibility are presented and summarized.

A specific field in which Universal Accessibility has been strongly pushed forward in the last years is the domain of Ambient Assisted Living (AAL), since it is crucial that all possible users are able to use them. A very complete survey on the most relevant activities regarding platforms for AAL applications is available at [Fagerberg 2010]. It is remarkable that many projects have dealt with the integration of targets / services in order to provide universal access. The most important lesson from those projects is the need of a common open platform for AAL applications that could have a real impact in the market at thus reach to the potential customers. Relevant efforts have carried out since then to propose a single architecture or to unify the existing ones in a single one, but unfortunately a consensus in this topic has not yet been achieved. Next, the most relevant initiatives will be presented:

2.2.1 openURC Alliance

The openURC Alliance is an international consortium of companies and institutions promoting the mainstream adoption of the International Standard ISO/IEC 24752, aka Universal Remote Console (URC) [ISO/IEC 2008], and associated standards and technical specifications to promote Universal Accessibility. It is believed that effective, intuitive, pervasive, and personalized User Interfaces (UIs) will largely determine the shape of technological products in the future. They will allow the simple and easy use of any device or service by any type of user, from the technological expert on mainstream consumer products to people with special needs, ensuring that every person has access to technology and technology products, living in a completely individual, personalized, user-friendly, interoperable, pervasive, and seamless environment [openURC2014].

The ISO/IEC 24752 specifies communications between a target device that a user wishes to access and operate, and a URC that presents the users with a remote user interface through which they can discover, select, access and operate the target device. The URC is a device or software through which the user accesses the target device. If the URC is software, it is typically hosted on the user's physical device, but distributed approaches are also possible [ISO/IEC 2013].

The most relevant contribution of the openURC Alliance is the Universal Control Hub (UCH) [openURC 2013a]. The Universal Control Hub (UCH) is a profiling of the URC framework, as specified in ISO/IEC 24752. In this profile, a gateway ("control hub") is used as a middle layer between a controller and a target device or service. The gateway translates the communications between any controller and any target; neither the controller nor the target needs to be URC compatible. A significant advantage of this approach is its expandability. The system is modular and provides an enormous potential for future expansion [openURC 2012].

2.2.2 UniversAAL

The UniversAAL project [UniversAAL 2014] is a recent undertaking which has the objective to integrate the various features developed in previous AAL projects, and to make available a unified platform to the R&D community. It is expected that this will be the starting point to an R&D ecosystem which will promote the development of the needed ICT applications for aging people, at work, in the community, and at home [Hanke 2011].

The UniversAAL architecture is made of a set of communication buses, namely, input, output, context, and services buses. Applications running on devices can register to one or more buses, receiving asynchronous notifications as soon as events occur. Input and output buses are used to interact with users. The context bus is an event based bus attached to context sources, whose events can be re-elaborated and transformed in high level events by components subscribed to the bus. The service bus is used to group all the services available in AAL-spaces. Serving as the user interface modelling technology for the dialogues that a service is going to present to the user, UniversAAL uses the Persona UI Framework, which is based in Xforms [Epelde 2014b].

2.2.3 Raising the Floor

Raising the Floor (RtF) [RtF 2014] is an international initiative to make the web and mobile technologies accessible to everyone with disability, literacy and aging-related barriers, regardless of their economic status. More specifically, Raising the Floor seeks to ensure: *(i)* that access technologies are available for all, *(ii)* that these access technologies are effective enough to provide access to the ever evolving technologies used to create Internet based information, services and communities, and *(iii)* that these access technologies are affordable for people of all socio-economic levels and communities.

The Global Public Inclusive Infrastructure (GPII) is the key project fostered by RtF. It will combine cloud computing, web, and platform services to make access simpler, more inclusive, available everywhere, and more affordable. When completed it will provide the infrastructure needed to make possible for companies, organizations, and society to put the web within reach of all by, making it easier and less expensive for consumers with disabilities, ICT and AT companies, Public Access Points, employers, educators, government agencies and others to create, disseminate, and support accessibility across technologies [GPII 2014].

Cloud4all and Prosperity4all are large scale projects funded by the European Commission as part of FP7. These projects provide funding for core parts of the GPII development, including standards work, preference server, federated repository of solutions, matchmaking and delivery as well as over a dozen implementation ranging from operating systems and browsers, to digital TV, kiosks and smart homes ([Zimmermann 2013], [Peissner 2014]).

2.3 Framework

In order to provide universal access to local devices and online services of the Information Society for all possible end users, applications, and use cases, the architecture depicted at Figure 2.1 is proposed. In this architecture, the interface between system modules is always given using the specifications of ISO/IEC 24752 Universal Remote Console standard (in the following referenced as URC in short).

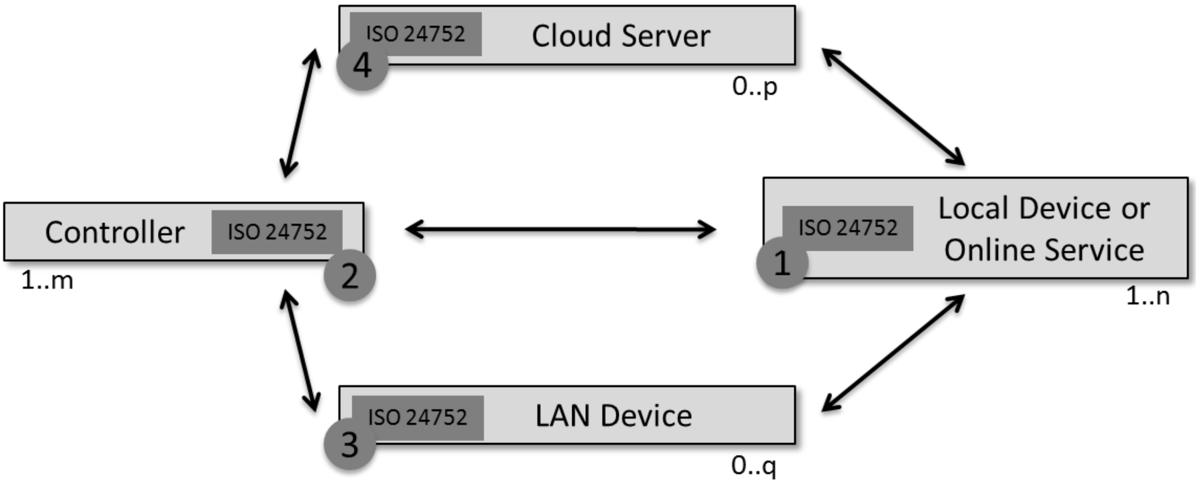

Figure 2.1. Architecture providing universal access to local devices and online services.

The architecture shown at Figure 2.1 allows different implementation configurations, which are described next:

1. **Target Device / Service URC Implementation**. The URC is implemented in the target device or service and it advertises the UI sockets that can be used by remote clients, for example by using the URC-HTTP protocol to remotely control it.

2. **Client Device URC Implementation**. The URC can be implemented in the client device as well. Client device can be a smartphone, tablet or any other device the end user chooses to remotely control a single or a group of target devices or services. Different pluggable user interfaces can be run at the client device. Proprietary communication protocols to the target devices have to be included in the URC implementation, for example using Target Adaptors as it is done in the UCH.

3. **LAN Device URC Implementation**. Devices such as switches, gateways, routers, or servers present in the local area network can be used to host URC implementations such as the UCH. In this configuration, the UCH translates the communications among all specific protocols of clients and targets that are available in the local area network. Thus, the URC specifications act as a common control language.

4. **Cloud Server URC Implementation**. Cloud servers can host URC implementations such as the UCH as well. Similarly to the LAN Device URC implementation, in this configuration the UCH uses the URC as a common control language. In this configuration internet access is needed. Communications latencies are the main limitations.

There is an additional configuration which is called the "**cascading UCHs architecture**" [Alexandersson 2011]. This configuration is very useful whenever several UCHs are available in the same context. They can be interconnected in a master-slave mode, for example using the URC-HTTP protocol. In this way, the master UCH exposes the UI sockets of the slave UCHs as well, and transparent control of remote devices and services through several UCHs is obtained.

Additionally, in order to provide support to the end users to accomplish complex tasks, an Activity Management System (AMS) could be integrated and implemented into the UCH. The AMS are systems that provide support to the end user in order to execute complex tasks, either by scheduling and executing those tasks automatically, or by guiding the users through such tasks. In this way, the users of the architecture may benefit from assistance during the execution of the tasks they have to deal with. This requirement is particularly important because the architecture is intended for universal use, and users with special needs such as people with cognitive impairments will also use the system and may have to be assisted during the execution of complex tasks.

Hence, an architecture that mixes universal access and activity management is needed. In this sense relevant research has been carried out in ([I2HOME 2009b], [Murua 2010]). As it can be seen in Figure 2.2, all the interaction between targets, users and the Activity Management System can be made using UI sockets which are placed in the Socket Layer. The Activity Management System can be implemented using a task engine. There are several available open source engines [Rich 2009]. The modelling of tasks and the interaction between them can be represented by task models [Paternò 2004]. The standard CEA-2018 which defines the semantics, and an XML notation for task models can be used for standardization purposes [ANSI/CEA 2008].

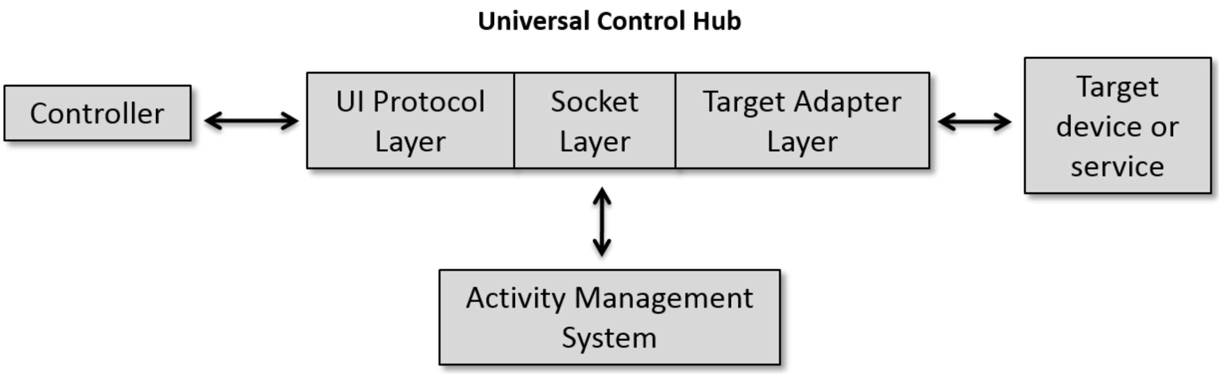

Figure 2.2. Activity Management System integrated in Universal Control Hub.

2.4 Challenges

As several European studies have pointed out during the last years, eAccessibility in Europe is still very low and further measures are needed to stimulate progress. People with disabilities in Europe continue to be confronted with many barriers to everyday ICT products / services that are now essential elements of social and economic life. Such eAccessibility deficits can be found across the spectrum of ICT products / services, for example telephony, TV, web and self-service terminals [MeAC 2008].

Remarkably, the situation is especially critic in ICTs, given their rapid advance of and the slow adjustment or regulation of the corresponding rights. It is therefore necessary, due to the increasingly evident risk of people with specific ICT needs being excluded from the new social and economic systems arising within the information and communication society, to rapidly tackle this problem. Hence, the levels of accessibility of conventional technologies have to be raised ([Monitoring eAccessibility 2011], [eAccessibility Impacts 2012]). In order to deal with this situation, three challenges have been identified, which are, the provision of Universal Accessibility to *(i)* single devices, *(ii)* internes services in a single context and, *(iii)* in a variety of contexts.

The provision of the Universal Accessibility has been focused in the Digital TV scenario, but as it will be shown in this doctoral dissertation the solution and the results can be applied successfully to many other ICT devices and domains.

2.4.1 Challenge 1. Universally Accessible Remote Controls

In this challenge, the provision on Universal Accessibility to daily life devices such as consumer electronics, domestic appliances and self-service terminals is analyzed. In particular, the case of the TV sets will be analyzed in detail, since TV sets are present in almost any home worldwide, and watching TV is one of the most frequent leisure activities [ITVE 2009]. Significant effort has been made in order to improve the user friendliness, appearance and usability of the TV remote controls. Anyway, the interaction paradigm based on infrared remote control technology has remained unchanged but a significant impact on accessibility has yet to be achieved [Weemote 2013].

As shown in Figure 2.3, current TV remote controls are very limiting for many users [Monitoring eAccessibility 2011]. The best way to ensure universal access to any device (such as the TV) is to provide a technological solution that allows to plug-in different user interfaces or remote controls. In this way, personalized remote controls could be deployed to meet the particular needs of each user [Epelde 2013a].

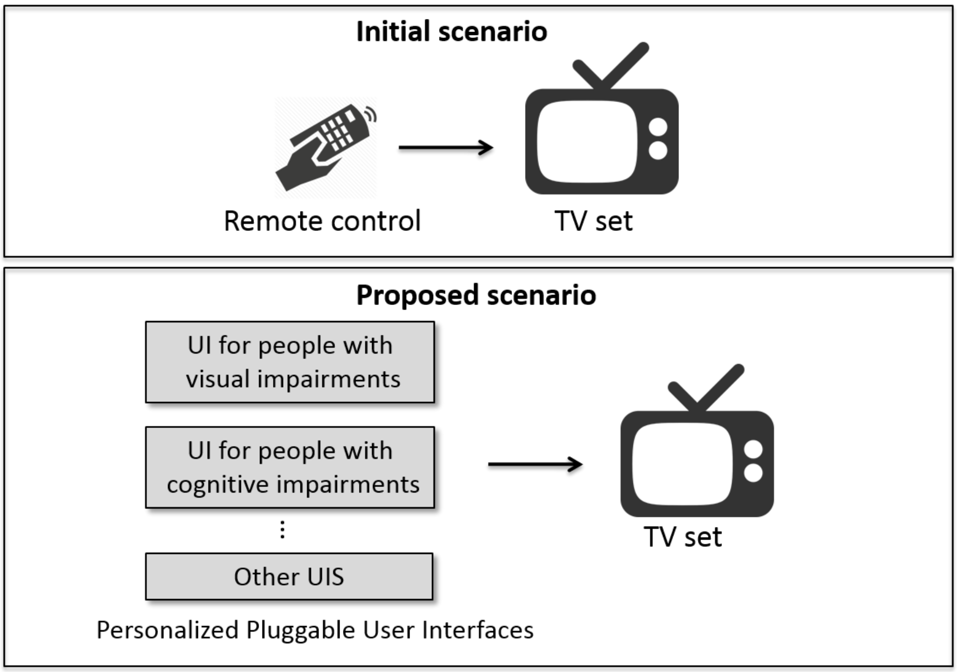

Figure 2.3. Universally Accessible TV Remote Control.

2.4.2 Challenge 2. Universally Accessible Online Services

Accessibility to TV services is still far away from being implemented to its fullest extent [Monitoring eAccessibility 2011]. The main challenge of not excluding people from accessing any digital TV's services was underlined by the interactive TV research community at [Gil 2003]. There are two main working areas directly related to making the TV interaction experience accessible, which are: content accessibility and access to digital TV services.

The main efforts on content accessibility have been focused in the standardization through regulatory agencies of the alternative content creation. For example, AENOR provides a standard reference on the creation of audio-description [UNE 2005] and another standard reference on the creation of teletext subtitles [UNE 2003]. It is remarkable, the ability of the DVB technology to transmit content composed of different streams of audio, video and data, which enables the distribution of the audio description, the sign language signing or the subtitles as additional channels. Thus, the user can select the combination of content streams to be rendered on its client device.

Regarding to the access to TV services, there is a growing interest in providing interactive services through the TV, as is reported in ([HbbTV 2010], [Orero 2014]). Several notable guides such as ([Carmichael 1999], [Rice 2004] & [Rice 2008]) offers detailed information on the appropriate design of digital services deployed on TV for particular user groups such as the older people or the visually impaired people. The main conclusion derived from these studies is that the best way to approach the problem is personalization, due to diverging requirements of the users.

Hence, as it is shown in Figure 2.4, a new approach to integrate all kind of interactive services (locally or remotely provided) with the TV set in a way that would allow personalizing the UI to the needs of each user group is proposed [Epelde 2013b].

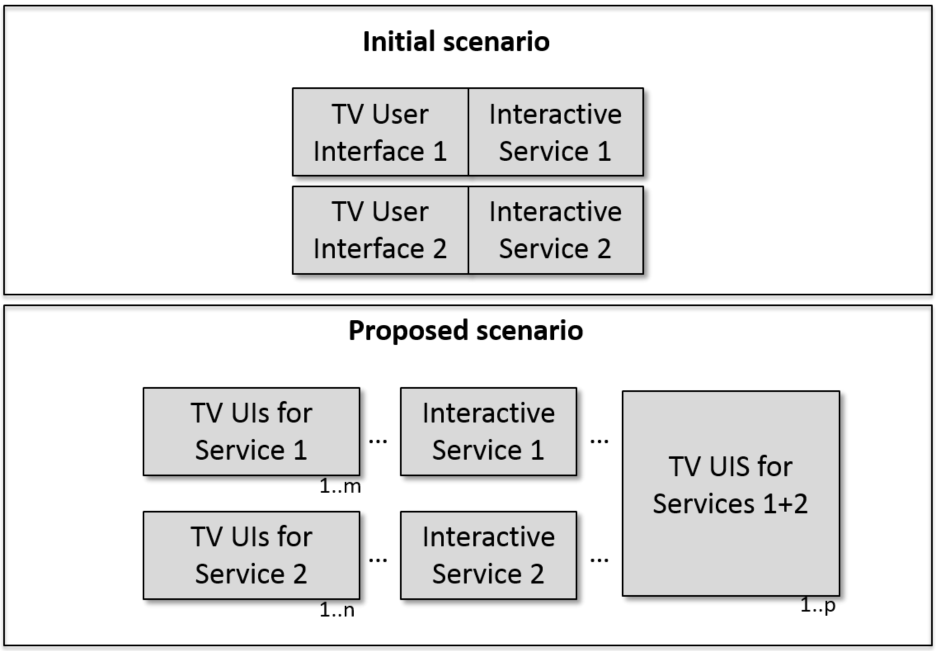

Figure 2.4. Universally Accessible TV Services.

2.4.3 Challenge 3. Multi-Context Universally Accessible Service Provision

Despite the achievements and advances in the user acceptance of technological products / services and their interaction, the shift toward multi-environment service consumption limits traditional systems' deployment [Burrell 2000]. From a design point of view, the main limitations of these services are *(i)* the limited consideration of the user's real-life context (e.g., not considering that user's needs and preferences changes from a home scenario to a work scenario or to an on-the-go scenario) and *(ii)* the lack of an architecture support to provide the required flexibility in terms of location, client device, interaction means, and content [Hong 2001].

As it is reported in several relevant studies [European Commission 2008], the European citizens' ICT usage evidence the need for an architecture that supports users' real-life context and its multi-device usage nature. Hence, as it is depicted in Figure 2.5, an architecture is needed in which interactive services can be reached from any ICT device available today and, remarkably, each device has to run tailored user interfaces in order to adapt to the particular requirements of all possible users.

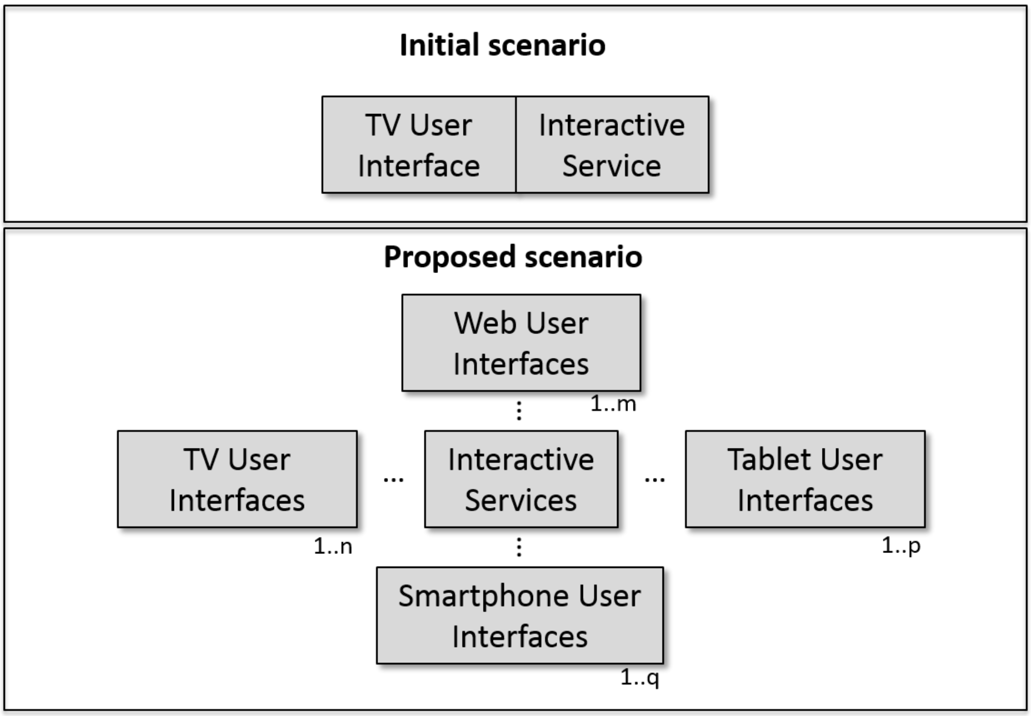

Figure 2.5. Multi-Context Universally Accessible Services Provision.

This challenge was met in [Epelde 2014a]. This publication is available in the annexes at the end of this doctoral dissertation.

2.5 Contributions

In the following subsections, the contributions to the challenges presented earlier are described.

2.5.1 Contribution 1: Universally Accessible TV Remote Control Architecture

We present an approach that provides universal accessibility for remotely operating the TV set. The novelty is provided in the description of how, by using the Universal Control Hub (UCH) [openURC 2013a] architecture, it is possible to achieve this goal.

The proposed architecture is depicted in Figure 2.6, where the TV is acting as a target to be remotely controlled (TV as a target use case). The UCH is a gateway-oriented architecture for implementing the Universal Remote Console (URC) [ISO/IEC 2008] framework [Zimmermann 2007]. Thus, the UCH is the gateway between any target device / service and any controller, exposing user interface sockets of all connected targets and facilitating pluggable user interfaces that plug into the sockets.

The main features of the UCH are as follows:

• It acts as a bridge between targets and controllers, each with its own communication and control protocol, that otherwise would be unable to talk to one another.

• Standard-based user interface sockets. The UCH is based on the URC framework previously described.

• A variety of user interface protocols. The UCH allows different user interface protocols (DHTML over HTTP, Flash, etc.) to be implemented and used by controllers.

• Globally available resource servers. The UCH can get distributed resources, such as resource sheet, pluggable user interfaces and other run-time components of the UCH from resource servers.

The main requirement to implement this solution, and to integrate the TV as a UCH's target device, is the remote controllability of the TV set. The requirements to integrate a target to the UCH are described below.

The target device must have an interface for clients to remotely control the complete functionality of the target. In more detail, there are three categories of requirement on the networking platform of a target:

• Discoverability: A target must be discoverable and identifiable on the home network. This can be implemented as the target advertising a service, or the target responding to search messages from the client, or both.

• Controllability: A target must be controllable, i.e., a client must be able to invoke its commands remotely.

• Eventing: A target must send out events to inform a client about its state changes.

These requirements would address the full integration of a TV set in the UCH. The TV set's remote control functionality integration into the UCH architecture is achieved by means of defining the required XML files (UI Socket, Target Description and Target Resource

Sheets) and implementing the corresponding code for the target adapter layer requirements (Target Discovery Module and Target Adapter). For more information see [openURC 2013a].

Once a TV set is integrated as a target in the UCH, it is possible both to develop a UCH's User Interface Protocol (UIPM) [openURC 2013a], or to use an existing one. Through the available UIPMs, the different pluggable UIs can remotely control the TV set, using the controller most comfortable for the user. Also, the UCH can be connected to different resource servers on the Internet that offer UIs and UCH integration modules that may be downloaded and used directly.

Figure 2.6 summarizes the proposed architecture for the TV set's accessible remote control. This figure shows different pluggable user interfaces that can interact with a TV set that has been integrated with the UCH as a target. A resource server object reflects the option of using the pluggable user interfaces and integration modules downloaded directly from the Internet.

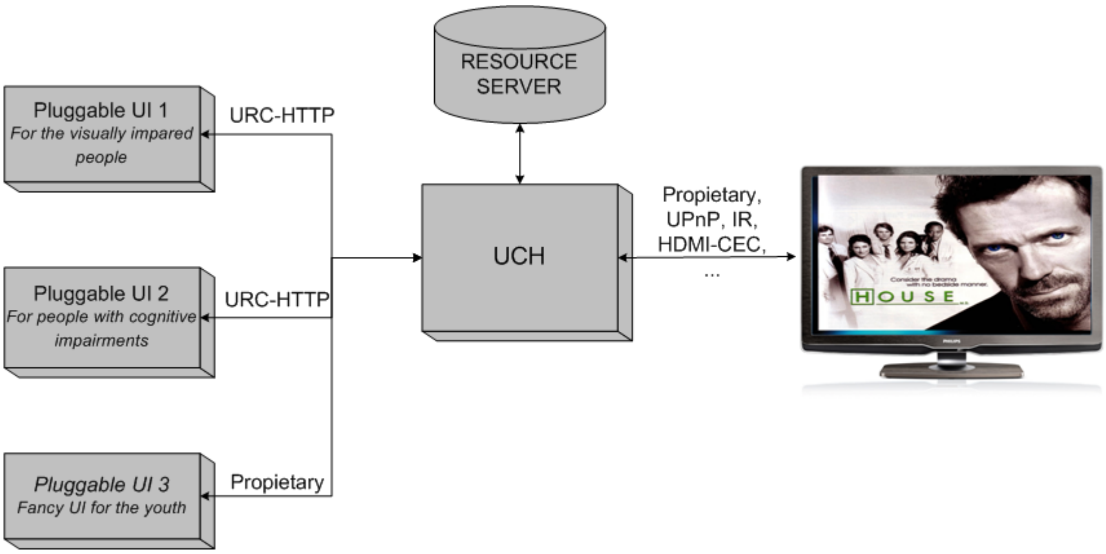

Figure 2.6. Universally Accessible TV Remote Control Architecture [Epelde 2013a].

<u>Implementation and validation</u>

The approach has been implemented in the I2HOME project [I2HOME 2009a]. Its full implementation and validation is described in [Epelde 2013a]. This paper is available at the annexes of this doctoral dissertation.

Several other projects have used this approach to provide universal access to different targets in a variety of contexts such as BrainAble FP7 Project [Navarro 2011], INREDIS Spanish CENIT Project [Gomez-Martinez 2010] and the Accessible Elevator project [Gauterin 2012].

<u>Discussion and closing remarks</u>

The architecture proposed in this section succeeded in providing universal access to a TV set. Besides, the results can be generalized, and the proposed architecture is valid to provide universal access to any local single or multiple hardware devices as well. In the previous case, the UCH has been used in order to implement the Universal Remote Console standard which enables the pluggable user interface concept and remote control of the TV set. In order to generalize this approach, the Target Device / Service URC Implementation is proposed as it is shown in Figure 2.1.

2.5.2 Contribution 2: Universally Accessible TV Services Architecture

This section presents a solution that provides universal accessibility for interacting with online services delivered through the TV. The novelty here is the description of how, by using the UCH architecture, it is possible to achieve this goal.

The proposed architecture is depicted in Figure 2.7. In the proposed solution, the TV acts as a controller which lets the user access the targeted services (TV as controller use case). Whenever the TV set is acting as a controller, then is able to interact with interactive services through the UCH architecture.

The requirements for implementing this solution are that the targeted services are capable of integration with the UCH, which means that they should have an access API or they should be based on web service technology, depending on the openness of the service providers.

Regarding the TV, the requirements for integrating a TV set as a controller in the UCH architecture, i.e. to use it as a pluggable user interface, are that the TV set must implement a bidirectional communication technology and a programmable user interface system.

The services integration into the UCH architecture is achieved by means of defining the required XML files (UI Socket, Target Description, Target Resource Sheets) and implementing the corresponding code for the target adapter layer requirements (Target Discovery Module and Target Adapter) for each interactive service. The interactive services can be running locally or on the Internet. For more information refer to [openURC 2013a].

Through the implementation of a UCH's User Interface Protocol (UIPM), it becomes possible to implement any TV set's compatible communication protocol. Using the UIPM's, the different pluggable UIs can be deployed to different TV. After achieving the integration of the services with the UCH and the required UIPM, UIs can be created for any service. This approach also allows the creation of aggregated UIs composed of different services.

At the same time, the UCH can be connected to different resource servers on the Internet that offer UIs and UCH integration modules that may be downloaded and used directly.

Figure 2.7 outlines the proposed approach to make interactive services accessible to all. This figure shows different target services integrated using their own protocols and accessed from different user interfaces running in a TV set. The resource server object reflects the option of using the UIs and integration modules downloaded directly from the Internet.

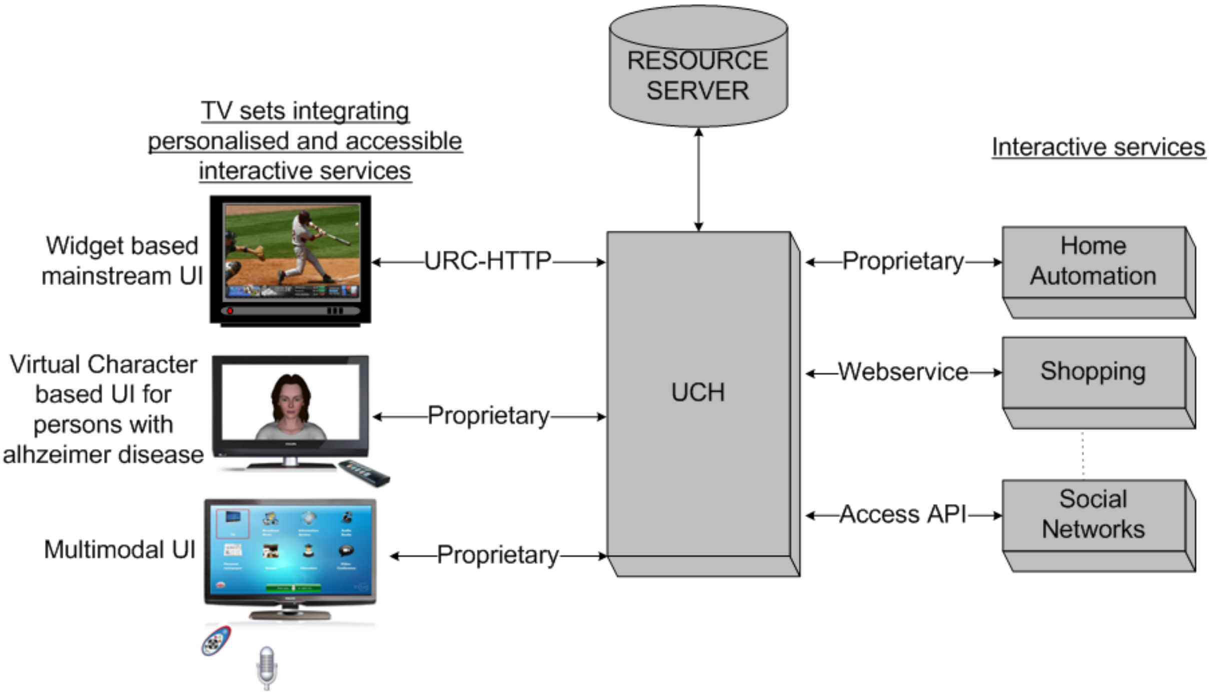

Figure 2.7. Universally Accessible TV Services Architecture [Epelde 2013b].

Implementation and validation

The approach has been implemented in projects such as I2HOME [I2HOME 2009a] and VITAL [VITAL 2009]. Its full implementation and validation is described in [Epelde 2013b]. This paper is available at the annexes of this doctoral dissertation. Several other projects have used this approach to provide universal access to online services in a variety of contexts such as in the eLearning [Rodriguez-Ascaso 2007], telehealth services provision [Epelde 2013c] or online banking [Sebastian 2014].

Discussion and closing remarks

The architecture proposed in this section succeeded in the provision universal access to online services from a TV set. As it can be seen in Figure 2.7, the online services can be accessed using different pluggable user interfaces running in the TV. These results can be generalized, and the proposed architecture can be upgraded to provide universal access to any online service from any client device running different pluggable user interfaces. To accomplish this goal, the URC standard can be implemented in a number of different configurations, which are shown in Section 2.3.

2.5.3 Contribution 3: Multi-Context Universally Accessible Service Provision Architecture

We present a contribution that provides universal accessibility for interacting with online services that can be consumed along several use contexts. In the previous two contributions presented in this chapter, a single use context was envisaged: the digital home. The novelty here is the description of how, by using the UCH architecture, it is possible to consume several online services in a variety of context and situations such as at home, on-the-go, or in public buildings such as hotels or hospitals.

The proposed architecture is depicted in Figure 2.8. The use case we have targeted is the provision of universal remote rehabilitation service. The architecture proposed is made up of three layers: the user layer, the cloud layer, and the hospital layer.

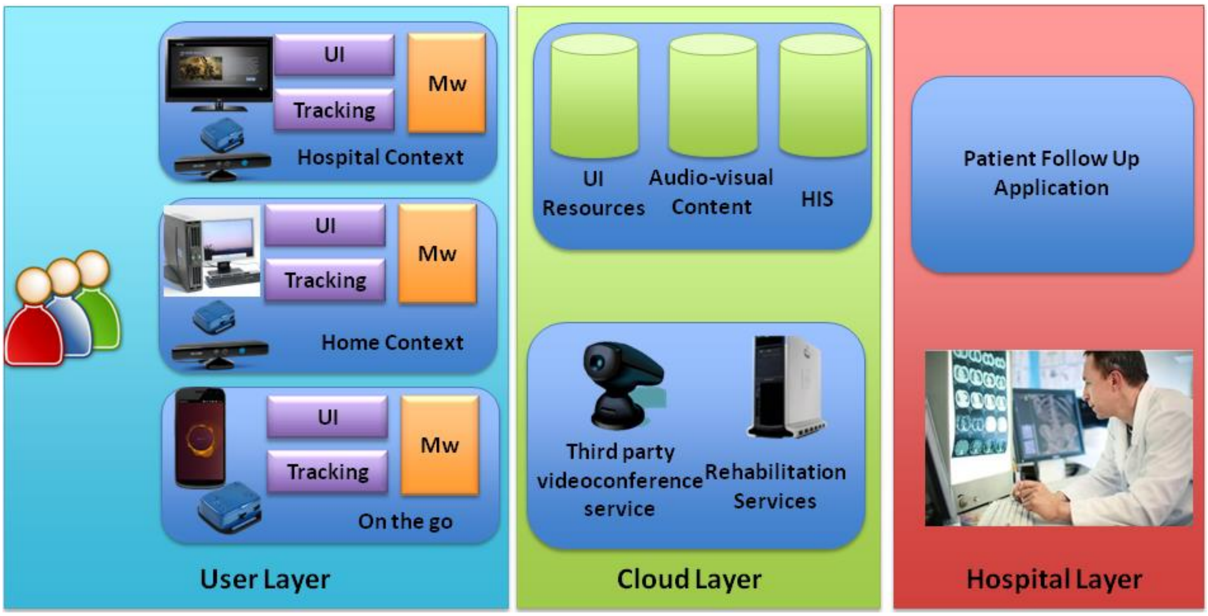

Figure 2.8. Multi-Context Universally Accessible Services Architecture [Epelde 2014a].

The user layer defines a common approximation for the different service consumption contexts that users traverse in their real lives (e.g., home context, hospital context, or on the go). Each service consumption context client is composed of a UCH middleware, a tracking solution, and a user interface. The UCH enables UI personalization and easy upgrading through its UI plug-and-play feature. In addition, the definition of a common interface specification for the different tracking systems in the UCH enables the seamless exchange of the tracking systems. Following a UCH middleware-based architecture approach, the system can be easily extended with new services (e.g., health services, home control) in the future and user interfaces that span across several services or targets can be deployed.

The cloud layer is responsible for ensuring the scalability of the services and it is composed of the following blocks: the UI resources repository and the audio-visual content repository, the rehabilitation services, and the hospital information system.

The UI repository follows the resource server concept introduced as part of the URC ecosystem and implements the interface and guidelines provided by the openURC Alliance [openURC 2013b]. This technology enables to incrementally support users with different needs and preferences and to upgrade UI elements or complete UIs based on users' capabilities and context evolution or maintenance tasks.

Several rehabilitation services were provided including *(i)* rehabilitation therapy prescription, *(ii)* therapy delivery to the user, *(iii)* rehabilitation session data retrieval from the user, and *(iv)* results assessment functionalities for the medical professionals. A videoconference service was included as well to establish direct communication between the medical professionals and the patients.

The main element of the hospital layer is the follow-up application, which implements the medical professionals' client to access rehabilitation services. The functionalities included rehabilitation therapy prescription and patient's therapy execution tracking results revision.

In summary, the inclusion of the UCH technology in the architecture approach enables the easy personalization of UIs, allows using URC and non-URC controller technologies (choice of client device), maximizes available interaction capabilities, and provides a platform for adding new services in the future. The presented approach proposes an architecture for service provision in users' real-life contexts (starting rehabilitation at hospital, moving home, and providing the chance to continue outdoors or while on the go). Apart from the localization choice, the solution allows having different service functionalities in user interface of each user device, providing the required service functionalities per scenario.

Implementation and validation

The approach has been implemented in the EREHAB project. Its full implementation and validation is described in [Epelde 2014a]. This paper is available at the annexes of this doctoral dissertation. Several other relevant projects have researched on this approach in order to provide multi-context universal access to online services such as GPII [Peissner 2014] or Cloud4All [Zimmermann 2013].

Discussion and closing remarks

Not only the patients, but the professional rehabilitators can also benefit from the URC technologies, in order to provide them with multi-context universal access to the system. Thanks to this new approach, the professionals can also benefit from all the advantages of the URC technology and can be provided with dedicated and context specific user interfaces to be used for example at the hospital, at home, on-the-go environments.

Second, an Activity Management System (AMS) could be integrated and implemented into the UCH. The AMS are those systems that provide support to the end user in order to accomplish complex tasks. In this way, the users of the aforementioned telerehabilitation system may benefit from assistance during the execution of the exercises prescribed. This requirement is particularly important because the system is intended for universal use, and users with special needs such as people with cognitive impairments may also use the system and may have to be assisted during the rehabilitation sessions.

2.6 Discussion on the results and future work

The contributions shown in this chapter demonstrate a continuous research activity carried out during more than 10 years on the provision Universal Accessibility to the Information Society.

Initial research was focused in the provision of Universal Accessibility to the digital TV and to the interactive services provided via the TV. But, as it has been shown in the previous sections, the results are directly applicable to provide universal access other targets such as home automation, self-service terminals, telephony, and many other devices currently available in our daily life. In the same line, the results are applicable as well to online services available nowadays. Thus, a standardized interface that unifies in a single access point all targets / services available is provided, which can offer personalized and context-dependant user interfaces for all.

Furthermore, the user interfaces can be built in order to provide seamless and unobtrusive interaction that matches the particular needs of each and every user. At this point, the use of international standards and specifications such as the Universal Remote Console or the Universal Control Hub makes it possible the creation of an ecosystem of developers, companies and third parties that can develop all the user interfaces needed.

In this context, despite the current development of large inclusive infrastructures such as Global Public Inclusive Infrastructures, it has been shown that URC technologies are playing a relevant role in those initiatives as well.

Finally, further research is going on in the following lines:

- Standardized user interface socket descriptions for common devices / services (such as TV sets, DVD player, video conference systems, calendars, etc.) have to be developed and made public for the user interface developers. This task will facilitate the provision of plug-and-play user interfaces for devices / services of different manufacturers / service providers.

- The Universal Control Hub needs to be securitized and a secure open source implementation has to be publicly distributed in order to foster the growth of the URC user community. Relevant efforts have been addressed specially at several research institutions in this sense, but still a secure open source implementation is still not available.

- Despite the effort carried out by some institutions, still more easy-to-use and free tools and development frameworks are needed in order to facilitate i) the development of URC compliant user interfaces and, ii) the integration of targets with the UCH. Similarly to the previous point, expensive advanced frameworks exist which limit the progress of the mainstream adoption of the technology.

- Progress has to be carried out in the development of user interface repositories, target and service adaptor repositories, user profiling techniques and user interface matchmaking algorithms in order to provide pervasive user interfaces for any context the users meet in their daily life.
- Lastly, open source implementations of an UCH integrated with an Activity Management System and easy to use task modelling tools are needed. Furthermore, demonstration prototypes which show the full potential of activity management support and the URC technologies are needed in order to mainstream its benefits into society.

Chapter 3

Decision Support

This Chapter describes research conducted in the field of Decision Support Systems (DSS), which are computer systems providing valuable advice or recommendations for decision making in difficult situations, where the amount of information and the complexity of its analysis may overwhelm the human in charge. DSS are a current hot topic in many areas, especially in health care systems, which need the design of DSS that capture, formalize, reuse and evolve the experience of the decision makers has been researched. In this chapter, we focus in three challenges that have been confronted during the duration of this thesis.

1. First, we tackle the design of an architecture for a Generic Semantically-enhanced Decision Support system that can support multiple related decisional tasks in complex scenarios.

2. Following, we deal with the design of an architecture for an Experience-based Decision Support System that can assist in the decision making in defined scenarios.

3. Finally, we face the definition of the process of experience acquisition, formalization, and reuse in Decision Support Systems. However, due to the limited extend of this Thesis, we will not reproduce the details already reported in the annexed papers.

This Chapter is structured as follows: Section 3.1 introduces the Decision Support concept; Section 3.2 describes the state of the art in the field; Section 3.3 gives a common framework for the developments in the Chapter; Section 3.4 introduces the challenges dealt with by the author and his research team; Section 3.5 describes the main contributions achieved in this field. Finally, Section 3.6 presents a discussion of the results reported in this Chapter, describing future work.

3.1 Decision Support Systems

Research on Decision Support Systems (DSS) started on the late 50’s and, since then, they have been applied to a wide spectrum of applications ([Keen 1980], [Eom 2006]), for example in the business and management economic sector. There is an intense interest in DSS in the healthcare sector, which is a particular application domain with a long history of pioneering developments. Historically, the focus of interest has been set strongly in the support to medical diagnosis. In this Thesis we have focused in the health sector as the main use case of this technology because most of it has been performed under projects in this area, which is rather sensitive due to its social relevance, as well as its complexities. In particular, we deal with Clinical Decision Support Systems (CDSS) [Sanchez 2014b]. CDSS are expected to *(i)* facilitate an efficient and effective decision making about individual patients, *(ii)* reduce preventable medical errors, *(iii)* improve the quality of healthcare provided to patients, and *(iv)* provide medical professionals with specific and needed knowledge at appropriate times and manner [Peleg 2006].

Numerous technologies for CDSS have been proposed ([Holbrook 2003], [Peleg 2006], [Berner 2007], [Sittig 2008]). Nevertheless, the integration of such systems in daily clinical environments has not been fully achieved yet. Several authors have reported the factors affecting this lack of success, identifying the main issues to solve in order to reach clinical deployment of CDSS.

The first issue is the digitalization of all previous knowledge, enabling a fully computer based decision support, removing manual, paper-based, procedures [Kawamoto 2005]. A very precise example are the clinical guidelines, which are mostly on paper nowadays, though there is growing trend to computerize them, allowing for automated search. However, actual clinical guidelines knowledge representation models do not allow reasoning because their main focus is on data alignment and integration. They are not properly components of CDSS.

A second issue is the actual CDSS integration in the clinical workflow, which will have a big impact on the reduction of the time elapsed between the introduction of patient clinical data and the generation of diagnostic answers driving the clinical process. In this sense, the integration of CDSS in the clinical systems already present in hospitals and medical centers requires extraordinary efforts. Ideally, CDSS should assist clinicians during all different tasks of their daily duties, and not only during specific activities [Holbrook 2003]. A closely related issue is whether CDSS provides timely advice, i.e. recommendations are given when needed, not later. Solving this issue requires fast reasoning processes providing real time responses [Peleg 2006]. Moreover, it requires global accessibility to the system, anywhere anytime.

The third big issue is maintainability, extensibility, and scalability. CDSS architectures must be optimal in the sense of achieving an optimal balance between cost and performance to maintain the underlying knowledge model and the criteria for reasoning of the system. For that purpose, knowledge representations must be directly understandable by domain experts. In the same manner, easy-to-use, and technology-transparent tools for domain experts need to be developed [Peleg 2006].

On top of that, mimicking the learning paradigm of clinicians, the knowledge and criteria embedded in an actual CDSS should evolve with daily experiences [Berner 2007], following an experience-based learning paradigm. Therefore, mechanisms for the quantitative and qualitative evaluation of the performance of the system, as well as of the quality of the knowledge stored in it, should be provided [Liu 2006]. Finally, there is a need of an architecture for CDSS allowing sharing and reusing CDS modules and services [Sittig 2008].

3.2 State of the art

The variety of technologies that have been applied to CDSS construction could easily excess the length of this Thesis, therefore in this section we will limit ourselves to the fields closely related to the Thesis contents, as related to the papers in Appendix 2t. Explicitly, Computational Intelligence tools, encompassing machine learning, bioinspired learning and optimization, fuzzy reasoning, will not be reviewed, because we have not dealt with them in this Thesis, though we are aware of their big impact and extensive use. Moreover, state of the art reviews are already provided in the accompanying papers.

3.2.1 Knowledge Engineering

Knowledge is an important asset for individuals, organizations, and society throughout the ages. Knowledge engineering (KE) techniques can efficiently be used to deal with some CDSS issues such as terminological interoperability, system maintainability, and source heterogeneity and disparity. More precisely, semantic technologies have been described in the literature as a promising approach to solve knowledge handling and decision support in the medical domain [Gnanambal 2010].

In particular, ontologies, defined as the explicit specification of a conceptualization [Gruber 1995], are a key technology to fulfil the needs for organized and standardized terminologies and reusability efficiently at a structural level [Houshiaryan 2005]. They also are beneficial when used for reasoning and inferring new knowledge [Yu 2006]; achieving fast query systems [Toro 2008]. Among the most widely used ontologies within the medical domain are the Semantic Web Application in Neuromedicine SWAN [Ciccarese 2008] and the Systematized Nomenclature of Medicine Clinical Terms SNOMED CT [Nyström 2010].

3.2.2 Set of Experience Knowledge Structure

Decision makers guide their current decisions on lessons learned from previous similar situations; however, much of the experience held by individuals is not capitalized by the organizations due to inappropriate knowledge representation and / or administration. This leads to decision reprocessing, inadequate response time and lack of flexibility to adapt when new environmental conditions are found.

The Set of Experience Knowledge Structure (SOEKS) [Sanin 2009a] was proposed to represent and reuse experience in an adequate knowledge representation. It is designed to store formal decision events explicitly, and it is built from four basic elements that are considered to be crucial in decision-making actions. These elements are variables (V), functions (F), constraints (C), and rules (R). Variables are used to represent knowledge in an attribute-value form, following the traditional approach for knowledge representation. The sets F, C, and R of SOEKS are different ways of relating knowledge variables in V. Functions V describe associations between a dependent variable and a set of input variables; therefore, SOEKS uses functions as a way to establish links among variables and to construct multi-objective goals (i.e., multiple functions). Constraints C are equalities or inequalities restricting the set of possible solutions, which can be used to control the performance of the system with respect to its goals. Finally, rules R are used to model inferences, and map actions to the conditions under which they should be executed. Rules express the connection between a condition and a consequence in the form if–then–else.

3.2.3 Decisional DNA

SOEKS is the basis for the creation of the decisional DNA (DDNA). The DDNA is computational a structure designed to capture decisional fingerprints of an individual or organization [Sanin 2009b]. The name includes the reference to biological DNA because of its structure and the ability that if offers to store experience within itself. Let us illustrate this metaphor: the four elements that comprise a SOEKS can be compared to the four basic nucleotides of DNA, and they are also connected in a way that resembles a gene. Gene guide hereditary responses in living organisms, by analogy a SOEKS guides experience-based responses in decision-making processes. A group of SOEKS of the same ‘‘type’’ (i.e., knowledge category) comprise a decisional chromosome, which stores decisional ‘‘strategies’’ for a specific category. Therefore, a collection of SOEKS chromosomes is equivalent to the DDNA strand of an organization managing the knowledge of different inference strategies. SOEKS and DDNA have been successfully applied in industrial environments, specifically for maintenance purposes, in conjunction with augmented reality (AR) techniques [Toro 2007], and in the fields of finances and energy research [Sanin 2012].

3.2.4 Multi-agent technology

Multi-Agent Systems (MAS) are systems in which many autonomous software agents are combined to solve large problems that are beyond the individual capabilities or knowledge of each agent [Isern 2010]. The main characteristics are analyzed at [Sycara 1998]. Different MAS have been already proposed for medical applications in general, and for clinical decision support in particular ([Isern 2010], [Shirabad 2012]). These systems were oriented to the reutilization of medical resources distributed in different health centers.

Regarding the use of MAS during the different stages of the clinical workflow (i.e. diagnosis, prognosis, treatment, evolution and prevention) in a CDSS, the work presented in [Shirabad 2012] supported the entire clinical decision making process with the use of MAS. Nevertheless knowledge reutilization between the different stages was not supported, since separate decision systems were proposed for each stage, and no learning mechanisms based on user experience were provided either.

3.3 Framework

In order to develop DSS that mimic the learning paradigm of human decision makers, experience-based approaches are needed in which the knowledge and criteria embedded in an actual DSS should evolve with the daily experiences. To achieve this goal, we have carried out an introductory reflection on expert-decision supported human learning methodology in order to identify the main elements and processes that produce the experience gain on humans. Based on this preliminary analysis, first, we propose a generic expert-supported experience acquisition model. Second, the corresponding computational architecture for a DSS is presented. This design is not tied to any particular computational technique or knowledge representation technique. Third, a computational architecture which implements the SOEKS and DDNA experience representation techniques is proposed. This final architecture serves as the general template for the DSS proposed in this Chapter.

3.3.1 Expert-supported experience acquisition model

This model refers to the process of learning from decisions when there is an expert who can provide an arguably good decision. Figure 3.1 depicts a time frame dynamics illustrating this process. At discrete instants in time, a learning agent (human or DSS) is confronted with Events E_i that require to make a decision. We call Decisional Events D_i to the decisions actually taken by the learning agent, while Expert Decisional Events D'_i are the decisions that the expert would take. The difference between them $\Delta\mathcal{E}_i$ is the decision error which provides the experience to correct future decisions; hence this experience is incorporated the next time instant that new decision is required. In this process, the learner agent gains experience in decision making.

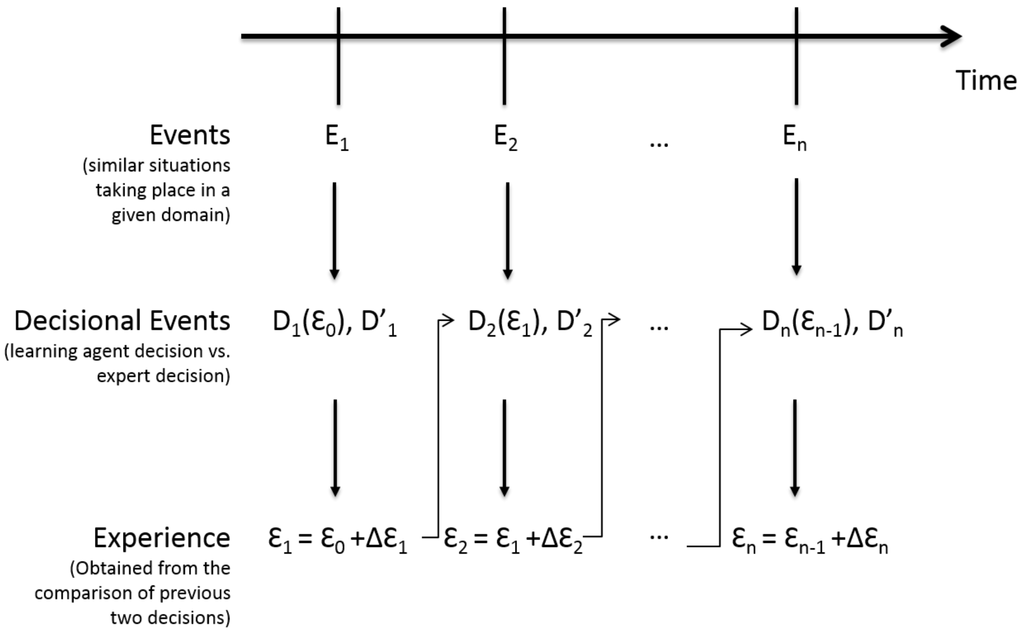

Figure 3.1. Expert-supported experience acquisition model.

3.3.2 Generic computational implementation

Figure 3.2 depicts a general implementation of the expert-supported experience acquisition model described at the previous Section. Its main modules are described next.

a. **DSS Experience Base**. The Experience Base is the module which stores the initial experience of the DSS under training, which is usually provided by a group of domain experts. There are a number of different techniques to model the experience of the system. In this Thesis we pursue systematically the use of semantic technologies that allow more rich and flexible representations.

b. **Learning Algorithm**. The Learning Algorithm carries out the new experience discovery over the previous Experience Base. In this Chapter, SOEKS and DDNA are proposed for learning from experience paradigm due to their advantages over other methods (see Sections 3.2.2 and 3.2.3).

c. **New Experience**. In the field of DSS, an important requirement is that the new knowledge and conclusions inferred from experience has to be formulated in a human understandable way, because decision makers will be always at the end of the chain making the real decisions. Hence, techniques with human understandable representations of the new knowledge and experience obtained are needed.

d. **Experience Supervision Procedure**. A procedure to check the validity of the new experience inferred is needed in order to ensure the correctness of the knowledge increments in the system. This procedure may involve domain experts in order to guarantee the validity of the new experience to be inserted in the DSS Experience Base. In fact, this mechanism ensures that the system is really acquiring the decision strategies of the expert.

As it can be seen in Figure 3.2, the process is cyclic. Hence, the periodicity of the update of the DSS Experience Base has to be established by the managers of the DSS.

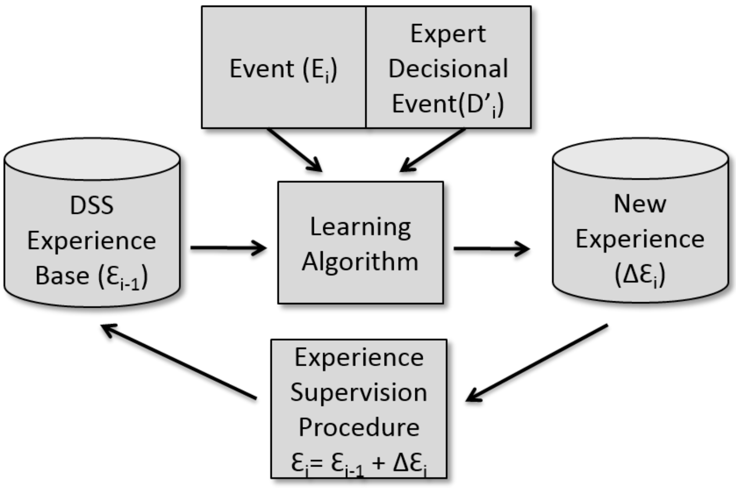

Figure 3.2. Computational architecture for the implementation of the expert-supported experience acquisition method for DSS.

3.3.3 SOEKS and DDNA based computational implementation

In this Chapter the use of SOEKS and DDNA experience representation techniques is proposed in order to solve current main limitations of the DSS and, especially to acquire, formalize and reuse the experience gathered by the DSS in a human understandable way. To meet this goal, the computing architecture that is depicted in Figure 3.3 is proposed. This architecture is the particularization of the previous architecture (Figure 3.2) for the SOEKS and DDNA technologies. As it can be seen in Figure 3.3, the Events and their corresponding Decisional Events provided by the experts are stored in SOEKS structures. Once a SOEKS is defined, the SOEKS reasoner seeks for exact or partial matches in the DDNA structure, in order to identify *(i)* pre-existing knowledge, *(ii)* experimental knowledge, or *(iii)* mixed knowledge. The whole process is repeated cyclically for each new event that enters into the system.

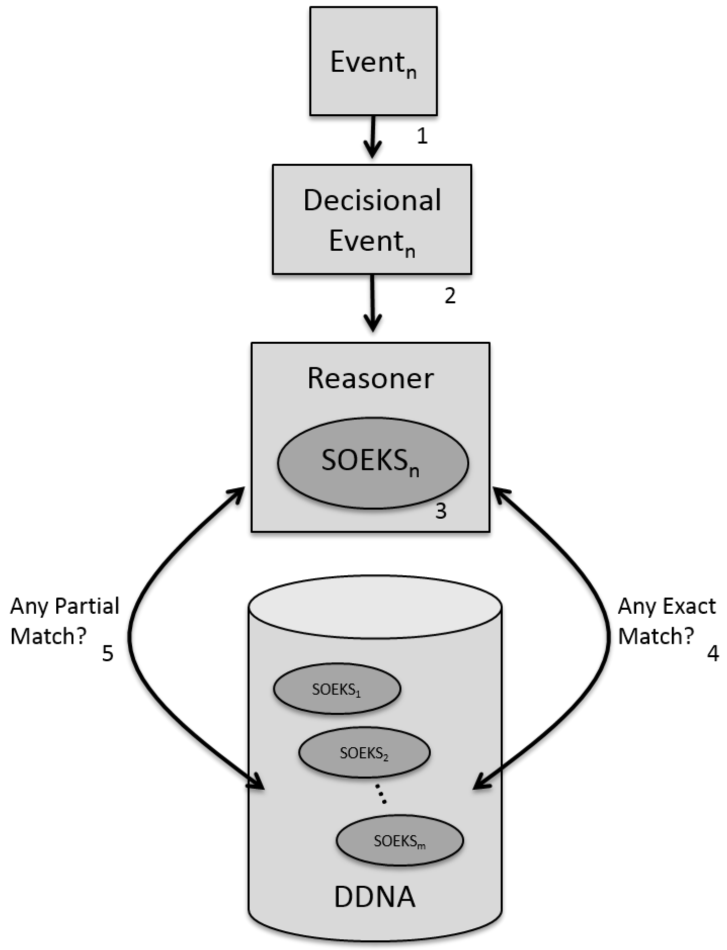

Figure 3.3. Computational architecture for the implementation of the SOEKS and DDNA based expert-supported experience acquisition method for DSS.

The algorithm for the identification of the type of knowledge is depicted in Figure 3.4. First, an exact match query of the new SOEKS is requested to the reasoner. In the case the answer is positive, this piece of knowledge is already available in the DDNA structure and, hence, it is labelled as pre-existing knowledge. In the case the answer is negative, a partial match query is requested. In the case the answer to this second query is negative, the knowledge is considered as a new knowledge entry in the system and, hence, it is labelled as experimental knowledge, and the corresponding SOEKS is added to the DDNA structure. In the case that the answer to the partial match query is affirmative, then some parts of the knowledge are already available in the DDNA structure and, therefore, the SOEKS is labelled as mixed knowledge. For this case, a similarity analysis is carried out next in order to identify the similarity degree with the other preexisting SOEKS in the DDNA structure. This analysis can be carried out with a several techniques such as Support Vector Machines (SVM) [Vapnik 1998] or Case Based Reasoning (CBR) [Maurente 2010]. Finally, the DDNA is updated accordingly to the results of the similarity analysis.

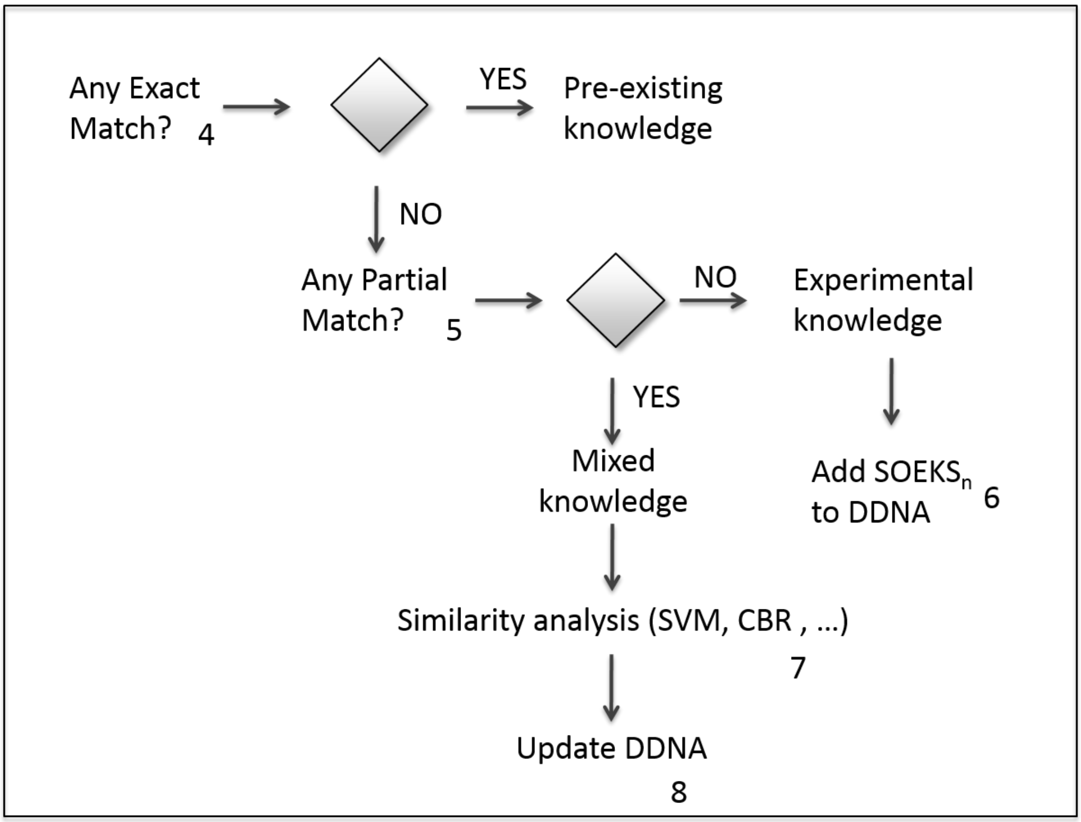

Figure 3.4. Algorithm for the knowledge classification and update of the DDNA structure.

3.4 Challenges

The issues discussed in Sections 3.1, 3.2 and 3.3 have driven our research efforts, translating into specific challenges that were dealt with in the framework of several applied research funding projects. Here we detail such challenges.

3.4.1 Challenge 1: Generic Semantically-enhanced Decision Support Systems

A key limitation faced by the DSS in complex scenarios, such as the clinical environments, is that they have to fit perfectly within the different tasks carried out in the main scenario workflow, which in the case of the clinical practice are diagnosis, prognosis, treatment, evolution and prevention ([Sanchez 2013], [Sanchez 2014b]). In order to achieve the integration with the main activities carried out in different scenarios, and to tackle with the more important limitations of the DSS detected so far, a generic architecture of a Semantically-enhanced DSS (S-DSS) is needed. The S-DSS proposed to meet this challenge [Sanchez 2013] must provide *(i)* specialization, to cover the different tasks performed during the clinical decision workflow stages, *(ii)* control, to handle the knowledge and the performance of the system, and also *(iii)* knowledge reutilization. Both specialization and control capabilities are adequately provided by multi-agent systems (MAS), where each agent can be oriented at specific tasks, also covering inter-agent communication and synchronization. On the other side, knowledge reutilization is supported by the application of semantic technologies. Therefore, the combination of semantic technologies and the MAS paradigm to create a Semantically-enhanced S-DSS (SDSS) is highly required. Such a system will help the decision makers to handle individual and collective decisions and will also learn from the different experiences to reuse this knowledge in future decisions.

3.4.2 Challenge 2: Experience-based Decision Support Systems

The early diagnosis of Alzheimer's disease is one challenging task in which computerized decision support may be greatly appreciated. Interest in CDSS for the early diagnosis of Alzheimer's disease (AD) is great, because it is the leading cause of dementia in developed countries [Monien 2009]. Diagnosis of AD is commonly carried out through the analysis of the results of different medical tests, which are multidisciplinary by nature, such as neurological, neuropsychological, and neuroimaging tests [Monien 2009]. In addition, recent advances in early diagnosis of AD date back the initial stages even 15 years before the first clinically recognizable symptoms become visible [Monien 2009]. Moreover, the biological cause for AD is to be discovered yet. During the patient evaluation process, a large number of parameters are generated. Hence, making a proper diagnosis becomes a knowledge handling problem. Therefore, there is a need for the medical and scientific community to discover which parameters are relevant and which are not with regard to an early diagnosis.

Recently, knowledge-based DSS have been proposed for the diagnosis of the Alzheimer's disease, which are based on semantic technologies for knowledge representation and a set of static production rules provided by domain experts acting as the criteria for the diagnosis [Sanchez 2011a]. In order to overcome the limitations of current DSS, Experience-based DSS (E-DSS) need to be developed, enabling the discovery of new knowledge in the system, and the generation of new rules for the diagnostic reasoning. To meet the challenge of designing an E-DSS, the optimal approach is to upgrade a state-of-the-art knowledge-based DSS which is actually running. The proposed approaches, reported in [Toro 2012], are the SOEKS [Sanin 2009a] and DDNA ([Sanin 2009b], [Sanin 2012]) under their Web Ontology Language (OWL) form [Sanin 2007], due to previous successful developments that required to capture previous experiences and discover new knowledge using bioinspired techniques and the reasoning capabilities offered by ontologies.

3.4.3 Challenge 3: Adaptive Decision Support Systems

Difficulties in knowledge base maintenance and update have been identified as a key factor in several relevant publications [Sittig 2008]. In order to provide a good performance, CDSS need to incorporate updated knowledge about the different domains, and / or decision criteria. This knowledge is generated from various sources, such as scientific publications, reference books and internal reports. In general, the specification of a knowledge domain is usually made by a group of domain experts, who share their knowledge reaching an agreement [Toro 2009]. The process steps are as follows: *(i)* literature review, *(ii)* evidence evaluation, *(iii)* drafting of the domain knowledge and decision criteria, *(iv)* consultation and peer review between different domain experts, and *(v)* approval of contents [SIGN 2011]. Next, three main issues arise at this point.

New findings and discoveries take place each and every day in the medical domain. Therefore content updating should be redone periodically. Most professional teams cannot assume the effort because they lack the resources needed for such tasks, and thus the knowledge supporting the DSS may easily become outdated, and even obsolete. The manual updating of domain rules has a great risk of introducing inconsistencies and semantic noise. On the other hand, the relevant-to-the-domain rulesets must be as extensible as possible. Therefore, tools for rule handling are required to facilitate the addition of new rules and ensuring the correctness of the updated system. Additionally, each rule has a different weight or importance in a decision. When the process of rule generation is performed by hand, rule weighting becomes subjective. Hence, new adaptive architectures are needed in order to keep DSS automatically updated. In order to achieve that, the proposed approach [Sanchez 2014a] uses the SOEKS [Sanin 2009a] and DDNA [Sanin 2009b] that learn and keep maintained from decisional events acquired and formalized by the use of experiential knowledge representation techniques.

3.5 Contributions

The contributions produced during this Thesis addressing the challenges presented in the previous section are described next.

3.5.1 Contribution 1: Generic Semantically-enhanced Clinical Decision Support System

The use of the agents-based paradigm provides the system with the so-desired modularity, and in this way scalability is also intrinsically accomplished by the system. In order to achieve this scalability, our system supports the inclusion of new agents, which could be implemented in the future and then incorporated. Figure 3.5 depicts an overview of the MAS architecture proposed for the clinical domain. There are nine distinct agents: *(i)* information agent, *(ii)* data translation agent, *(iii)* knowledge and decision agent, *(iv)* standards and interoperability agent, *(v)* reasoning agent, *(vi)* experience acquisition agent, *(vii)* application agent, *(viii)* user profiling agent and *(ix)* majordomo agent.

Information agent. The information agent gathers the information needed by the system, to be processed by other agents later. For this purpose it deals with the accessible information in the data repository of the architecture. In particular, the different data bases and sources in the repository may be heterogeneous in terms of serialization formats, communication protocols, size, implemented security levels, and location.

Data translation agent. It aligns the data structure of the data repository to the knowledge and decision model stored in the knowledge repository, called KREG Model, which consists of 4 layers: *(i)* Knowledge layer, containing the set of domain ontologies of the system, *(ii)* Rule layer, composed by a set of rules with the criteria for reasoning, *(iii)* Experience layer, containing the set of decisional events that model the experience of the system, and *(iv)* a Clinical Guideline layer containing the knowledge model of the clinical protocols and recommendations.

Knowledge and decision agent. The knowledge and decision agent deals with the creation, edition and visualization of the KREG Model, and it is aimed at guaranteeing the maintainability and extensibility of the knowledge of the system. Tools adapted to each of the 4 layers of the KREG Model are proposed: *(i)* graphical ontology editors and tools for knowledge extraction from evidence-based medicine sources; *(ii)* tools for rule edition and visualization, as well as for the extraction of the decision criteria embedded in the clinical guideline semantic models; *(iii)* tools for the visualization and navigation of decisional events in the experience model of the system; and finally *(iv)* tools for the digitalization of the knowledge of clinical guidelines.

Standards and interoperability agent. This agent is in charge of aligning the KREG model with standards that will provide the system with interoperability for the communication with other clinical systems and possible CDSS. It will also allow the creation of shareable and understandable clinical decision support services, which open new business model for clinical decision support, e.g. Clinical Decision Support As A Service (CDSaaS). Standards covered by this agent include *(i)* EHR related standards, such as HL7 and ISO 13606, *(ii)* standardized ontologies, as for instance SNOMED CT, ICD-10, UMLS, as well as *(iii)* standards for clinical guideline representation (GLIF).

Reasoning agent. The reasoning agent interacts with the KREG Model, a classical semantic reasoner and the query engine, in order to obtain inferred responses that will aid clinicians during decision making. Fast querying and reasoning techniques used to provide time efficient performance are needed here and the use of Reflexive Ontologies to provide quasi-real time responses from those knowledge sources is proposed [Toro, 2008].

Experience acquisition and handling agent. Clinicians learn new criteria for decision making during their daily experiences. Following this same paradigm, the experience acquisition and handling agent gathers and stores the experience of clinicians or other users in the system, for the evolution of the initial knowledge and rule models. In fact, the experience acquisition and handling agent provides automatic maintenance and updating of the KREG model. The use of the Set Of Experience Knowledge Structure (SOEKS) and Decisional

DNA (DDNA) technologies to evolve the rule model of a CDSS with acquired experience is proposed [Toro 2012].

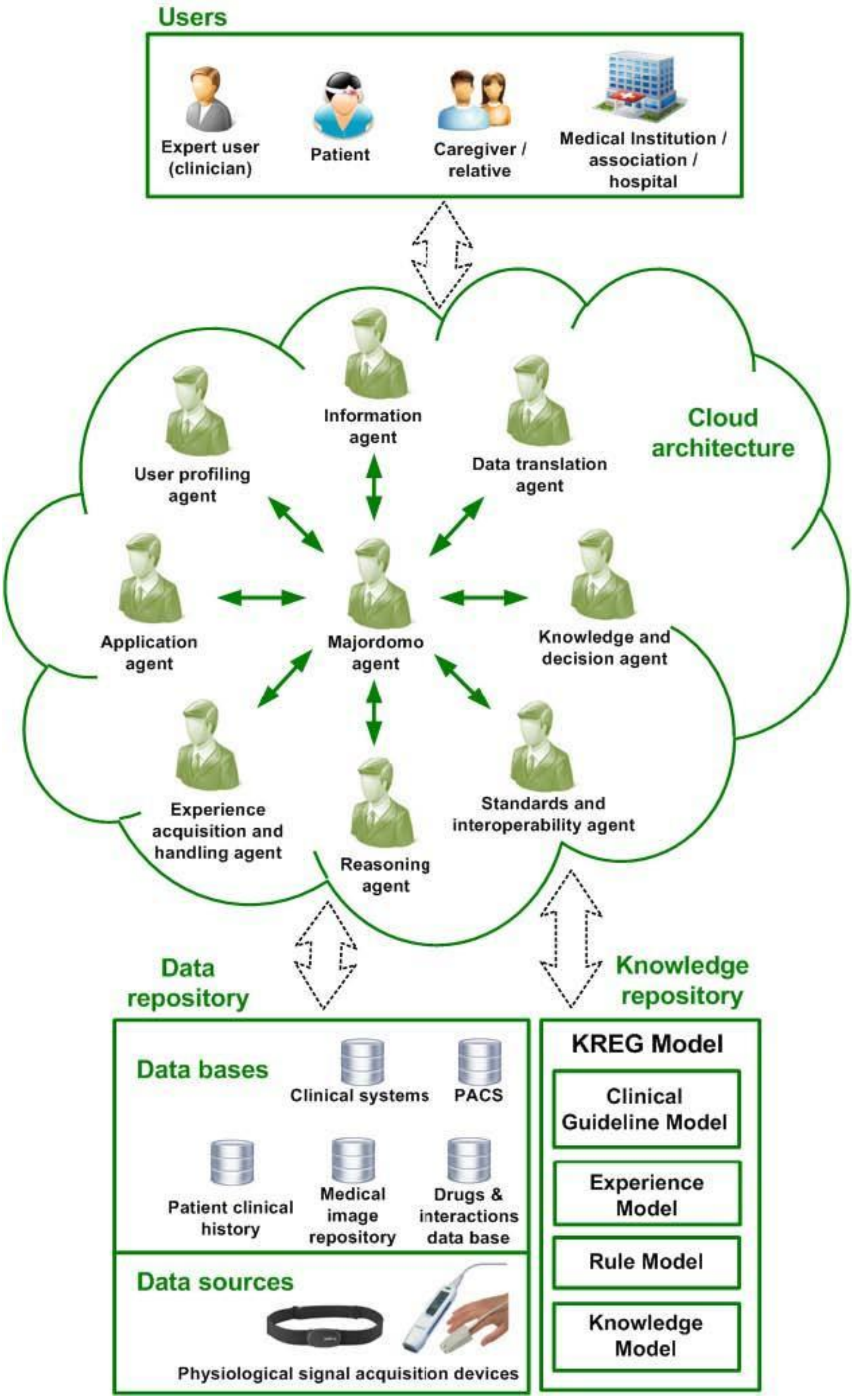

Figure 3.5. Generic Semantically-enhanced Clinical Decision Support System Architecture [Sanchez 2013].

Application agent. The application agent is in charge of the interaction between the user and the system, that will be held by graphical user interfaces (GUI) oriented at different purposes: *(i)* decision support, *(ii)* authoring tools for the edition or visualization of the underlying models, and *(iii)* patient interface for accessing clinical results, non-clinical results and physiological signals coming from user medical devices. Visual analytic techniques will be presented to facilitate the visualization of patient data, criteria for decision, next steps on the process, and most probable diagnosis or suitable treatments for a specific patient, among others.

User-profiling agent. The user-profiling agent detects the different users in the system, characterizes them, and provides them the corresponding accessible user interfaces. The following users of the system are considered: *(i)* clinicians or domain expert users, *(ii)* patients, *(iii)* patient relatives or caregivers, and *(iv)* medical institutions, associations or hospitals.

Majordomo agent. The majordomo agent is in charge of the synchronization and control of the agents in the platform. In our approach agents are explicitly not allowed to talk to each other. For that purpose they must interact through the majordomo. Thereby, security issues are reduced and inconsistencies due to simultaneous communications between different agents are avoided (asynchronism). Whereas the rest of the agents are specialized in different task, the majordomo agent specialization is the control and performance of the rest of the system.

Implementation

The proposed generic Semantically-enhanced Clinical Decision System was designed and implemented in LIFE project as a case study for the Breast Cancer Functional Unit (BFU) of the Valencia University General Hospital. It is fully described in [Sanchez 2013]. Additionally, a methodological evaluation of the system which lasted 15 months was performed, including i) verification, ii) validation, iii) evaluation of the human factors, and iv) evaluation of the clinical effects of the system. The results obtained were very promising and they will be published in a relevant journal in the next future.

Discussion and closing remarks

The presented contribution reported the definition of a generic architecture of Semantically- Enhanced Decision Support System, oriented to solve critical challenges found in the literature, such as modularity, scalability and complex decision workflow scenarios. Multi-agent systems and semantic technologies have been combined in an innovative way to meet aforementioned issues. Next, further improvements are needed in order to cope with the remaining limitations such as capturing and reusing the experience of the decision makers. The next contributions in this chapter deal with these goals.

3.5.2 Contribution 2: Experience-based Clinical Decision Support System for the early diagnosis of Alzheimer's Disease

The architecture of an Experience-based CDSS (ECDSS) [Toro 2012] for the early diagnosis of AD is described. The main expected benefit of the proposed ECDSS is that the experience of the physician using this system is stored in it. With this experience the system is able to *(i)* make explicit the implicit knowledge contained in the system and *(ii)* generate new criteria to drive clinical reasoning.

The proposed system is the evolution of a previous work presented by [Sanchez 2011a] in which a knowledge-based CDSS for the diagnosis of AD was introduced. The system was based on ontologies for knowledge representation and a semantic reasoning process that inferred diagnoses for patients. The semantic reasoning was driven by a static set of production rules provided by AD experts. The previous system has been extended with the application of SOEKS and DDNA to provide it with the ability to evolve the rule set and discover new rules. The architecture of the ECDSS consists of five layers (Figure 3.6): a data layer, a translation layer, ontology and reasoning layer, an experience layer, and an application layer. Each layer is described next.

Data layer. Heterogeneous and spatially disperse databases (DBs) store the data that feed the ECDSS presented in this section. These DBs, which can be provided and maintained by different organizations, are all accessible to our system and they form the data layer of the architecture.

Translation layer. The translation layer performs an alignment between data in the DB of the data layer to knowledge that is stored in the ontology and reasoning layer; each DB is related to a translation module in the translation layer. In this way, DB does not need to be aligned or intercommunicate directly; they remain decentralized.

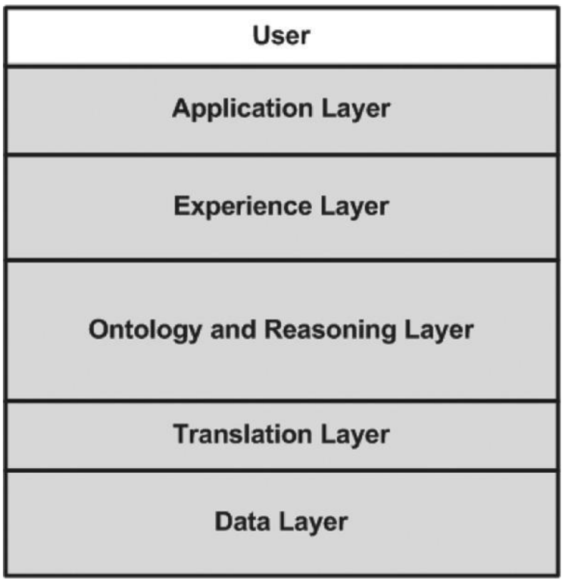

Figure 3.6. Experience-based Clinical Decision Support System architecture [Toro 2012].

The ontology and reasoning layer. It contains the knowledge of the system and performs reasoning processes for clinical decision support. Figure 3.7 shows the structure of the ontology and reasoning layer. Ontologies were chosen as the knowledge containers of the system. In particular, an ontology made of three different ontologies model this domain of diagnosis of AD: the Mind ontology (which contains the medical tests results on patients) [Sanchez 2011a] and the supporting ontologies SWAN (which links to accepted medical hypotheses and publications) [Ciccarese 2008] and SNOMED CT (for standardization purposes on terminology) [Nyström 2010]. The intrinsic semantics embedded in the ontologies can lead to the discovery of new knowledge, such as diagnoses from implicit knowledge or new connections in the model when queried and inferred using production rules and description logic (DL) reasoners. Additionally, domain experts have generated a set of production rules that drive the semantic reasoning process [Sanchez 2011].

Experience layer. It is based on SOEKS and DDNA. It stores the experience of the user (the methodology and criteria used for the diagnosis process) in forms that represent the formal decision events in an explicit way. This experience is then applied, and new knowledge and new rules that drive the diagnosis are discovered by the system. In this way, not only are diagnoses suggested to physicians but new or modified rules to achieve those diagnoses are also supplied.

Application layer. It deals with the interaction between the user and the system. A graphical user interface (GUI) gathers the inputs given by users and presents the results to physicians to provide support for decision making.

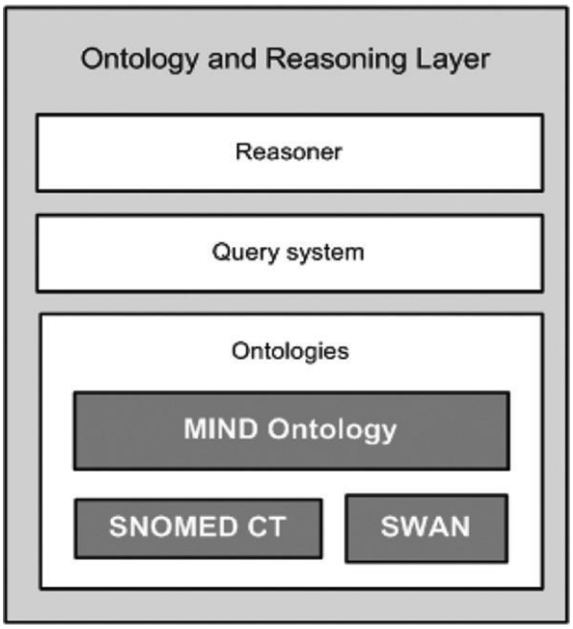

Figure 3.7. Proposed structure of the ontology and reasoning layer [Toro 2012].

Implementation

The proposed ECDSS was designed and implemented in MIND project. It is fully described in [Toro 2012]. This paper is available at the annexes of this doctoral dissertation.

Discussion and closing remarks

The system proposed is very promising, because it does not rely only on the criteria given by the domain experts providing the initial rule set but also relies on the experience of the domain experts that are using the system. With this experience, some of the rules may be modified or some other may be generated in order to have a more accurate rule set, and therefore, a more accurate decision can be taken. In Section 3.4.3 Contribution 3: Adaptive Clinical Decision Support System, an experience acquisition and evolution process is proposed.

3.5.3 Contribution 3: Adaptive Clinical Decision Support System

A Decisional Event represents a decision made on an individual, and on a decision category, for which a set of recommendations have been generated based on a given set of rules. The action of making the decision implies the selection of a final decision by the decision maker. Such final decision can be made according to the provided recommendations or not. Next, the Decisional Event is stored into a SOEKS, including *(i)* data associated with the individuals, *(ii)* variable values and constraints, *(iii)* rules applying to decision domain of the decision category, and *(iv)* applying functions.

The set of SOEKS stored into Decisional Chromosomes and Decisional DNA follows a temporal succession. Once Decisional Events are acquired into a SOEKS structure, the information they contain can be used by algorithms evolving the rulesets. Some of those algorithms allow to *(i)* gradually and repeatedly correct rules as well as deprecate them relying on the existing experience, and *(ii)* generate new rules. Three particular rule managing algorithms are described in [Sanchez 2014a].

Suggested changes on rules resulting from those methods will result in a secondary rule set. Such secondary ruleset will then be analyzed by a committee of domain experts, that will discuss on which of those changes are to be included in the primary ruleset of the DSS. Figure 3.8 illustrates the complete experience acquisition process, including the generation of SOEKS and the evolution of the ruleset.

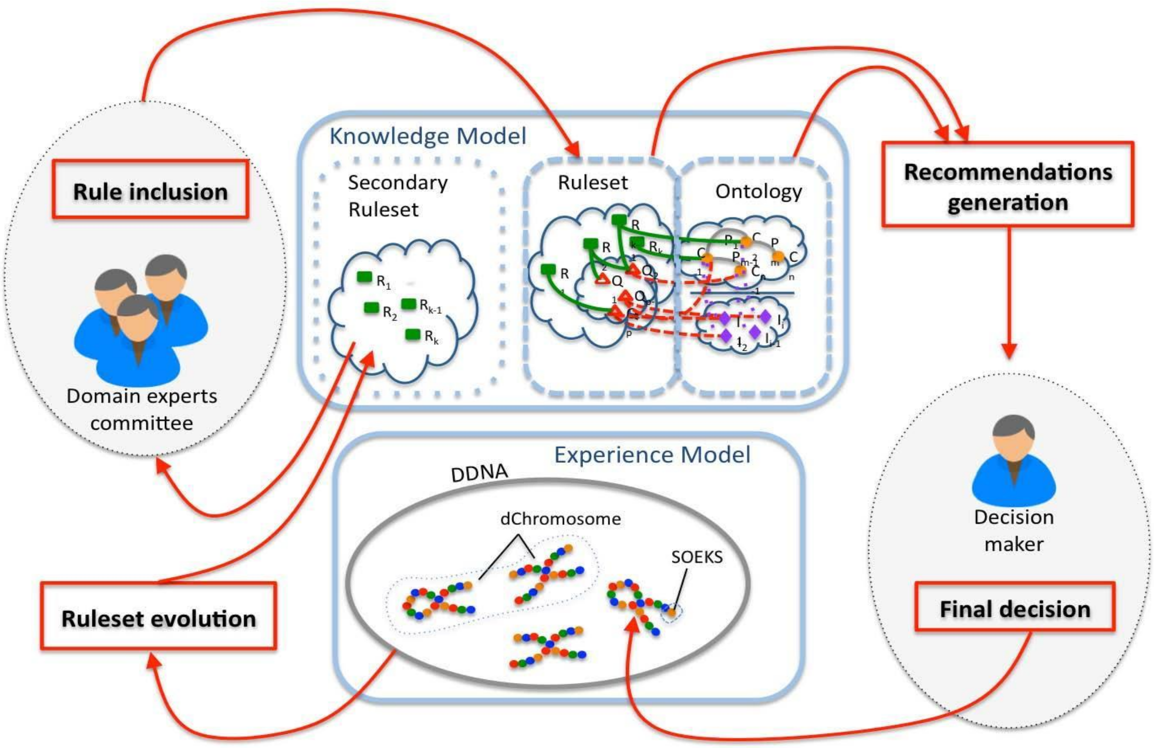

Figure 3.8. Experience acquisition process [Sanchez 2014a].

Implementation and validation

The proposed experience acquisition process was designed and implemented in the LIFE project as a case study for the Breast Cancer Functional Unit (BFU) of the Valencia University General Hospital. The process has been validated with 71 example patients. It is fully described in [Sanchez 2014a].

Discussion and closing remarks

In order to ensure the correct experience adoption process through long periods of time, experience validation and revision methods are necessary. To meet these requirements, further research on decision traceability and experience quality measurement has to be carried out and integrated in the proposed architecture. Besides, the proposed experience acquisition process can be completed by means of the integration of the consequences of the decisions in the system as well. The consequences of the decisions are very valuable pieces of information that have to be formalized, added and reused in the experience model of the DSS.

3.6 Discussion and future work

The contributions reported in this Chapter demonstrate a continuous research activity carried out during more than 6 years on Decision Support Systems (DSS). In this Chapter, we described contributions dealing with the issue of designing innovative DSS that capture, formalize, reuse and evolve the experience of the decision makers. This global challenge has been split in three partial challenges. Next, the main results and the future work lines will be highlighted.

The first challenge consisted in the definition on a generic architecture of Semantically-Enhanced Decision Support System, oriented to solve some of the challenges found in the literature, such as supporting multiple related decisional tasks in complex scenarios. In order to cover the aforementioned problems of DSS, we have proposed the combination of the following technologies: *(i)* multi-agent systems, which provide the system with modularity and scalability, *(ii)* semantic technologies, which provide re-use of knowledge and flexible knowledge representation models to support extensibility, *(iii)* the Reflexive Ontologies (RO) technique, which speeds up reasoning processes, improving the overall efficiency of the system and providing timely advice, and *(iv)* experience-based reasoning techniques such as SOEKS and DDNA, with which the discovery of new knowledge is possible and provide automatic maintainability of the system and the knowledge in it.

The second challenge has dealt with the definition of an Experience-based DSS (E-DSS) that enables the discovery of new knowledge and new rules in the system. In particular, an E-DSS that support the clinicians in the early diagnosis of Alzheimer's Disease (AD) has been carried out. Furthermore, it is also a research tool that could help them determine the most relevant parameters for the diagnosis of AD and its cause. The system proposed does not rely only on the criteria given by the domain experts providing the rule set but also relies on the experience of the domain experts that are using the system. With this experience, some of the rules may be modified or some other may be generated in order to have a more accurate rule set. Additionally, SOEKS has been shown to be a valid technology for the discovery of new rules.

Regarding the third challenge, an experience-based approach that allows the (semi-) automatic maintenance and update of generic Semantically-enhanced Clinical Decision Support Systems (S-CDSSS) has been presented, which is based in an experience-driven learning process that evolves the ruleset of a S-CDSS based on the previous Decisional Events experienced by physicians (their day-to-day expertise).

Such evolution process allows the discovery of new knowledge in the system (intrinsic Knowledge) (a) facilitating the evaluation of the decisions made previously and the analysis of the actions followed, in order to improve the performance at clinical, ethical or economical levels, (b) allowing the training of new team members or facilitating current members to keep up-to-date, and (c) suggesting new knowledge that could be validated, driving clinical research activities or trials. In this sense, our approach could foster research activities of the medical team.

Remarkably, the use of SOEKS and DDNA is a contribution in the field of decision support systems that takes existing elements from rule-based and expert systems to create intelligent experience-based systems.

Furthermore, relevant improvements can be proposed for future DSS. In this sense, the integration of the consequences of the decisions taken in the experience base of the DSS would contribute to complete the experience stored in the system. As it can be seen in Figure 3.9, the two information sources that provide experience can be combined in future DSS: the expert decisions and the real consequences of the taken decisions. Therefore, a system following this model would be able to mimic the good expert decisions, those leading to desired consequences, while minimizing the error in the consequence domain.

Additionally, another relevant feature that should be added to future DSS is the traceability of the experience stored in the system (see dotted lines in Figure 3.9), which implies traceability of the taken decisions and the corresponding consequences. This process would allow the verification of the experience contained in the system and its amendment in the case that wrong entries are detected.

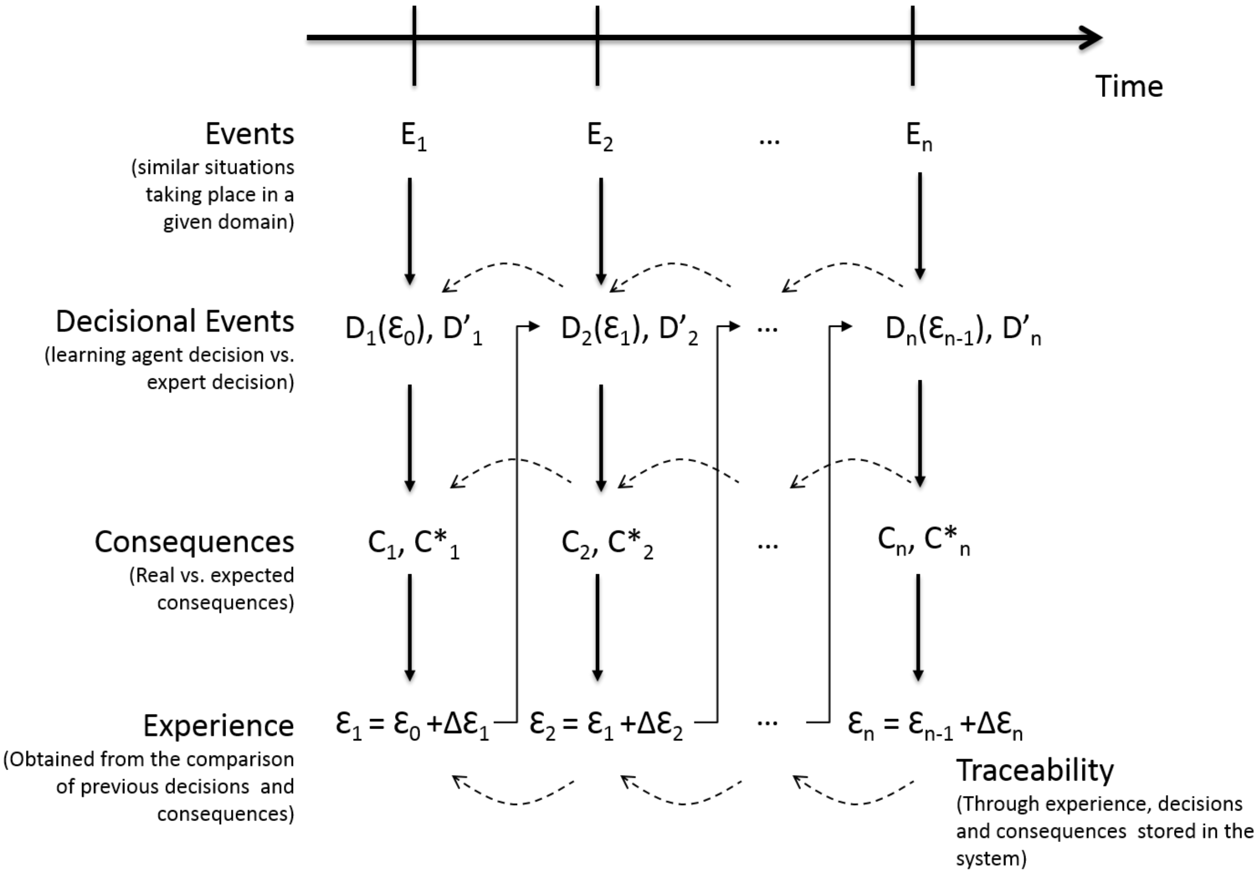

Figure 3.9. Enhanced experience acquisition model.

Chapter 4

Assistive Technologies

This Chapter describes the research conducted in the field of Assistive Technologies. The main contributions have been performed in different contexts such as Ambient Assisted Living, telerehabilitation and autonomous navigation, in which the needs of different target users with special needs, such as elderly people, people with Alzheimer's Disease, stroke patients, and people with visual impairments, have been considered. The relevance of Human-Computer Interaction for each scenario will be highlighted, since research on ways to facilitate the interaction between people and computers is the key element for the success of each assistive solution.

In this chapter, we focus in the following four challenges:

1. The design of a natural interaction method between elderly people with Alzheimer's Disease and Ambient Assisted Living environments.

2. The design of a realistic and engaging joint telerehabilitation method for elderly people at home.

3. The design of an immersive virtual reality and robot assisted telerehabilitation method of the upper limb on people with stroke.

4. The design of an autonomous outdoors navigation system of people with visual impairments has been considered.

This Chapter is structured as follows: Section 4.1 introduces the basic ideas and motivation behind Assistive Technologies; Section 4.2 describes the state of the art in the field; Section 4.3 describes the general framework of the Chapter; Section 4.4 introduces the challenges tackled by the author and his research team; Section 4.5 describes the main contributions achieved. Finally, Section 4.6 presents a discussion of the results reported in this chapter, describing future work.

4.1 Assistive Technologies: motivation

Assistive Technologies were first defined in the Technology-Related Assistance Act [Tech Act, 1988] as "any item, piece of equipment, or product system, whether acquired commercially off the shelf, modified, or customized, that is used to increase, maintain, or improve functional capabilities of individuals with disabilities". It is apparent that software or online services were not included in this definition.

Several years later, Assistive Technologies definition was revised and completed as “any product (including devices, equipment, instruments, technology and software) specifically produced or generally available, for preventing, compensating for, monitoring, relieving or neutralizing impairments, activity limitations and participation restrictions. Assistive Technologies are used by individuals with disabilities in order to perform functions that might be difficult or impossible otherwise” [ISO 2007]. Assistive technologies can include mobility devices as well as hardware, software, and peripherals that assist people with disabilities in accessing computers or other information technologies which are the focus of this Thesis. Additionally, standardization efforts have been carried out in this field in order to establish a classification of assistive products especially produced, or generally available, for persons with disability. Another related remarkable standardization effort, trying to consolidate an international common language, has been carried out by the World Health Organization in order to provide an International Classification of Functioning, Disability and Health (ICF) [WHO 2014].

The Assistive Technology domain is very wide and highly interrelated with several other economic sectors, such as welfare services, e-Health sector, Ambient Assisted Living [Stack 2009]. The current population of Assistive Technologies potential users is large. Furthermore, it is expected to continue growing in the years to come. As an example, there are nowadays approximately 45 million people in Europe suffering from a chronic health problem or disability. Furthermore, the aging of population implies that more people will have to live with some sort of disability. The number of people over 60 in the EU increases nowadays by more than two million per year. Available demographic statistics show that the share of people aged 65 years or over in the total population is projected to increase from 17.1% to 30.0%, and the number is projected to rise from 84.6 million in 2008 to 151.5 million in 2060 [Eurostat 2011]. These demographic shifts are going to be an important driver of assistive products demand, as well as for innovations in many technological related areas [Stack 2009]. Many assistive technology devices are addressed to the needs of the elderly, which, under the aforementioned demographic conditions, is an ever growing market. For example, in Sweden, about 70% assistive devices prescribed go to people aged over 65. Hence, assistive technology economic relevance grows each year mainly because of two relevant circumstances: i) aging population is demanding solutions to maintain independence and quality of life [WHO 2011] and, ii) there are a number of habits in our society which produce kinds of illness that lead to subsequent chronic conditions and disabilities, such as stroke [McKay 2004].

An important characteristic of this situation is a growing diversity of citizens, in the terms of people with different capabilities and needs claiming their right to keep on active, independent and enjoying the best possible quality [Eurostat 2011]. In this sense, from a governance point of view, is has to be stressed our society has the moral obligation to ensure equal access to all of its services to all citizens regardless of their capabilities, education or technical skills [European Commission 2010]. In parallel, the following barriers to the mainstream adoption of assistive technologies have been detected:

- Language, interoperability, standardization and cost [Stack 2009].
- Provision of appropriate training to the disabled end-user [Stack 2009].
- Familiarity, willingness to ask for help, trust in the technology, privacy, and design challenges [Fischer 2014].
- Understanding the user context and providing the required personalized assistive services [Mokhtori 2012].
- User interface design for natural interaction with the provided services [Mokhtori 2012].
- Support for performing daily living activities such as bathing, changing clothes and preparing meals [Mokhtori 2012].
- The complexity of the users' profile defined by their abilities [Mokhtori 2012].
- Access to assistive products and technologies, alterations to the physical environment, social support and relationships, and adjusted health and social care services [Randstrom 2012].

Due to this general situation, there is an enormous demand for innovation of Assistive Technologies that excel in the customization of the user interfaces to fit to the particular needs of the users.

4.2 State of the Art

In this section, we aggregate the state of the art review on relevant topics for the mainstream provision of assistive technologies.

4.2.1 Abstract User Interface Description Languages

The separation of the user interface of an application, device or a service from its core functionality is a key design issue to provide adaptability and flexibility of implementation. Based on user interface independent and modular design concept, specialists can develop user interfaces for specific context of use (user, device, scenario). Following this design guideline, user interfaces can be updated or upgraded independently from the core computational functionalities implemented. Furthermore, these user interfaces can be automatically generated or adapted to enable universal access or enhance user experience. Diverse Abstract User Interface Definition Languages (AUIDL) have been proposed [Guerrero 2009] to achieve this design goal. The main XML-compliant AUIDLs that provide device-independence and modality-independence are: *(i)* User Interface Markup Language (UIML), *(ii)* USer Interface eXtensible Markup Language (UsiXML), *(iii)* The eXtensible Interface Markup Language (XIML), *(iv)* XForms, *(v)* Concurrent Task Trees (CTT) + MariaXML, and *(vi)* The Universal Remote Console (URC) framework. In order to compare of the AUIDLs, several reference frameworks are available ([Fonseca 2010], [Trewin 2004]). The results of these comparisons are available at [Epelde 2014b], which show that Universal Remote Console URC [ISO/IEC 2008] is an appropriate candidate to be used in mainstream applications in order to provide standardized user interface abstraction.

4.2.2 Automatic User Interface generation

Designing user interfaces manually for every target user group, platform and application is a very inefficient user interface development methodology. The automatic user interface generation could be very useful to solve this problem. The process, however, requires guiding logic specifications, formalized from usability knowledge and represented in a form that an automatic UI generation system can use [Dubey 2011]. A first approach to the automatic user interface generation is the automatic user interface adaptation [Florins 2006], especially when dealing with devices with different form factors. One important issue when developing automatic user interfaces is to maintain the consistency of those interfaces, in such a way that the familiarity of the user with them is ensured all the time [Nichols 2006].

For the automatic generation of the user interface layout, three methods are the most widely used *(i)* apply a set of rules in order to translate from an abstract UI to a concrete one [Kavaldjian 2009], *(ii)* solve a constraint-satisfaction problem, where the interactors and layout are chosen to optimize a numerical function [Song 2008], and *(iii)* hybrid approaches. Latest research in the field aims at extending the URC's proposing an adapt-at-runtime approach. A new component called GenURC within the URC environment generates a personal and context-driven user interface in a two-step process. A rich grouping file is used as an intermediate user interface description, containing "flexion points" for runtime adaptations based on the use context. This approach will allow for the integration of the URC framework with the GPII user preference model [Zimmermann 2013].

4.2.3 Natural Human Computer Interaction

Natural interaction is often taken as a synonym of intuitive interaction. Intuitive interaction has been defined as "interaction based on the use of knowledge that people have gained from other products and / or experiences in the past" [Blackler 2010]. There is a wealth of technologies and research conducted in this field in the last years holding the promise of easier and more personalized interaction. We comment on the most salient ones:

Hand gesture recognition via computer vision is a technology that is obtaining big success both in research and at commercial level (for example, using Kinect from Microsoft). Hand gestures can be classified into two categories: static and dynamic. The use of hand gestures as a natural interface is based on research on gesture taxonomy, its representations, and recognition techniques [Hasan 2014].

Multi-touch devices consisting of a touch screen (e.g., computer display, table, wall, etc.) or touchpad, as well as software that manages information from multiple simultaneous touch points, as opposed to the one-touch touch screens. In recent years, the market has seen the proliferation of hardware devices capable of multi-touch and gestural input (such as iPad and Microsoft Surface). Recent research confirms the adequacy of multi-touch tabletop devices for assistive technologies. For instance, they have been demonstrated successfully for the elderly [Loureiro 2011].

Avatars are virtual characters that can be displayed in different screens such as tablets, laptops, or TVs. Their aim is to simulate interaction with real persons or assistants. Recent research results confirmed that elderly users follow some instructions much better when interacting with the avatar [Ortiz 2007].

Binaural sounds (or 3D sounds) are those that can be localized in space, by a person with normal hearing capabilities, due to interaural differences. These sounds can be used for a variety of applications. Typically, they have been used by the gaming industry in order to increase the realism of the game and player engagement. Recently, it has been discovered that 3D sounds are faster to interpret, more accurate and more reliable than similar instructions given in natural language. Also binaural audio perception is less affected by increased cognitive load of users [Giudice 2008]. These outcomes pave the way to use this technology in new application scenarios such as navigation support tools.

Other technologies that also can fit in this category are: speech processing techniques and artificial dialog systems [Heras 2014].

4.3 Framework

In order to provide advanced assistive services (including tele-health and tele-care services), that can be adapted to the needs of all end user categories, applications and use contexts, the architecture depicted at Figure 4.1 is proposed.

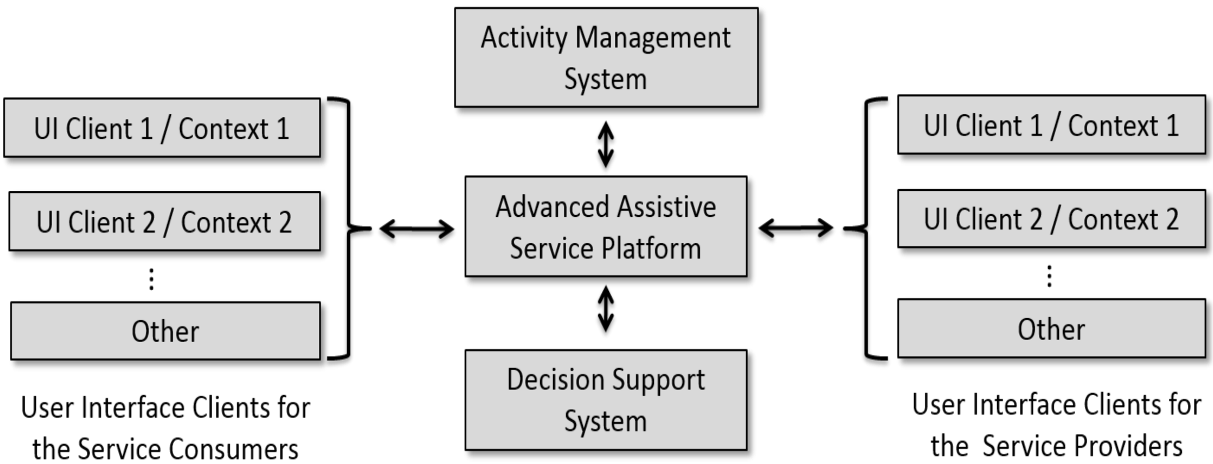

Figure 4.1. Advanced assistive services provision architecture.

The architecture portrayed in Figure 4.1 for the provision of advanced assistive services includes several modules, which are described next:

a) **Advanced Assistive Service Platform**. The platform, typically hosted in the cloud, provides support to both service providers and consumers, and stores all service data, including the data generated by the service providers and the feedback data from the service consumers. The data can be generated in a number of different scenarios or context. In the case of medical applications, the service providers are medical professionals giving medical services, the service consumers are patients receiving those medical services, and the services can be consumed in a number of different contexts such as at home, on-the-go, on travel, etc.

b) **Service Consumer UI Clients**. These User Interface (UI) clients include software and hardware components. Hardware can be TV, smartphone, tablet or PC computers. The software may include modules such as: i) assistive service information, ii) user interaction interface, which may include different interaction modalities, i.e. graphical user interfaces, avatar, etc., iii) communication with local devices performing particular activities, i.e. tracking or monitoring of the person that is consuming the services, and iv) feedback communication to the service platform.

c) **Service Provider UI Clients**. They can be developed analogously to the ones for the Service Consumers. In this way, the service providers can benefit as well of the multi-context and personalized access to the assistive service platform. They can use different devices to access the system (laptop, tablet, ...) and use it from different contexts.

a) **Activity Management System**. This system is intended to provide support to the service consumers in order to accomplish complex tasks, such as telerehabilitation sessions. The service sessions can be modelled using task models, which are run in a task engine, and the outputs are delivered to the user by means of the user interface. This module is particularly relevant for users with special needs, such as people with cognitive impairments that may have to be assisted while using the system.

b) **Decision Support System.** This component supports healthcare professionals in the management of the healthcare data generated by the system, since the system as it is could overload the doctors with data coming from the patients. Hence, in order to increase the performance of the medical team, an intermediate component which analyses the data, detects anomalous situations, and triggers the corresponding alarms, would be needed.

Finally, in order to provide universal access to both service providers and consumers, architectures such as the UCH (see Chapter 2) can be used. Due to the different implementation configurations that are available, the UCH may be implemented in the clients and / or in the service platform. The final configuration will depend on the particular characteristics of the assistive service to deliver.

4.4 Challenges

The issues discussed in the previous sections have driven our research efforts, and they have been translated into specific challenges that were tackled within several applied research funding projects. Here we detail such challenges.

4.4.1 Challenge 1: Natural interaction with Alzheimer's Disease patients

Patients suffering from a mild to moderate stage of progression of Alzheimer's disease typically present cognitive and functional impairments affecting memory, concentration, and learning [Salmon 2009]. This decline of functions, together with the lack of information technology (IT) skills in the generation of people of 60 and over, poses a barrier to exploit the opportunities offered by technology. This is a very important issue, since European population in becoming older at a fast pace [Eurostat 2011], and because technology has been identified as a tool that can be used to promote independent living, improve the safety and autonomy of people with dementia, and support their quality of life [Topo 2009].

Remarkably, people with dementia are not used to learn to operate new devices. Limitations in knowledge and understanding of technology add to the limitations in user communication with the technological products [Nygard 2008]. However, the ACTION participatory design model [Bertrand 2006] (which comprises the identification of user needs, early program development, testing and refining) defends the possibility that people with dementia are able to enjoy computer training sessions and gain considerable satisfaction from learning a new skill they previously thought was not feasible.

In this context, we have been working on several projects (such as I2HOME) addressing the challenge of designing new architectures, based on industry standards for the digital home, with the focus of facilitating the interaction of elderly and disabled people with domestic electronic and communication devices. An universal access architecture was designed in order to facilitate the interaction between ovens, washers, dishwashers, air conditioners, etc., in order to facilitate the future integration of technologies and devices in the homes of people with disabilities. In other words, the integration of new electric and electronic devices in their future living environments can be done easily without the need to make physical or technological adaptations in their homes, to buy a whole set of new devices, or to learn new and complex ways to use the electronic devices they will have at their homes. To this end, interoperability architectures for the digital home, such as the Universal Control Hub [openURC 2013a], have been proposed.

Therefore, the next challenge to meet was to demonstrate that intuitive interaction systems could be developed on top of the aforementioned interoperability architectures in order to facilitate interaction of people with special needs, such as the people suffering from different degrees of cognitive decline from mild cognitive impairment (MCI) to moderate Alzheimer's disease (AD). In this sense, we sought intuitive interface designs, i.e. interfaces that were simple to use and effortless to learn for them. Reports on how this challenge was met are in ([Carrasco 2008] & [Diaz-Orueta 2014]).

4.4.2 Challenge 2: Realistic and engaging joint telerehabilitation for the elderly

Traditionally, telerehabilitation is defined as the use of telecommunications to provide remote rehabilitation services. As several studies point out, the benefits of providing rehabilitation services in the user natural environment (where patients live, work, and/or interact socially), rather than in the clinical setting, are increased functional outcome, enhanced patient satisfaction, and reduction in needed therapy duration and cost [Brienza 2013]. One of the main beneficiaries of telerehabilitation, according to posed challenges and market trends [Simpson 2013], are people with disabilities. The population aging trend has a direct impact on the sustainability of health systems, which is especially true for rehabilitation, because it is generally characterized by repetitive low intensity sessions over a long time period [Parmanto 2009]. Traditionally, physical rehabilitation assessment has been based on assessment scales, and manual tools such as the goniometer and the dynamometer. Recently, A wide variety of robotic systems specifically targeted at rehabilitation have been developed and have confirmed their therapeutic benefits. The elevated cost of such robot-based therapies makes them unavailable in most of the cases for home rehabilitation [Kwakkel 2008]. Regarding joint rehabilitation, different technologies are used for position sensing, movement analysis, and joint angle estimation. It has been identified that inertial sensors are a good solution for home rehabilitation, due to the information they can provide for clinical assessment, their small size, and their relatively low cost and easy interface with computers [Zheng 2005].

In recent years, with evolution of the main game console controllers to wireless and gesture technologies including motion-sensing technologies, there has been an active research area testing the validity of these devices for rehabilitation [Deutsch 2008]. Besides, research on seniors using VR technology has shown that virtual humans (avatars) improve interaction with machines by elder people ([Ortiz 2007], [Carrasco 2008]). Summarizing, in order to foster joint telerehabilitation acceptance by the elderly people, engaging systems have to be designed that can be acceptable by them, so that they can increase the motivation of the patients and the adherence to the therapy, and improve the rehabilitation assessment carried out by the medical professionals. Reports on how we met this challenge was in [Epelde 2014a].

4.4.3 Challenge 3: Upper limb telerehabilitation for patients with stroke

Cerebrovascular accidents (CVA) and spinal cord injuries (SCI) are currently the most common causes of paralysis and paresis with reported prevalence of 12,000 cases per million and 800 cases per million, respectively. Disabilities following CVA (hemiplegia) or SCI (paraplegia, tetraplegia) severely impair motor functions (e.g., standing, walking, reaching and grasping) and prevent the affected individuals from healthy-like, full and autonomous participation in daily activities. Moreover, the societal habits increase the number of such episodes [McKay 2004].

One of the possible intervention points where innovations may help to palliate the burden of healthcare systems is stroke rehabilitation. Neurorehabilitation is a process that aims to recover the capabilities to carry out regular activities, lost by a neurological disease, by re-learning or by active problem resolution. Neurorehabilitation is based on the concept of Neuroplasticity: The brain ability to establish new connections between neurons that are able to substitute lost sinapsis to a greater or lesser extent. This is usually achieved by repetitive therapies. New paradigms have been defined, such as the task oriented rehabilitation process, which is based on the functional task achievement, which seeks training physical, cognitive, psychological and sensitive aspects as well [Cano 2012].

The latest advancements in robotics and neuroscience have shown that robotic systems or exoskeletons can facilitate functional task oriented rehabilitation processes. According to several authors, this type of therapy is more efficient for the reduction of the effects of altered motor control. Robot or exoskeleton assisted rehabilitation systems, which are based on neurorehabilitation principles, are tools that not only help patients move the arm with precision; they also help reduce the fatigue of the therapist during the rehabilitation process. This type of rehabilitation is usually developed immersed in a virtual reality environment. Additionally, this type of system provides the therapists with tools to make complete and objective studies of the evolution of the patients [De Mauro, 2012a].

One of the challenges of virtual reality based robot assisted upper limb rehabilitation, is patients' immersion within the therapy scenario, achieving an improved rehabilitation progress. The difficulty lies in the lack of a realistic representation of the arm in the available games caused by a lack of bioinspiration in the solution. This lack of realism hinders the identification of the patient with the virtual world, negatively affecting the active role of the patient, and his motivation. Therefore, the development of more realistic arm models improves three key factors (bioinspiration, active role of the patient, and motivation) implied in the identified challenge. Additionally, the analysis of state of the art on robotic device based rehabilitation therapies has underlined the need of remote therapy support and the definition of a structured movement quantification data format, interoperable with other rehabilitation systems.

A realistic 3D representation of the arm serving as an interaction mechanism with the virtual world in the rehabilitation therapy is proposed. This would make the user more aware of the movements that he / she is making and would improve rehabilitation outcomes. It also would increase user motivation and engagement in the therapy. Additionally, multimodal patient monitoring could be also developed, together with tools for online patient assessment. These developments would allow the physician to review the therapy without being in the same place and time, optimizing the use of hospital's human resources. This challenge is currently under research by the author and his research team. Preliminary publications available are ([DeMauro 2012a], [Epelde 2013d]).

4.4.4 Challenge 4: Autonomous navigation of people with visual impairments

The population of blind and visually impaired in Europe is estimated over 30 million. On average, 1 in 30 Europeans experience sight loss. Furthermore, sight loss is closely related to old age in Europe, where age-related eye conditions are its most common cause, resulting in

1 in 3 senior citizens over 65 experiencing it [EBU 2013]. Being able to navigate autonomously is one of the most relevant needs for blind people. Some navigation systems especially designed for blind people are entering in the market such as the Kapten Mobility from Kapsys. Nevertheless, its precision is very low for guiding blind people in normal settings such as sidewalks, and the interaction paradigm, which is based in oral natural language instructions, is not adapted to the needs of the blind people, leading to confusing and unsafe situations [Kapsys 2013].

Research on autonomous navigation systems which use spatialised audio (also known as binaural or 3D sounds) information [Blauert 1983] for guiding blind people was defined first on 1985 [Loomis 1985]. Binaural sounds are those that can be localized in space by a person with normal hearing capabilities due to interaural differences, i.e. such as bells or finger snaps. They can be used to guide people in space, simply playing periodically short 3D sounds, and training the person to follow them along the whole path to cover. Originally intended for the gaming industry, dedicated 3D sounds libraries are available for the generation of 3D sounds that can be used for the navigation guiding task [OpenAl 2014]. Furthermore, recently it has been discovered that spatialised audio instructions are faster to interpret, more accurate and more reliable than instructions given in natural language. Also spatialised audio perception is less affected by increased cognitive load on users than language information [Giudice 2008].

Additionally, relevant progress is being carried out regarding satellite positioning technology. The European Geostationary Navigation Overlay Service (EGNOS), which is essentially Europe's precursor to the GALILEO system, is currently providing a terrestrial commercial data service named EDAS (EGNOS Data Access Service). It offers GPS data correction for providing increased positioning accuracy and integrity [GSA 2014].

Hence, a high precision navigation system could be developed which uses the latest positioning Global Navigation Satellite System (GNSS) technologies and the binaural sounds in order to guide the blind people in a safe, efficient and comfortable way along predefined routes, both for urban and suburban scenarios. Research on this topic is currently being conducted by the author and his research team. Preliminary publications available are ([Otaegui 2013], [Carrasco 2013] & [Carrasco 2014a]).

4.5 Contributions

The contributions made while tackling with the challenges presented in the previous section are described next.

4.5.1 Contribution 1: Natural dialog system for people with Alzheimer’s Disease with Ambient Assisted Living scenarios

First, a system to provide natural interaction with the people with mild to severe Alzheimer’s disease (AD) was designed. The goal was to simulate a virtual assistant by means of displaying a realistic avatar on the TV screen. The avatar behaviour was to be programmed by a caregiver, and its goal was to deliver relevant messages, reminders and short instructions related to agenda or to housekeeping. Whenever the avatar had to deliver a message to the end user, the TV broadcast would be interrupted. In order to get the feedback or acknowledgements from the end user, the avatar would ask the user to press certain buttons in the remote control of the TV. Those pressed buttons were stored in the system as well as the reaction times. In case no reaction was received from the user the question was to be repeated a number of times. Once the dialog with the avatar had finished, TV broadcast would be resumed. Figure 4.2 illustrates the final design of the system.

Figure 4.2. Interface to provide natural interaction with people with Alzheimer’s Disease [Diaz-Orueta 2014].

Regarding the data communication between the end user and the caregiver, the architecture described at Section 2.4.2 “Contribution 2: Universally Accessible TV Services” was selected. In this architecture, the UCH was hosted in a server. In this server, a dedicated service was developed for the caregiver in order to control the avatar. In this way, the caregiver schedules reminders and notifications for the user through the UCH. For this purpose a custom service application was needed. The application required the caregiver to enter the notification, the time at which it should be triggered, and the text that the avatar will voice.

The server also included an avatar rendering and streaming engine which was connected to the UCH as a pluggable user interface. Special care was put on the natural and realistic representation of the avatar. When the notification event was triggered, the pluggable user interface generated the avatar and streamed it in real-time to the STB. The UCH can remotely control the STB and also changed the TV channel to show the avatar. Using this technique a true virtual assistant was simulated on the TV screen. Special attention was put on the voice of the avatar and in the synchronization of the lips of the avatar with the voice as well. First, the voice of the avatar had to be realistic, and, second, the avatar had to be lip-synchronized with its speech to ensure that the avatar's facial movements appear natural. To accomplish these requirements, the avatar rendering engine was synchronized with a high quality text-to-speech synthesizer.

Finally, in order to get feedback or acknowledgements, the user is asked by the avatar to press specific buttons on the remote control. These events will be captured by the STB, and then relayed to the UCH, who forwarded them to the caregiver's application. The caregiver's service was implemented with various rule sets that allow performing an escalation plan depending on the user responses.

Implementation and validation

The proposed interaction architecture was implemented during the realization of the I2HOME project. Full implementation and validation is described in ([Carrasco 2008], [Diaz-Orueta 2014]). The tests demonstrated that this approach worked very well for most of the users that took part in the validation: 20 participants, who ranged from moderate to severe AD, were able to interact with the avatar on the TV, and it was observed that in most of the cases they followed the instructions given by the avatar successfully. Further result analysis showed that participants showing better cognitive and functional state in specific neuropsychological tests showed a better performance in the TV task suggested by the avatar. The derived conclusion is that neuropsychological assessment may be used as a useful complementary tool for assistive technology developers in order to further optimize the interaction interfaces to the elderly with different cognitive and functional profiles.

Discussion and closing remarks

The work carried out in this section succeeded in demonstrating that even people with severe dementia can benefit from the technological progress, and interact with home appliances in Ambient Assisted Living environments such as the digital home of the future.

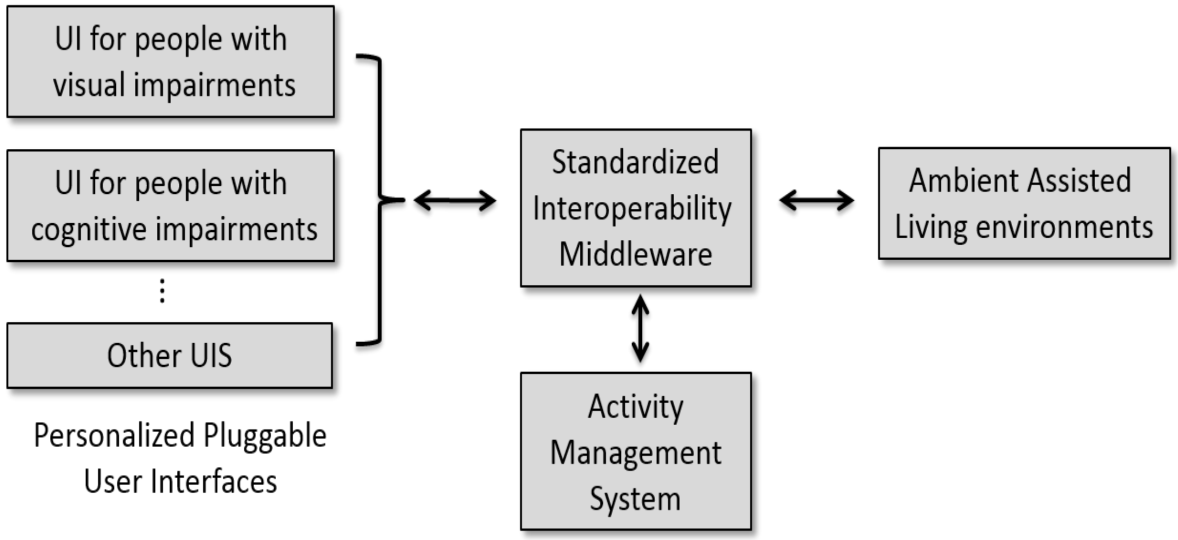

Figure 4.3. Functional layout on natural interaction on Ambient Assisted Living environments.

Results can be generalized, and it can be affirmed that most people can interact with local devices and online services at any context, if the appropriately tailored user interfaces are provided. This concept has been depicted at Figure 4.3, and it is a simplification of the framework architecture proposed at Figure 4.1. This system was implemented by the author in [Murua 2010].

4.5.2 Contribution 2: Realistic and engaging telerehabilitation for elderly people

In order to increase the motivation for using the system by elderly people, and to maximize the adherence to the rehabilitation treatment prescribed by the rehabilitation expert, a realistic virtual physiotherapist, which was shown on TV set, was designed as the main element of the interaction for the seniors' telerehabilitation therapy guidance. The concept was to simulate as closely as possible a rehabilitation session conducted by a physiotherapist using mainstream ICT technologies. In order to achieve user acceptance and convince them to follow a virtual therapist's instructions, a familiar and convincing look was specifically designed in collaboration with medical professionals. The voice of the virtual therapist was selected from a casting to meet the therapist profile in mind.

The virtual physiotherapist would welcome the user at the beginning of each session and explain the goals of the session. Next, a dummy virtual human would reproduce the prescribed exercises on the TV, and the voice of the virtual physiotherapist on the backstage would encourage the patient to follow the same exercises at the same speed. At the time of the design of the system, a simple model was selected for the dummy virtual human to avoid stigmatization. The developed virtual therapist and dummy concepts are depicted at Figure 4.4.

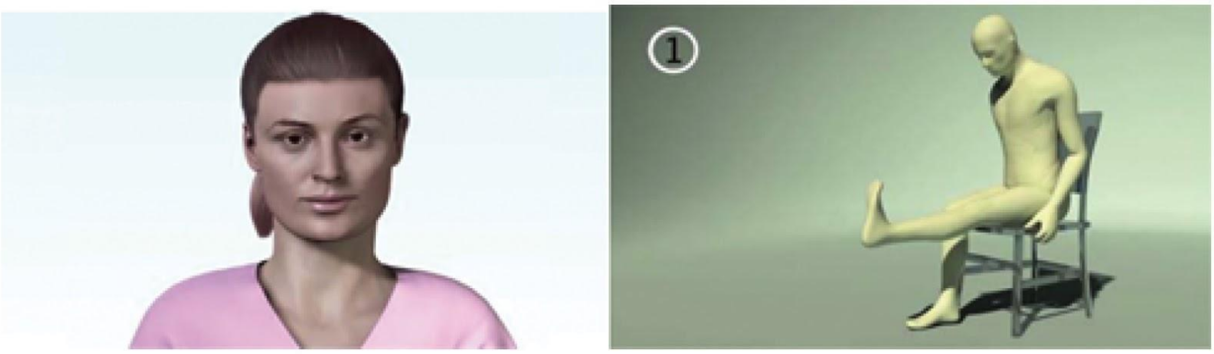

Figure 4.4. Avatars designed to provide telerehabilitation services to the elderly people [Epelde 2014a].

Additionally, a patient tracking system was needed in order to measure his movements. Precise joint angle measurement was required for specific rehabilitation therapy (elbow, shoulder, etc.) assessments. In addition to a precise and reliable solution, a home rehabilitation deployment should keep at the minimum the number of device technologies used, configuration needs, and costs. As suggested by the literature analysis, the approach's implementation has made use of a device that integrates the inertial sensors with magnetometers [STT 2013]. The selected solution provides precise orientations, angular velocities, and accelerations in real time and it provides Bluetooth connectivity and serial port profile implementation.

Regarding the architecture of the communications between the patient and the rehabilitation experts, the architecture described at Section 2.4.3 “Multi-Context Universally Accessible Service Provision Architecture” was selected. In order to facilitate the tests, a local server was chosen as the base client for the user tests. This server was in charge of performing the following tasks: i) render the virtual physiotherapist and dummy human, ii) stream it to the TV, iii) retrieve and pre-process the kinematic information provided by the inertial sensors and iv) upload resulting biomechanical data to the cloud for the examination of the rehabilitation experts.

Figure 4.5. Final setup to provide telerehabilitation services to the elderly people at their homes.

Information received from the inertial sensors was pre-processed in order to calculate each flexion / extension angle for the selected biomechanical model. Then, the prescribed exercise repetition was assigned with the processed joint angle time−history data set and uploaded to the cloud using the defined rehabilitation service. Alarms per maximum / minimum joint angle flexion / extension were also defined currently to ease rehabilitation assessment by the therapist.

<u>Implementation and validation</u>

The interaction system for the provision of telerehabilitation services was implemented in EREHAB project. In line with the results obtained in I2HOME, the tests demonstrated that this approach worked very well for most of the users that took part in the validation. This time 13 rehabilitation professionals and 19 elderly people with knee replacement took part in the tests. Both medical experts and patients confirmed the suitability of the system. Additionally, several participants remarked the need of providing several realistic avatars for the patients as well (instead of the dummy human), in order to increase patient identification and engagement.

<u>Discussion and closing remarks</u>

The work proposed succeeded in demonstrating that telerehabilitation services can be adapted to new use contexts such as telerehabilitation by elderly people at home. The results obtained can be generalized in order to include all possible tele-health or tele-care services, end users and use context. The architecture proposed is depicted in Figure 4.6, and it is a particular application of the framework architecture depicted at Figure 4.1.

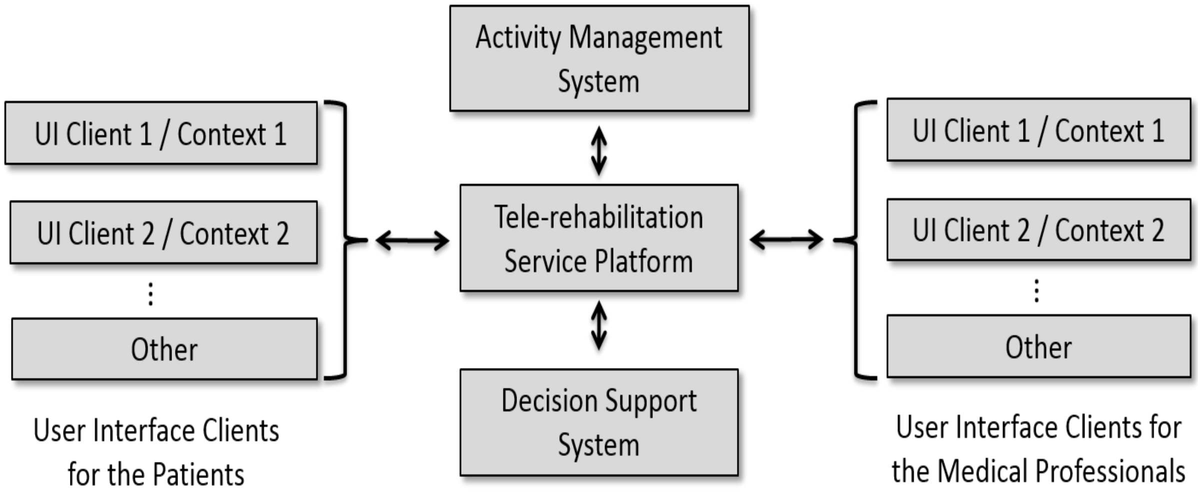

Figure 4.6. Functional layout of tele-health / care service architecture.

4.5.3 Contribution 3: Upper limb virtualization for rehabilitation of stroke patients

A system called Rehabilitation Centre has been designed to meet the challenge described at section 4.4.3. The Rehabilitation Centre provides the user with the necessary virtual reality games to carry out the rehabilitation exercises. While the user is performing the exercises, the system monitors and records multimodal data. On the one hand, a webcam records the user for an offline analysis of the movement (see Figure 4.7). On the other hand, joint's movement data is recorded for a more exhaustive study of the exercises carried out by the user. Joint's movement data is later processed and presented graphically by visualization tools.

Figure 4.7. Stroke patient using the Rehabilitation Centre [Epelde 2013d].

The Rehabilitation Centre is composed of an Armeo Spring exoskeleton [Armeo 2014], a PC, a webcam and its corresponding software. The Rehabilitation Centre's software is composed of three modules: Games Module, Video Recording Module, and Data Recording Module.

The Games Module is the responsible for capturing the movement data from the Armeo, for graphically representing the user movements and for implementing the games' logic. The data is processed translating it into the movements of the virtual arm. For the virtual arm movement generation, skeletal animation techniques have been used. These techniques mainly consist on dividing the model in two parts for animation development: the skin representation, and the hierarchical interconnection of bones. In order to develop a realistic arm model, skinning technique has been used. This technique consists of associating the bones with the vertices. In some cases, the vertices can be associated to more than one bone, therefore, weights are established so the vertices act as real as possible. Figure 4.8 shows the representation of the developed virtual arm. Arm's skeleton is represented in green, while the vertices are identified by the purple color. The virtual arms' representation has six degrees of freedom (DOF): two in the shoulder, two in the elbow and two in the wrist, which allows representing arm's movements with high fidelity.

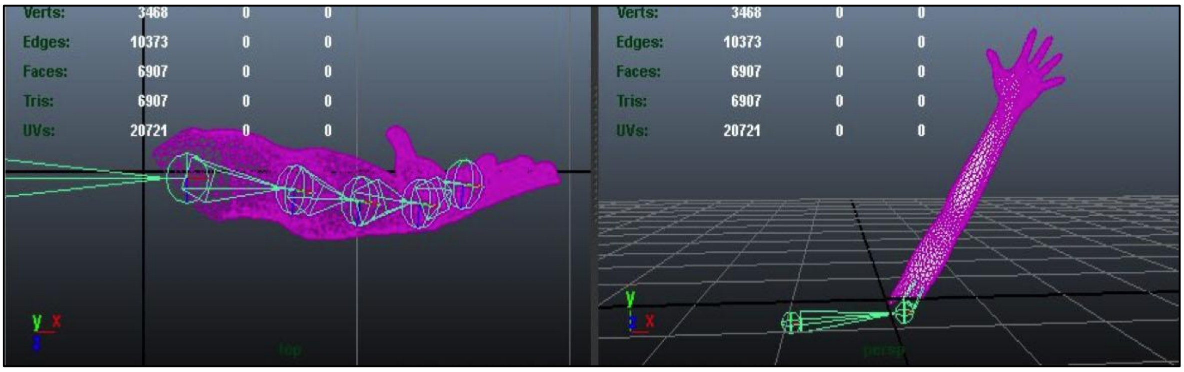

Figure 4.8. Virtual arm representation [Epelde2013d].

To generate the movement of the virtual arm, the data gathered from the Armeo has been processed to obtain the angles at the 6DOF. The realistic representation of the arm permits the user to be conscious of the movements he / she is doing as shown by studies in immersive virtual reality used with patients with phantom limb pain [Murray 2007]. Many people who has suffered a cerebrovascular accident, is not conscious of their upper limb movements. Hence, a virtual representation of their limb can help them seeing an action and reaction effect. This effect can make patients feel more identified with their limbs, which can increase their motivation with the rehabilitation, obtaining better results on the rehabilitation process.

With the aim of providing the user with a more entertaining rehabilitation process, several games have been developed. The games are based on object reaching and grasping tasks. These tasks have been selected because they are repeatedly used in users' daily living activities. Figure 4.9 shows a game in which the subject has to grasp a glass of water and to approach it to his mouth to simulate the process of drinking.

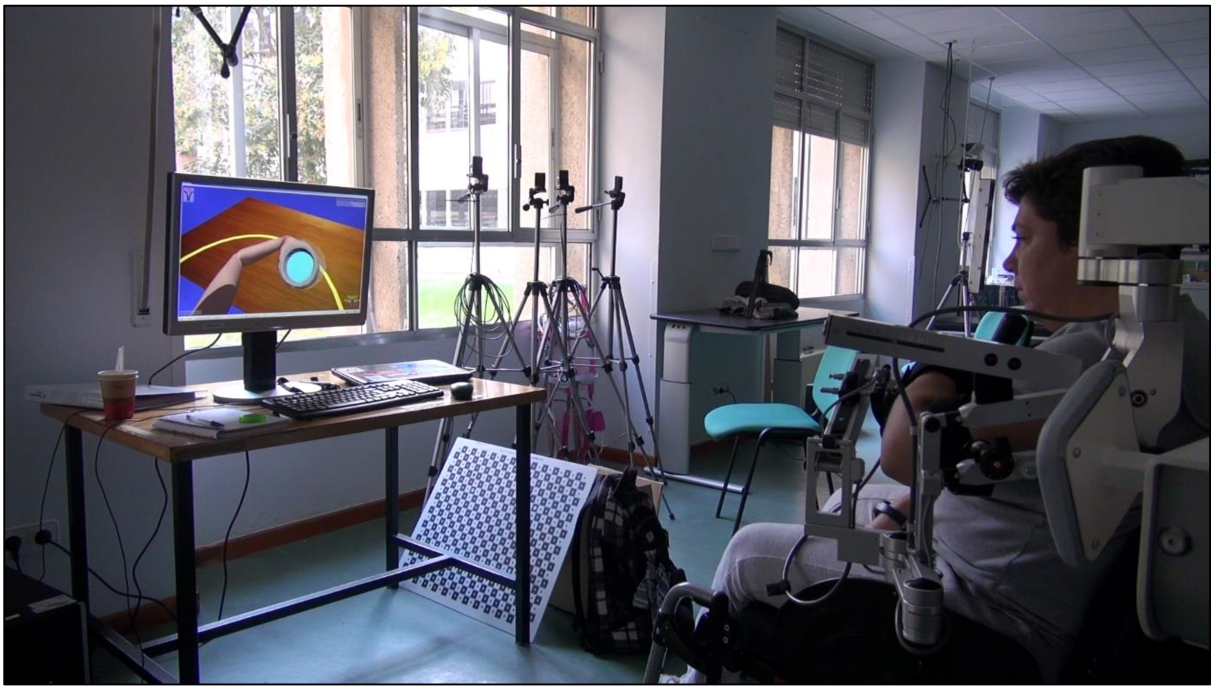

Figure 4.9. Example of the reaching and grasping rehabilitation setup.

Implementation and validation

The previous virtual reality and robot assisted upper limb rehabilitation system for the stroke patients was implemented in HYPER project. Its implementation is preliminarily described in [Epelde 2013d]. The validation of this approach is currently taking place in the National Paraplegics Hospital of Toledo, reference center in Spain in the integral rehabilitation of patients with spinal cord injury. Further publications will be produced with its results in a near future.

Discussion and closing remarks

The work proposed in this section succeeded in demonstrating that immersive telerehabilitation services can be developed to new use contexts such as stroke telerehabilitation. In the same way as in previous sections, the results obtained can be generalized in order to adapt different health services, end users, exoskeletons and use context. The architecture proposed at Figure 4.6 is valid in the stroke telerehabilitation context as well. Particularly, in this case the clients for the patients will include: i) immersive virtual reality games, and ii) communication with the exoskeletons that track and assist the user. In this architecture, the Universal Control Hub can be installed in the clients to provide plug-and-play game connectivity (to the user interface) and to the robot.

4.5.4 Contribution 4: Binaural sound guidance for people with visual impairments

An innovative system for the safe and autonomous navigation of blind and partially sighted people based on binaural audio guidance is proposed, which also covers pre-journey activities for journey planning and post-journey activities including sharing experiences and recommendations. The architecture of the ARGUS autonomous navigation concept is depicted in Figure 4.10.

Figure 4.10. Architecture of the ARGUS autonomous navigation system for blind people [Carrasco 2014a].

First, an accessible user website is provided to the target users of the system in order to perform the journey planning activities such as the route generation. The accessible website is hosted in the ARGUS Service Platform. Second, by means of an app running in an Android Smartphone provided with Internet connection, the route to be followed can be downloaded from the user website. Then, once on the route, an external High-Performance Positioning Unit (HPPU) corrects the GPS signals with EDAS data for obtaining accurate user positions and, using an Inertial Navigation System (INS), the user's heading is also calculated. Additionally, dead reckoning is implemented in the HPPU in order to support the user in areas with limited satellite coverage. The HPPU continuously transfers the updated user position and heading in real time to the Smartphone. Then, the Smartphone uses a navigation algorithm that compares the actual current user position and heading with the route to follow, and computes the binaural acoustic cues that will be transmitted in order to guide the user through the planned route. Bone conduction open headsets will be used in order to allow the user to hear surrounding sounds. Finally, the user website is available after the journey for sharing recommendations, points of interests or performed tracks with friends or relatives through mainstream social networks.

Implementation and validation

The system for the autonomous navigation of blind people has been implemented in the ARGUS project. Its implementation is described in [Carrasco 2014a]. The validation of this approach took place recently in three European cities: San Sebastián (Spain), Madrid (Spain) and Soest (Germany). 28 people with visual impairments took part in the user tests. The results obtained were successful. All users were able to reach their destination using the binaural guiding concept, despite the fact that only a short training session of 5 minutes was been given to them previously to the tests. A journal publication in which the final user tests and its results will be fully described is currently in progress.

Discussion and closing remarks

The work proposed in this section demonstrated autonomous and safe guidance of the blind users by means of 3D sounds. In the same way as in previous sections, the results obtained can be generalized in order to adapt different end users, positioning devices and use context. To accomplish this goal, the ARGUS service platform should be completed with *(i)* an Activity Management System (AMS), and *(ii)* a Decision Support Systems (DSS). Both systems could be integrated in the Service Platform. On the one hand, the AMS supports the users to perform any complex task such as the training, setup, use and troubleshooting of the navigation system. On the other hand, the DSS adds further benefits such as navigation data analysis, flow optimizations, personalized recommendations and real-time route assistance. In the latter, the route to accomplish is not something fixed that has been provided at the beginning of the trip, but it is a dynamic route plan that is being updated accordingly to the actual situations of the user or the track. In this way, in case of unexpected events such as road works, or obstacles, the user could be driven in real-time through safer streets.

4.6 Discussion on the results and future work

The contributions reported in this chapter demonstrate a continuous research activity carried out during the last years on the field of Assistive Technology, and, particularly, in the research and development of natural Human-Computer interaction methods for groups of people with particular interactivity needs such as the elderly, Alzheimer's Disease patients, and people with visual impairments.

Initial contributions were focused in the provision of a natural interaction method for people with Alzheimer's Disease in Ambient Assisted Living scenarios. A realistic avatar was displayed on the TV to engage with the users in short dialogs to inform the user about particular agenda or housekeeping aspects. Results show that even people with severe Alzheimer's Disease can interact successfully. This result is particularly relevant since it is evidence that even people affected with severely conditions are able to communicate and continue benefiting from Information and Communication Technologies if they are provided with tailored user interfaces. Furthermore, the results can be generalized by integrating task models and activity management systems with the avatars or other interaction paradigms.

Next work focused on the research and development of a joint telerehabilitation solution for the elderly users at home. Results obtained pointed in the same direction of the previous research. Whenever tailored user interfaces to the needs of the end users are provided, significant increase is made in terms of acceptance, motivation and effectiveness of the treatment delivered. Here it is remarkable that a stronger personalization of the system was even requested by the end users, in the sense of substituting the dummy avatar by more realistic avatars that can augment the identification and the immersion of the patients in the rehabilitation therapy proposed by the virtual physiotherapist. Remarkably, the integration of decision support systems in the service platform can significantly facilitate the assessment of the patients and increase the efficiency of the telerehabilitation systems.

The third work introduced in the chapter continues the research line with the immersion and identification of the stroke patient in the rehabilitation of the upper limb. In this case, an exoskeleton and a virtual reality setup were mixed in order to increase the effectiveness of the rehabilitation and the adherence to the therapy. Results show the importance of mixing the concepts of rehabilitation, gaming, immersion and daily living activities, in order to further motivate the end users during the whole duration of the therapy. In the same way, as the previous research work, decision support system may play a significant role in this scenario as well.

Finally, the fourth contribution presented discusses on a system based on binaural sound (or 3D sounds) to guide people with visual impairments to navigate independently through unknown outdoors scenarios. The results obtained in this last contribution also highlight that whenever natural interaction methods are implemented, such as 3D sounds, the target users are able to use them with very little training, and motivation and acceptance on the system obtains high scores. In the same way as in the previous scenarios, activity management and decision support technologies can help to provide a better and safer service to the end users.

At the light of all these findings, it can be summarized that in order to reduce the digital gap, technologies and standards that enable the customization of the user interfaces have to be promoted, so that all users can be provided with the interfaces that match their capabilities or need. At the same time, a main drawback is the high development effort required to implement tailored user interfaces for the needs of all possible end users. To accomplish this challenge, open standards such as the Universal Remote Console URC should be endorsed in order to create an open market on user interfaces for all.

Additionally, further research in the automatic generation, composition and adaptation of user interfaces would be very beneficial for the society. Particularly research challenges to address are: i) the automatic profiling of the interaction needs of the users, ii) the automatic matching of the interaction needs with the different interaction paradigms, and iii) the automatic adaptation of the user interfaces to the varying capabilities of the end users.

Finally, activity management and decision support technologies will play a significant role in the next generation of assistive products. Among other benefits, the mentioned technologies will facilitate the execution of complex tasks and a way to achieve valuable knowledge to better support the users. Research has to continue on these technologies in order to pave the way to these smarter assistive solutions.

Chapter 5

Conclusions and further work

This Chapter summarizes the conclusions of the research conducted in this Thesis in the fields of Universal Accessibility, Assistive Technologies and Decision Support Systems. A general conclusion of the Thesis is that these three knowledge fields are complementary and they will enable the creation of a new generation of smarter assistive products, that among other remarkable benefits, will require no learning from the users' side, and will adapt pervasively and seamlessly to our everyday life. Initially intended for the elderly and for people with disabilities, it is expected that eventually the whole population will benefit from them as well. To achieve these Smart Assistive Products, further research lines are identified as well.

This chapter is structured as follows: Section 5.1 summarizes the technologies and applications that have been introduced in the previous Chapters, discussing the mapping of technologies into application domains; Section 5.2 discusses the role of the Thesis contributions to solve user needs; Section 5.3 gives some concluding remarks; finally, Section 5.4 introduces some lines for future work.

5.1 Contributions vs. Application Sectors

In this section, an analysis of the distribution of the proposed technologies that have been described in Chapters 2, 3 and 4, over the Universal Accessibility, Assistive Technologies and Decision Support domains has been carried out. The map is summarized at Table 5.1.

As it can be seen in Table 5.1, proposed technologies can be classified in three different categories regarding the application domains, which are: core to the domain (C), supplementary to the domain (S), and not applicable (N). Core to the domain category means that the technology has been developed deliberately for the targeted particular domain. Supporting to the domain category means that the technology can be applied as well in a secondary domain. Finally, not applicable category means that a direct application in the targeted domain is not expected.

The general comment to the analysis on Table 5.1 is that most technologies introduced in the previous chapters are complementary, because they cover aspects that are somehow disjoint, leaving application space to other technologies, such that combining them better solutions are obtained to cope with the challenges in different application domains.

Table 5.1. Map of the distribution of proposed technologies over application domains discussed in the Thesis.

Technologies\Applications	***Univer. Access.***	***Assistive Products***	***Decision Support***
URC / UCH	**C**	S	N
Pluggable User Interfaces	**C**	S	N
Activity Management Systems	**C**	S	N
Avatars	N	**C**	N
Binaural sounds	N	**C**	N
Communication systems (videoconference, ...)	N	**C**	N
Dialog systems	S	**C**	S
Monitoring Systems	S	**C**	S
Home Automation	**C**	**C**	S
Adaptive User Interfaces	**C**	S	S
Ubiquitous User Interfaces	**C**	S	S
User Profiling Techniques and Standards	**C**	**C**	S
Knowledge Representation Techniques (ontologies,...)	S	S	**C**
Experience Representation Techniques (SOEKS, DDNA, ...)	S	S	**C**
Reasoning and Continuous Learning Techniques	S	S	**C**

Legend: (C) Core Domain, (S) Supporting Domain, (N) Not Applicable

In this sense, URC / UCH, Activity Management Systems and pluggable user interfaces, initially designed to provide Universal Access, can be used as create innovative assistive products as well. Avatars, binaural sounds and communication systems are very much tailored to specific users and applications. Dialog systems can be really expanded to cover universal communication and to contribute to enhance usability of decision support systems. Monitoring systems will provide a very important role in decision support systems because they will feed them with personalized data, and with appropriate user interfacing technology they can be used by all. Home automation plays a similar role. It will provide valuable information on activity and habits for decision support and can be used by anyone with the appropriate middleware architectures such as the UCH. Adaptive and ubiquitous user interfaces are aimed to provide universal access, but they will expand to cover assistive products. Decision support will contribute to the personalization of user interfaces with the support of user profiling techniques. Finally, knowledge and experience representation techniques along with reasoning and continuous learning techniques will expand from current usage to support in the adaptation of the best user interfaces for the targeted application, user needs and use context.

5.2 Contributions vs. User Requirements

As it was highlighted in Section 4.1, there are a number of needs that current assistive products in the market do not meet in many cases, such as, for example, minimum training, or adaptation to context of use. Table 5.2 presents an analysis carried out to identify the mapping between the main needs of the users and the technologies presented in this Thesis that could be used to solve them.

Table 5.2. Analysis between users' needs and proposed technologies.

Users' need	***Technology enablers***
Natural interaction, familiarity, minimize training	User profiling, Activity Management Systems, pluggable user interfaces, avatars, binaural sounds, dialog systems, adaptive user interfaces, experience representation and reasoning techniques.
Interoperability & Standardization	Universal Remote Console (URC) Standard, Universal Control Hub (UCH).
Affordable solutions	Open market of user interfaces and target adaptors based on URC standard.
Context adaptation	Universal Control Hub, Activity Management Systems, ubiquitous user interfaces, knowledge and reasoning techniques.
Personalized services	User profiling, knowledge representation and reasoning techniques
Personalized user interface	User profiling, pluggable user interfaces, adaptive user interfaces, knowledge representation and reasoning techniques.
Support to daily living activities	Home Automation, UCH, Activity Management Systems, pluggable user interfaces, binaural sounds.
Social interaction & ask for	Avatars, communication systems, dialog systems.

help	
Health and social services integration	Monitoring systems, UCH, knowledge and experience representation and reasoning techniques.
Minimize alterations to the physical environment	UCH, pluggable user interfaces.

5.3 Closing remarks

In the light of the contributions described in the previous chapters, and the analysis carried out in the previous sections, it can be affirmed that there is a promising future in the field Smart Assistive Technologies, because there are many exciting scientific and technological problems to be solved trying to remove the main barriers that people, with or without disabilities, find in the assistive products nowadays.

To accomplish this goal several technologies have been described in the previous chapters, which are related to relevant aspects such as Universal Accessibility, Human-Computer Interaction and Decision Support.

Briefly, based on the contributions described in the previous chapters, future Smart Assistive Technologies will have the following main characteristics:

1. First, they will provide universal access to all devices and services available in the Information Society. Thanks to standards such as the Universal Remote Console (URC) and its main implementation the Universal Control Hub, architectures that allow the universal access concept will be deployed along our society. These architectures implement the pluggable user interface concept in order to provide a best match with the interactivity needs of each person for each target application, context of use and personal preferences.

2. Second, they will allow a wide variety of user interfaces to be deployed in order to support the users in a personalized way in any context or situation. Thanks to this approach the users will be able to interact with the context using their preferred modalities in a natural, pervasive and seamless way.

3. Finally, the user interfaces and the services we consume will be smart enough to capture and process the user experience to adapt to our changes in our daily living style in a smooth and unobtrusive way. This means, for example, that they will adapt transparently to hardware substitutions in our daily contexts such as TV, fridge, or oven replacement in the home context. The services that we consume such as the health services will adapt as well to any change in our physical condition as well.

5.4 Future work

In order to make the Smart Assistive Systems come true, research has to continue in a number of lines, such as:

1. **Open Ecosystem**. In order to mainstream the Smart Assistive Technologies, an open source ecosystem is needed in which any interested party can freely interact. To make this happen, several requirements are needed, such as: *(i)* availability of universal access specifications and implementations such as the URC / UCH, *(ii)* tool and application development frameworks, and *(iii)* user interface and target adaptor repositories for public download.

2. **User Profiling and Best Matching Interaction Modalities Specification**. Interaction abilities and limitations of the end users have to be properly analyzed, categorized and standardized. This is a very important step, and effort in activities as the International Classification of Functioning, Disability and Health should continue. Furthermore, research has to continue on matching specifications of each disability and the most suitable interaction methods. This is a key step for the future automatized user interface generation.

3. **Personalized User Interface Generation and Adaptation Services**. In parallel to the previous research line, work has to continue in the automatic provision and adaptation of user interfaces for any target or service that is requested by any user at any context. Since *ad hoc* user interface development is time consuming and costly, this is the only way to really ensure that all citizens are enabled to fully interact with the increasingly number of devices and services that will be available in a near future in the Information Society.

4. **Data Privacy, Security and Trust**. Methodologies for ensuring data privacy and security of the users at any moment and use context have to be researched and implemented. Is very important that the users feel that they can rely on the developed assistive products and to gain their trust. Hence, any improper use of the system has to be detected and safely prevented.

5. **Experience Acquisition Methods based on Decisions and Consequences.** Appropriate methods have to be devised in order to include the consequences of the decisions in the Experience Base of DSS. In this way, Decisional Events and their consequences have to be added to SOEKS and DDNA, and algorithms that update and evolve the Experience Base have to be researched.

6. **Experience Traceability and Assessment Methodologies**. Furthermore, methodologies and tools for the evaluation and traceability of the quality and quantity of knowledge and experience gained through the system have to be explored. The experience gained with the system will be very valuable because it will collect the experience of the users and this input will be used as feedback to enhance the system.

Hence, it is crucial that the quality and quantity of knowledge and experience are properly traced, measured and assessed.

References

[Abascal 2013] J. Abascal, A. Civit, C. Nicolle, ”Universal Accessibility and the Digital Divide”, in the Proceedings of the 14th IFIP TC13 Conference on Human-Computer Interaction, INTERACT 2013 Workshop on Rethinking Universal Accessibility: A broader approach considering the digital gap, 2013.

[Alexandersson 2010] J. Alexandersson, J. Bund, E. Carrasco, G. Epelde, M. Klima, E. Urdaneta, G. Vanderheiden, G. Zimmermann and I. Zinnikus, “Injecting the Universal Remote Console Ecosystem: The Open URC Alliance”, in Proceedings of the 5th European Conference on Smart Sensing and Context, EuroSSC 2010, LNCS vol. 6446, pp. 195-198, Springer, 2010.

[Alexandersson 2011] J. Alexandersson, J. Bund, E. Carrasco, G. Epelde, M. Klíma, E. Urdaneta, G. Vanderheiden, G. Zimmermann, and I. Zinnikus, "openURC: Standardisation towards User Interfaces for Everyone, Everywhere, on Anything”, in Proceedings of the 4. AAL-Kongress 2011, AAL, pp.117-125, Springer, 2011.

[ANSI/CEA 2008] ANSI/CEA-2018 Task Model Description standard, (CE TASK 1.0), 2008. http://www.ce.org/Standards/browseByCommittee_4467.asp

[Armeo 2014] Armeo Spring, http://www.hocoma.com/products/armeo/armeospring/, Hocoma, 2014.

[Berner 2007] E.S. Berner, “Clinical Decision Support Systems, Theory and Practice”. Second Edition. Springer, New York, 2007.

[Bertrand 2006] R.M. Bertrand, *et al.* “Are all caregivers created equal? Stress in caregivers to adults with and without dementia”. J. Aging Health 18, 534–551, 2006.

[Blackler 2010] A. Blackler, *et al.* “Investigating users’ intuitive interaction with complex artefacts”. App. Ergon. 41, 72–92, 2010.

[Blauert 1983] J. Blauert. “Spatial hearing: the psychophysics of human sound localization”. MIT Press, Cambridge, Massachusetts, 1983.

[Brienza 2013] D. M. Brienza and M. McCue. ‘‘Introduction to Telerehabilitation.’’ In Telerehabilitation, edited by S. Kumar and E. R. Cohn, 1−11. London: Springer-Verlag, 2013.

[Burrell 2000] J. Burrell, P. Treadwell, and G. K. Gay. ‘‘Designing for Context: Usability in a Ubiquitous Environment.’’ In Proceedings of the 2000 Conference on Universal Usability, edited by J. Thomas, 80−84. New York: ACM, 2000.

[Burstein 2008] F. Burstein, C. W. Holsapple, “Handbook on Decision Support Systems”. Berlin: Springer Verlag, 2008.

[Cano 2012] R. Cano-de-la-Cuerda, *et al.*, “Teorías y modelos de control y aprendizaje motor. Aplicaciones clínicas en neurorrehabilitación”. Neurología, (0), 2012.

[Carmichael 1999] A. Carmichael, “Style guide for the design of interactive television for elderly users”,Technical Report, 1999.

[Carrasco 2007] E. Carrasco, C. M. Göllner, A. Ortiz, I. García, C. Buiza, E. Urdaneta, *et al.*, “Enhanced TV for the promotion of active ageing”, in Proceedings of the 9th European Association for the Advancement of Assistive Technology in Europe Conference, AAATE 2007, ATRS vol. 20, pp. 159-163, IOS Press, 2007.

[Carrasco 2008] E. Carrasco, G. Epelde, A. Moreno, A. Ortiz, I. Garcia, C. Buiza, *et al.*, “Natural interaction between avatars and persons with alzheimer's disease”, in Proceedings of the 11th International Conference on Computers Helping People with Special Needs, ICCHP 2008, LNCS vol. 5105, pp. 38-45, Springer, 2008.

[Carrasco 2009] E. Carrasco, A. Murua, G. Epelde, X. Valencia, C. Buiza, E. Urdaneta, *et al.*, "Video conference system for alzheimer's patients at home," in Roots for the Future of Ambient Intelligence - Adjunct Proceedings, 3rd European Conference on Ambient Intelligence, AmI 2009, pp. 316-321, 2009.

[Carrasco 2013] E. Carrasco, E. Loyo, O. Otaegui, C. Fösleitner, J. Spiller, D. Patti, *et al.*, “Autonomous navigation based on binaural guidance for people with visual impairment”, in Proceedings of the 12th European Association for the Advancement of Assistive Technology in Europe Conference, AAATE 2013, ATRS vol. 33, pp. 690-694, IOS Press, 2013.

[Carrasco 2014a] E. Carrasco, E. Loyo, O. Otaegui, C. Fösleitner, M. Dubielzig, R. Olmedo, *et al.*, “ARGUS autonomous navigation system for people with visual impairments”, in Proceedings of the 15th International Conference on Computers Helping People with Special Needs, ICCHP 2014, LNCS vol. 8548, pp. 100-107, Springer, 2014.

[Carrasco 2014b] E. Carrasco, E. Sanchez, A. Artetxe, C. Toro, M. Graña, F. Guijarro, J.M. Susperregui, and A. Aguirre, “Hygehos Home: an innovative remote follow-up system for chronic patients”, in Proceedings of the International Conference on Innovation In Medicine and Healthcare, InMed 2014, San Sebastián, 2014.

[Ciccarese 2008] P. Ciccarese, *et al.* ‘‘The SWAN Biomedical Discourse Ontology.’’ Journal of Biomedical Informatics 41, pp. 739–51, 2008.

[Cooper 2004] A. Cooper, “The Inmates Are Running the Asylum: Why High-Tech Products Drive Us Crazy and How to Restore the Sanity”, Macmillan Publishing Co, 2004.

[DeMauro 2010] A. De Mauro, E. Carrasco, D. Oyarzun, A. Ardanza, C. Paloc, A. Gil, *et al.*, "Virtual reality system in conjunction with neurorobotics and neuroprosthetics for rehabilitation in cerebrovascular accidents and spinal cord injuries," in Proceedings of the 10th IEEE International Conference on Information Technology and Applications in Biomedicine, ITAB 2010, pp.1-3, IEEE, 2010.

[DeMauro 2011a] A. De Mauro, A. Ardanza, C. Chen, E. Carrasco, D. Oyarzun, D. Torricelli, *et al.*, “Virtual reality and hybrid technology for neurorehabilitations”, in Proceedings of the 11th International Conference on Computational Science and Its Applications, ICCSA 2011 ,LNCS vol. 6785, pp. 582-591, Springer, 2011.

[DeMauro 2011b] A. De Mauro, E. Carrasco, D. Oyarzun, A. Ardanza, A. Frizera Neto, D. Torricelli, *et al.*, "Virtual reality system in conjunction with neurorobotics and neuroprosthetics for rehabilitation of motor disorders," in Proceedings of the 18th Medicine Meets Virtual Reality Conference, MMVR 2011, SHTI vol. 163, pp. 163-165, IOS Press, 2011.

[DeMauro 2012a] A. De Mauro, E. Carrasco, D. Oyarzun, A. Ardanza, A. Frizera-Neto, D. Torricelli, *et al.*, “Chapter 4 - Advanced Hybrid Technology for Neurorehabilitation: The HYPER Project”, in Advances in Robotics & Virtual Reality, ISRL vol. 26, pp. 89-108, Springer, 2012.

[DeMauro 2012b] A. De Mauro, E. Carrasco, A. Ardanza, J. Herrán, E. Ochoteco, and G. Cabañero, “Balance rehabilitation and virtual reality: the HYPER Project”, in Proceedings of the AAL SUMMIT 2012, 2012.

[Deutsch 2008] J. E. Deutsch, M. Borbely, J. Filler, K. Huhn, and P. Guarrera-Bowlby. ‘‘Use of a Low-Cost, Commercially Available Gaming Console (Wii) for Rehabilitation of an Adolescent with Cerebral Palsy.’’ Physical Therapy 88, no. 10, 1196−207, 2008.

[Diaz-Orueta 2014] U. Diaz-Orueta, A. Etxaniz, M. F. Gonzalez, C. Buiza, E. Urdaneta, J. Yanguas, E. Carrasco, and G.Epelde, "Erratum to: Role of cognitive and functional performance in the interactions between elderly people with cognitive decline and an avatar on TV (Erratum to:Univ Access Inf Soc, 10.1007/s10209-013-0288-1)," in Universal Access in the Information Society, vol. 13, Springer, 2014. IF=0.397 (2013).

[Dubey 2011] G. Dubey, “A Survey on Guiding Logic for Automatic User Interface Generation”, in Universal Access in Human-Computer Interaction: Design for All and eInclusion, LNCS 6765, pp: 365-372, Springer, 2011.

[eAccesibility Impacts 2012] eAccesibility Impacts, “Study on Economic Assessment for Improving e-Accessibility Services and Products”, Final Report, European Commission, 2012.

[EBU 2013] European Blind Union. “Key facts and figures concerning blindness and sight loss”. http://www.euroblind.org/resources/information/nr/215. Last accessed on 2013-06-12.

[Eom 2006] S. Eom and E. Kim. “A survey of decision support system applications (1995-2001)”, JOURNAL OF THE OPERATIONAL RESEARCH SOCIETY, Vol. 57, Issue 11, pp. 1264-1278, 2006.

[Epelde 2009] G. Epelde, E. Carrasco, G. Zimmermann, J. Bund, M. Dubielzig, and J. Alexandersson, "URC based accessible TV," in Proceedings of the 7th European Conference on European Interactive Television Conference, EuroITV'09 , pp. 111-114, ACM, 2009.

[Epelde 2012a] G. Epelde, E. Carrasco, I. Gómez-Fraga, K. Vivanco, J.M. Jiménez, O. Rueda, A. Bizkarguenaga, D. Sevilla, and P. Sanchez, "ERehab: Ubiquitous Multidevice Personalised Telerehabilitation Platform", in Proceedings of the AAL Forum 2012, pp. 387-391, AALA, 2013.

[Epelde 2012b] G. Epelde, E. Carrasco, G. Zimmermann, J. Alesandersson, J. Bund, and G. Vanderheiden, “Open standards based public procurement policy for large market uptake and new entrants barrier lowering”, in Proceedings of the AAL SUMMIT 2012, 2012.

[Epelde 2013a] G. Epelde, E. Carrasco, G. Zimmermann, J. Alexandersson, R. Neßelrath, and M. Dubielzig, "Universal Remote Console-based next-generation accessible television," in Universal Access in the Information Society, vol. 12, pp. 73-87, Springer, 2013. IF=0.397.

[Epelde 2013b] G. Epelde, X. Valencia, E. Carrasco, J. Posada, J. Abascal, U. Diaz-Orueta, *et al.*, "Providing universally accessible interactive services through TV sets: Implementation and validation with elderly users," in Multimedia Tools and Applications, vol. 67, pp. 497-528, Springer, 2013. IF=1.058.

[Epelde 2013c] G. Epelde, E. Carrasco, S. Rajasekharan, J. Abascal, J.M. Jiménez, K. Vivanco, I. Gómez-Fraga, and X. Valencia, "Smart Medical System for the Universal Remote Delivery of Rehabilitation", in InImpact: The Journal of Innovation Impact, Special Edition on Innovation in Medicine and Healthcare, vol. 6, num. 1, pp. 98-109, 2013.

[Epelde 2013d] G. Epelde, X. Valencia, A. Ardanza, E. Fanchon, A. De Mauro, F. M. Rueda, E. Carrasco, and S. Rajasekharan, "Virtual arm representation and multimodal monitoring for the upper limb robot assisted teletherapy," in Proceedings of the International Congress on Neurotechnology, Electronics and Informatics, NEUROTECHNIX 2013, pp. 69-80, SCITEPRESS Digital Library, 2013.

[Epelde 2014a] G. Epelde, E. Carrasco, S. Rajasekharan, J. M. Jiménez, K. Vivanco, I. Gómez-Fraga, *et al.*, "Universal remote delivery of rehabilitation: Validation with seniors' joint rehabilitation therapy," in Cybernetics and Systems: An International Journal, vol. 45, pp. 109-122, Taylor & Francis Inc., 2014. IF=0.507 (2013).

[Epelde 2014b] G. Epelde, "User Interface Abstraction for enabling TV set based Inclusive Access to the Information Society", Doctoral Thesis, University of the Basque Country, 2014.

[Eurostat 2011] Eurostat, "Demography Report 2010: More, older and more diverse Europeans", European Commission, 2011.

[European Commission 2008] European Commission. "Seniorwatch 2—Assessment of the Senior Market for ICT Progress and Developments". Brussels, Belgium: European Commission, 2008.

[European Commission 2010] "European Disability Strategy 2010-2020: A Renewed Commitment to a Barrier-Free Europe", European Commission, 2010.

[Fagerberg 2010] G. Fagerberg, A. Kung, R. Wichert, M.-R. Tazari, B. Jean-Bart, G. Bauer, G. Zimmermann, F. Furfari, F. Potortì, S. Chessa, M. Hellenschmidt, J. Gorman, J. Alexandersson, J. Bund, E. Carrasco, *et al.*, "Platforms for AAL applications", in Proceedings of the 5th European Conference on Smart Sensing and Context, EuroSSC 2010, LNCS vol. 6446, pp. 177-201, Springer, 2010.

[Fischer 2014] S. H. Fischer, *et al.*, "Acceptance and use of health information technology by community-dwelling elders", International Journal of Medical Informatics, 83(9), 2014.

[Florins 2006] M. Florins, *et al.* "Splitting rules for graceful degradation of user interfaces". In Proceedings of the Working Conference on Advanced Visual Interfaces, pp. 59–66, 2006.

[Fonseca 2010] J.M. Fonseca, *et al.* "Model-Based UI XG Final Report". page 32, 2010. Accessible at: http://www.w3.org/2005/Incubator/modelbased-ui/XGR-mbui-20100504/. Last accessed on 2014-06-09.

[Gauterin 2012] A. Gauterin, *et al.*, "Accessible Elevator", In Proceeding of the Technik für ein selbstbestimmtes Leben - 5. Deutscher AAL-Kongress, VDE Verlag, 2012.

[Gil 2003] J. Gill, S. Perera. "Accessible universal design of interactive digital television." In: Proceedings of the 1st European Conference on Interactive Television (EuroITV 2003), Brighton, UK. 83–89, 2003.

[Giudice 2008] N. A. Giudice, *et al.* "Environmental Learning without Vision: Effects of Cognitive Load on Interface Design". Proceedings of the 9th International Conference on Low Vision, Vision 2008, Montreal, Quebec, Canada, 2008.

[Gnanambal 2010] S. Gnanambal and M. Thangaraj. ''Research Directions in Semantic Web on Healthcare.'' Journal of Computer Science 1, pp. 449–53, 2010.

[Gomez-Martinez 2010] E. Gomez-Martinez, *et al.*, “Performance Modeling and Analysis of the Universal Control Hub”, in Computer Performance Engineering, LNCS 6342, pp. 160-174, Springer, 2010.

[GPII 2014] “Global Public Inclusive Infrastructure GPII”, http://gpii.net/, 2014.

[Gruber 1995] T. R. Gruber. ‘‘Toward Principles for the Design of Ontologies Used for Knowledge Sharing.’’ International Journal of Human–Computer Studies 43, nos. 5–6 , pp. 907–28, 1995.

[GSA 2014] “The European Geostationary Navigation Overlay Service (EGNOS)”, European Global Navigation Satellite Systems Agency, http://www.gsa.europa.eu/egnos/edas , 2014.

[Guerrero 2009] J. Guerrero-Garcia, *et al.* “A Theoretical Survey of User Interface Description Languages: Preliminary Results”. In Latin American Web Congress, 2009. LA-WEB '09, pages 36-43. IEEE, 2009.

[Hanke 2011] S. Hanke, C. Mayer, O. Hoeftberger, H. Boos, R. Wichert, M.R. Tazari, P. Wolf, and F. Furfari, “universAAL – An Open and Consolidated AAL Platform”, in Proceedings of the 4th Ambient Assisted Living Kongress, Ambient Assisted Living, pp 127-140, Springer, 2011.

[Hasan 2014] H. Hasan, and S. Abdul-Kareem. “Human-computer interaction using vision-based hand gesture recognition systems: a survey”, Neural Computing & Applications, Vol. 25, Num. 2, pp. 251-261, Springer, 2014.

[HbbTV 2010] TS 102 796–V1.1.1 “Hybrid broadcast broadband TV”. ETSI, Sophia Antipolis Cedex, HbbTV, 2010.

[Heras 2014] S. Heras, V. Botti & V. Julian. “Modelling dialogues in agent societies”, in Engineering Applications of Artificial Intelligence, Vol. 34, pp. 208-226, 2014.

[Holbrook 2003] A. Holbrook, S. Xu, J. Banting. “What Factors Determine The Success of Clinical Decision Support Systems?”, AMIA Annu Symp Proc 2003, 862, 2003.

[Hong 2001] J.I. Hong and J. A. Landay. ‘‘An Infrastructure Approach to Context-Aware Computing.’’, Human−Computer Interaction 16, no. 2, 287−303, 2001.

[Houshiaryan 2005] K. Houshiaryan, *et al.* ‘‘Customized Ontology-Based Intelligent Medical Terminology Tool.’’ In Proceedings of 7th International Workshop on Enterprise Networking and Computing in Healthcare Industry, pp. 320–24, IEEE, 2005.

[I2HOME 2009a] I2HOME FP6 project, “Intuitive interaction for everyone with home appliances based on industry standards”, http://www.i2home.org/, 2009.

[I2HOME 2009b] B.Rosa, *et al.* “D7.2: Specification, Activity Management System”, Public Deliverable, I2HOME project, 2009. Available at: http://www.i2home.org/Publications/Deliverables/tabid/80/Default.aspx

[Isern 2010] D. Isern, D. Sanchez, A. Moreno. “Agents applied in health care: A review”. International Journal of Medical Informatics 79, pp. 145-166, 2010.

[ISO/IEC 2008] ISO/IEC 24752-1/5:2008 “Information technology - User interfaces - Universal remote console”, ISO, 2008.

[ISO/IEC 2013] ISO/IEC 24752-1:2013 “Overview of the Universal Remote Console framework”, Public annex, ISO, 2013.

[ISO 2007] ISO 9999:2007, “Assistive products for persons with disability -- Classification and terminology”, ISO, 2007.

[ISO 2010] ISO 9241-210:2010 “Ergonomics of Human−System Interaction—Part 210: Human-Centered Design for Interactive Systems”. Geneva, Switzerland: International Organization for Standardization, ISO, 2010.

[ITVE 2009] International Television Expert Group, “Television - International Key Facts”, http://www.international-television.org/, 2009.

[Kapsys 2013] Kapten Mobility. “Kapsys”, http://www.kapsys.com . Last accessed on 2013-06-12.

[Kavaldjian 2009] S. Kavaldjian, *et al.*, “Semi-automatic user interface generation considering pointing granularity”. In Proceedings of the 2009 International Conference on Systems, Man and Cybernetics, pp. 2052–2058, 2009.

[Kawamoto 2005] K. Kawamoto, *et al.*, “Improving clinical practice using clinical decision support systems: a systematic review of trials to identify features critical to success”. BMJ. 330(7494):765, 2005.

[Keen 1980] P. Keen, "Decision support systems: a research perspective."Cambridge, Mass. : Center for Information Systems Research, Afred P. Sloan School of Management. http://hdl.handle.net/1721.1/47172, 1980.

[Klima 2009] M. Klima, M. Macik, E. Urdaneta, C. Buiza, E. Carrasco, G. Epelde, *et al.*, "User Interfaces for the Digital Home on the basis of Open Industrial Standards," in Ambient Intelligence Perspectives - Selected Papers from the 1st International Ambient Intelligence Forum 2008, AmIF 2008, AISE vol. 1, pp. 144-152, IOS Press, 2009.

[Klironomos 2005] I. Klironomos (edit.), *et al.* “White Paper: Promoting Design for All and e-Accessibility in Europe”. Institute of Computer Science, EDeAN, 2005.

[Kurniawan 2010] H. Kurniawan, S. Arteaga, and R. Manduchi, “A General Education Course on Universal Access, Disability, Technology and Society”, in the Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility, ASSETS 2010, ACM, 2010.

[Kwakkel 2008] G. Kwakkel, B. J. Kollen, and H. I. Krebs. ‘‘Effects of Robot-Assisted Therapy on Upper Limb Recovery after Stroke: A Systematic Review.’’ Neurorehabilitation and Neural Repair 22, no. 2, 111−21, 2008.

[Leitner 2012] G. Leitner, *et al.*, “Reducing the Entry Threshold of AAL Systems: Preliminary Results from Casa Vecchia”, LNCS 7382, Springer, 2012.

[Liu 2006] J. Liu, J.C. Wyatt, D.G. Altman, “Decision tools in health care: focus on the problem, not the solution”. BMC Med Inform Decis Mak 6(4), 2006.

[Loomis 1985] J.M. Loomis, “Digital map and navigation system for the visually impaired”. Unpublished paper, Department of Psychology, University of California, Santa Barbara, July 25, 1985. Available at: http://www.geog.ucsb.edu/pgs/papers/loomis_1985.pdf Last Access: 2014-03-31.

[Loureiro 2011] B. Loureiro and R. Rodrigues, “Multi-Touch as a Natural User Interface for Elders: A Survey”, in Proceedings of the 6th Iberian Information Systems and Technologies Conference, IEEE, 2011.

[Luger 1993] G. F. Luger and W. A. Stubblefield. “Artificial intelligence - structures and strategies for complex problem solving (2. ed.)”. Benjamin/Cummings, 1993.

[Maurente 2010] E. C. Maurente, S. Ocampo Edye, D. Herrera Delgado, and Rodriguez García. “Innovations and Advances in Computer Sciences and Engineering”, chapter Evaluation of Case Based Reasoning for Clinical Decision Support Systems applied to Acute, pages 259–264. Springer, 2010.

[Mayer 2012] C. Mayer, *et al.*, “AALuis, a User Interface Layer That Brings Device Independence to Users of AAL Systems”. In Computers Helping People with Special Needs, LNCS 7382, pages 650-657. Springer, 2012.

[McKay 2004] J. McKay, G.A. Mensah & K. Greenlund, “The atlas of heart disease and stroke”. World Health Organization, 2004.

[MeAC 2008] “Measuring Progress of eAccessibility in Europe”, Final Report, http://www.eaccessibility-progress.eu/, 2008.

[Mokhtari 2012] M. Mokhtari, *et al.*, “New Trends to Support Independence in Persons with Mild Dementia - A Mini-Review”, Gerontology, 58(6), 2012.

[Monien 2009] B. Monien, L. Apostolova, and G. Bitan, ‘‘Early Diagnostics and Therapeutics for Alzheimer’s Disease—How Early Can We Get There?’’ Expert Review of Neurotherapeutics 6, pp. 1293–1306, 2009.

[Monitoring eAccessibility 2011] “Monitoring eAccessibility in Europe”, Annual Report, http://www.eaccessibility-monitoring.eu/, 2011.

[Murray 2007] C.D. Murray, *et al.*, “The treatment of phantom limb pain using immersive virtual reality: Three case studies”. Disability and Rehabilitation, 29(18), 1465–1469, 2007.

[Murua 2010] A. Murua, X. Valencia, E. Carrasco, G. Zimmermann, B. Rosa, J. Bund, *et al.*, "Universally accessible task-based user interfaces," in Proceedings of the 12th IEEE International Conference on e-Health Networking, Application and Services, HEALTHCOM 2010, pp. 1-6, IEEE, 2010.

[Navarro 2011] A.A. Navarro, *et al.*, “Context-Awareness as an Enhancement of Brain-Computer Interfaces”, in Ambient Assisted Living, LNCS 6693, pp. 216-22, Springer, 2011.

[Nichols 2006] J. Nichols. “Automatically generating high-quality user interfaces for appliances”. Ph.D. thesis, Carnegie Mellon University, 2006.

[Nicolle 2001] C. Nicolle, and J. Abascal, “Inclusive Design Guidelines for HCI”, CRC Press, 2001.

[Nygard 2008] L. Nygard, “The meaning of everyday technology as experienced by people with dementia who live alone”. Dementia 7, 481–502, 2008.

[Nyström 2010] M. Nyström, *et al.* ‘‘Enriching a Primary Health Care Version of ICD-10 Using SNOMED CT Mapping.’’ Journal of Biomedical Semantics 1, no. 7, 2010.

[OpenAl 2014] “OpenAL Soft”, http://kcat.strangesoft.net/openal.html, 2014.

[openURC 2012] “URC Technical Primer 1.0”, Draft Technical Report 2012-10-22, openURC Alliance, 2012.

[openURC 2013a] “Universal Control Hub 1.0”, Approved Technical Report 2013-12-17, openURC Alliance, 2013.

[openURC 2013b]. “Resource Server HTTP Interface 1.0”, Approved Technical Report 2014-03-04, openURC Alliance, 2013.

[openURC 2014] “openURC Alliance”, http://www.openurc.org/, openURC Alliance, 2014.

[Orero 2014] P. Orero, J. Birch and A. Lambourne, “Media accessibility in HBBTV: Interaction for all”, in Proceedings of International Broadcasting Convention Conference, IBC 2014, 2014.

[Ortiz 2007] A. Ortiz, M.P. Carretero, D. Oyarzun, *et al.*, “Elderly users in ambient intelligence: Does an avatar improve the interaction?”, In Proceedings of the 9th Conference on User Interfaces for All, Universal Access in Ambient Intelligence Environments, LNCS 4397, pp. 99-114, Springer 2007.

[OSGi 2014] OSGi Alliance, http://www.osgi.org/, 2014.

[Otaegui 2012a] O. Otaegui, E. Loyo, E. Carrasco, C. Fösleitner, J. Spiller, D. Patti, R. Olmedo, M. Dubielzig, "ARGUS: Assisting peRsonal GUidance System for people with visual impairment", in Proceedings of the 17th International Conference on Urban Planning and Regional Development in the Information Society GeoMultimedia 2012, REAL CORP 2012, 2012.

[Otaegui 2012b] O. Otaegui, E. Loyo, E. Carrasco, C. Fösleitner, J. Spiller, M. Schrenk,D. Patti, R. Olmedo, and M. Dubielzig, "ARGUS: Assisting Personal Guidance System for People with Visual Impairment" in Proceedings of the 48th ISOCARP Congress 2012.

[Otaegui 2013] O. Otaegui, E. Loyo, E. Carrasco, C. Fösleitner, J. Spiller, D. Patti, R. Olmedo, M. Dubielzig, "ARGUS: Assisting peRsonal GUidance System for people with visual impairment", in Proceedings of the 9th Intelligent Transport Systems European Congress, ITS 2013, 2013.

[Parmanto 2009] B. Parmanto and A. Saptono. ''Telerehabilitation: State-of-the-Art from an Informatics Perspective.'' International Journal of TeleRehabilitation 1, no. 1: 73−84, 2009.

[Paternò 2004] F. Paternò, "ConcurTaskTrees: an engineered notation for task models". In The handbook of task analysis for human-computer interaction, pages 483-503. Lawrence Erlbaum Associates, 2004.

[Paternò 2009] F. Paternò, C. Santoro and L.D. Spano, "MARIA: A universal, declarative, multiple abstraction-level language for service-oriented applications in ubiquitous environments". ACM Transactions on Computer-Human Interaction, 16(4):19, ACM, 2009.

[Peissner 2014] M. Peissner, *et al.*, "Requirements for the Successful Market Adoption of Adaptive User Interfaces for Accessibility", in Universal Access in Human-Computer Interaction. Design for All and Accessibility Practice, LNCS 8516, Springer, 2014.

[Peleg 2006] M. Peleg and S.W. Tu, "Decision support, knowledge representation and management in medicine", in: Haux, R., Kulikowski, C. (Eds) 2006 IMIA Yearbook of Medical Informatics: Assessing Information - Technologies for Health. Schattauer Verlagsgesellschaft mbH, Stuttgart, pp 72-80, 2006.

[Randstrom 2012] K.B. Randstrom, *et al.*, "Impact of environmental factors in home rehabilitation - a qualitative study from the perspective of older persons using the International Classification of Functioning, Disability and Health to describe facilitators and barriers", Disability and Rehabilitation, 34(9), 2012.

[Rice 2004] M.D. Rice, “Personalisation of interactive television for visually impaired viewers”. In Proceedings for the 2nd Cambridge Workshop on Universal Assistive Technology, Cambridge University, UK. 45–48, 2004.

[Rice 2008] M.D. Rice, N. Alm, “Designing new interfaces for digital interactive television usable by older adults”, Comput Entertain 6:1–20, 2008.

[Rich 2009] C. Rich, “Building Task-Based User Interfaces With ANSI/CEA-2018”. IEEE Computer, Vol. 42, No. 9, August 2009.

[Rodriguez-Ascaso 2007] A. Rodriguez-Ascaso, *et al.*, “Towards universal access to eLearning”, in the Proceedings of the 11th International Conference on User Modeling,UM 2007, 2007.

[RtF 2014] Raising the Floor, http://raisingthefloor.org/about, 2014.

[Salmon 2009] D.P Salmon and M.W. Bondi, “Neuropsychological assessment of dementia”. Ann. Rev. Psychol. 60, 1–26, 2009.

[Sanchez 2011a] E. Sanchez, C. Toro, E. Carrasco, P. Bonachela, C. Parra, G. Bueno, *et al.*, "A knowledge-based clinical decision support system for the diagnosis of Alzheimer disease," in Proceedings of 13th IEEE International Conference on e-Health Networking, Applications and Services, HEALTHCOM 2011, pp. 351-357, IEEE, 2011.

[Sanchez 2011b] E. Sanchez, C. Toro, E. Carrasco, G. Bueno, C. Parra, P. Bonachela, *et al.*, “An architecture for the semantic enhancement of clinical decision support systems”, in Proceedings of the 15th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems, KES 2011, LNAI vol. 6882, pp. 611-620, Springer, 2011.

[Sanchez 2012] E. Sanchez, C. Toro, A. Artetxe, M. Graña, E. Carrasco, and F. Guijarro, “A semantic clinical decision support system: Conceptual architecture and implementation guidelines”, in Proceedings of the 16th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems, KES 2012, FAIA vol. 243, pp. 1390-1399, IOS Press, 2012.

[Sanchez 2013] E. Sanchez, C. Toro, A. Artetxe, M. Graña, C. Sanin, E. Szczerbicki, E. Carrasco, and F. Guijarro, "Bridging challenges of clinical decision support systems with a semantic approach. A case study on breast cancer," in Pattern Recognition Letters, vol. 34, pp. 1758-1768, Elsevier, 2013. IF=1.062.

[Sanchez 2014a] E. Sanchez, W. Peng, C. Toro, C. Sanin, M. Graña, E. Szczerbicki, E. Carrasco, F. Guijarro, and L. Brualla, "Decisional DNA for modeling and reuse of experiential clinical assessments in breast cancer diagnosis and treatment," in Neurocomputing, vol. 146, pp. 308-318, Elsevier, 2014. IF=2.005 (2013).

[Sanchez 2014b] E. Sanchez, “Semantically Steered Clinical Decision Support Systems”, Doctoral Thesis, University of the Basque Country, 2014.

[Sanin 2007] C. Sanin, E. Szczerbicki and C. Toro, “An OWL Ontology of Set of Experience Knowledge Structure.’’ Journal of Universal Computer Science 13, no. 2, pp. 209–23, 2007.

[Sanin 2009a] C. Sanin and E. Szczerbicki, ‘‘Experience-Based Knowledge Representation: SOEKS.’’ Cybernetics and Systems 40, no. 2, pp. 99–122, 2009.

[Sanin 2009b] C. Sanin, L. Mancilla-Amaya, E. Szczerbicki and P. Cayford Howell, ‘‘Application of a Multi-Domain Knowledge Structure: The Decisional DNA.’’ In Intelligent Systems for Knowledge Management, vol. 252, edited by N. T. Nguyen and E. Szczerbicki, 65–86. Berlin: Springer, 2009.

[Sanin 2012] C. Sanin, C. Toro, Z. Haoxi, E. Sanchez, E. Szczerbicki, E. Carrasco, *et al.*, "Decisional DNA: A multi-technology shareable knowledge structure for decisional experience," in Neurocomputing, vol. 88, pp. 42-53, Elsevier, 2012. IF=1.634.

[Sebastian 2014] K. Sebastian, *et al.* “A Showcase for Accessible Online Banking”, in Universal Access in Human-Computer Interaction. Design for All and Accessibility Practice, LNCS 8516, Springer, 2014.

[Shirabad 2012] J.S. Shirabad, S. Wilk, W. Michalowski and K. Farion, “Implementing an Integrative Multi-agent Clinical Decision Support System with Open Source Software”. Journal of Medical Systems 36(1), 123-137, 2012.

[SIGN 2011] Scottish Intercollegiate Guidelines Network SIGN. “Sign 50: A guideline developer’s handbook”. Revised edition. Technical report, Scottish Intercollegiate Guidelines Network, Edinburgh, November 2011.

[Simpson 2013] J. Simpson, ‘‘Challenges and Trends Driving Telerehabilitation.’’ In Telerehabilitation, edited by S. Kumar and E. R. Cohn, 13−27. London: Springer-Verlag, 2013.

[Sittig 2008] D.F. Sittig, A. Wright, J.A. Osheroff, B. Middleton, J.M. Teich, J.S. Ash, E. Campbell, and D.W Bates. “Grand challenges in clinical decision support”. Journal of biomedical informatics, 41(2):387–392, 2008.

[Song 2008] K. Song, and K. Lee, “Generating multimodal user interfaces for Web services”. Interacting with Computers 20(4-5), 480–490, 2008.

[Stack 2009] J. Stack, *et al.*, “Analysing and federating the European assistive technology ICT industry”, European Commission, 2009.

[Stephanidis 1997] C. Stephanidis, D. Akoumianakis and J. Ziegler, “Universal accessibility and standardisation: New opportunities and prospects”, in Advancement of Assistive Technology, ATRS 3, pp. 39-43, IOS Press, 1997.

[Stephanidis 2001] C. Stephanidis, (Ed.), *et al.*, "User Interfaces for All: Concepts, Methods and Tools". Lawrence Erlbaum Associates, 2001.

[Sycara 1998] K.P. Sycara, "Multiagent Systems". AI Magazine 19(2), 79-92, 1998.

[STT 2013] STT Systems. 2013. ''IBS Sensor.'' Available at: http://www.stt.es/en/products/inertialsensor/ ibs-sensor/hardware/ (accessed September 27, 2013).

[TechAct 1988] "Technology Related Assistance for Individuals with Disabilities Act of 1988", 29 U.S.C. § 2202 (West, 1988), Public Law (PL) 100-407.

[Toro 2012] C. Toro, E. Sanchez, E. Carrasco, L. Mancilla-Amaya, C. Sanin, E. Szczerbicki, *et al.*, "Using set of Experience Knowledge Structure to extend a rule set of clinical decision support system for alzheimer's disease diagnosis," in Cybernetics and Systems: An International Journal, vol. 43, pp. 81-95, Taylor & Francis Inc., 2012. IF=0.973.

[Topo 2009] P. Topo, "Technology studies to meet the needs of people with dementia and their caregivers a literature review". J. Appl. Gerontol. 28, 5–37, 2009.

[Toro 2007] C. Toro, C. Sanin, J. Vaquero, J. Posada and E. Szczerbicki. ''Knowledge Based Industrial Maintenance Using Portable Devices and Augmented Reality.'' In Knowledge-Based Intelligent Information and Engineering Systems. 11th International Conference, KES 2007, XVII Italian Workshop on Neural Networks, edited by B. Apolloni, R. J. Howlett and L. Jain, 295–302. Berlin: Springer, 2007.

[Toro 2008] C. Toro, C. Sanin, E. Szczerbicki and J. Posada, ''Reflexive Ontologies: Enhancing Ontologies with Self-Contained Queries.'' Cybernetics and Systems 39, pp. 171–89, 2008.

[Toro 2009] C. Toro, M. Graña, J. Posada, J. Vaquero and E. Szczerbicki. "Domain modeling based on engineering standards". In Proceedings of 13th International Conference on Knowledge-Based Intelligent Information and Engineering Systems, LNCS 5711, pp. 95–102, Springer, 2009.

[Trewin 2004] S. Trewin, G. Zimmermann and G. Vanderheiden, "Abstract representations as a basis for usable user interfaces". Interacting with Computers, 16(3):477-506, 2004.

[UNE 2003] UNE 153010:2003, "Subtitling for deaf and hard-of-hearing people. Subtitling by teletext". AENOR, Barcelona, 2003.

[UNE 2005] UNE 153020:2005, "Audio description for visually impaired people. Guidelines for audio description procedures and for the preparation of audio guides". AENOR, Barcelona, 2005.

[UniversAAL 2014] "UNIVERsal open platform and reference Specification for Ambient Assisted Living", UniversAAL Project, http://www.universaal.org/, 2014.

[Vapnik 1998] V. N. Vapnik. "Statistical Learning Theory". Wiley-Interscience, September, 1998.

[VITAL 2009] VITAL FP6, "Vital assistance for the elderly", http://www.ist-vital.org/, 2009.

[Weemote 2013] "Weemote X". http://weemote.com/, 2013.

[WHO 2011] "Global Health and Aging". Geneva, Switzerland: World Health Organization, 2011.

[WHO 2014] "International Classification of Functioning, Disability and Health (ICF)", http://www.who.int/classifications/icf/en/, World Health Organization, 2014.

[Yanguas 2008] J. Yanguas, E. Urdaneta, C. Buiza, E. Carrasco, M. Klima, M. Macik, *et al.*, "I2HOME: Including elderly people in the information society by means of intuitive user interfaces," in The Gerontologist, vol. 48, pp. 24-24, The Gerontological Society of America, 2008.

[Yu 2006] W.D. Yu and S.R. Jonnalagadda, ‘‘Semantic Web and Mining in Healthcare.’’ In Proceedings of the 11th IEEE International Conference on e-Health Networking, Applications and Services, pp. 198–201, IEEE, 2006.

[Zheng 2005] H. Zheng, N. Black, and N. Harris. ‘‘Position-Sensing Technologies for Movement Analysis in Stroke Rehabilitation.’’ Medical and Biological Engineering and Computing 43, no. 4, 413−20, 2005.

[Zimmermann 2007] G. Zimmermann & G. Vanderheiden, "The universal control hub: An open platform for remote user interfaces in the digital home". In: Jacko, J.A., (eds.), Human-Computer Interaction, vol. 4551 of LNCS, pp. 1040–1049, Springer, Berlin (2007).

[Zimmermann 2010a] G. Zimmermann, J. Alexandersson, C. Buiza, E. Urdaneta, U. Diaz, E. Carrasco, *et al.*, "Chapter 6 - Meeting the needs of diverse user groups: Benefits and costs of pluggable user interfaces in designing for older people and people with cognitive impairments", in Intelligent Technologies for Bridging the Grey Digital Divide, pp. 80-93, IGI Global, 2010.

[Zimmermann 2010b] G. Zimmermann, "URC and WSDL – Towards Personal User Interfaces for Web Services", in Proceedings of the 5th European Conference on Smart Sensing and Context, EuroSCC 2010, LNCS 6446, pp. 184-187, Springer, 2010.

[Zimmermann 2013] G. Zimmermann, *et al.*, "GenURC: generation platform for personal and context-driven user interfaces", in Proceedings of the 10th International Cross-Disciplinary Conference on Web Accessibility, ACM, 2013.

Appendix 1 Relevant projects

7.1 I2HOME

PROJECT: **I2HOME – Intuitive Interaction for Everyone with Home Appliances based on Industry Standards** FP6 – 033502 (http://www.i2home.org/)
FUNDING ENTITY: European Commission – FP6 IST – 2005-2.5.11 eInclusion
DURATION From: September 2006 To: December 2009
COORDINATOR: Dr. Jan Alexandersson, DFKI

The main goal of I2HOME was to develop an interoperability architecture (a gateway) that could be used in home environment to provide universal access to all systems and devices present in the digital home. Furthermore, this architecture had to support a wide range of standards (such as DLNA, UPnP, Zigbee, …) in order to provide connectivity to the widest range of devices and services as possible. Finally, an implementation of this architecture was to be developed and tested with a sample of end users such as people with visual impairments, elderly people with no cognitive impairment and elderly people with Alzheimer's Disease. I2HOME met successfully its goals producing the Universal Control Hub (UCH), which is an implementation of the ISO 24752 Universal Remote Console specifications.

The author had a double role in the project, as a Researcher on Human-Computer Interaction and Universal Accessibility, and as the Technical Manager of the Project (temporarily substituting Dr. Gottfried Zimmermann). Besides its industrial impact, the project achieved relevant publications: [Carrasco 2009], [Carrasco 2008], [Carrasco 2007], [Diaz-Orueta 2014], [Epelde 2013c], [Epelde 2009], [Klima 2009], [Murua 2010], [Zimmermann 2010], & [Yanguas 2008].

7.2 VITAL

PROJECT: **VITAL - Vital Assistance For The Elderly** FP6 - 030600 (http://www.ist-vital.org/)
FUNDING ENTITY: European Commission – FP6 IST – 2005-2.5.11 eInclusion
DURATION From: September 2006 To: December 2009
COORDINATOR: Dr. Oliver Keller, DFKI

The main goal of VITAL was to specify and develop an open architecture that could be used to provide tailored services for the elderly people that could be used for them in a simple and natural way. The TV was chosen at that time as the best user interface for them to interact with, and several exemplary information and entertainment services were designed and developed. Due to communication with I2HOME project, VITAL adopted the UCH architecture as well. Finally, a wide validation with elderly users without cognitive impairments was carried out.

The main role of the author in the project was to conduct research on Human-Computer Interaction and Universal Accessibility. The main publications obtained in the project are: [Epelde 2013c], & [Epelde 2013d].

7.3 HYPER

PROJECT: **HYPER – Hybrid Neuroprosthetic and Neurorobotic Devices for Functional Compensation and Rehabilitation of Motor Disorders** (http://www.car.upm-csic.es/bioingenieria/hyper/)
FUNDING ENTITY: Ministerio de Ciencia e Innovación, CONSOLIDER-INGENIO 2010
DURATION From: January 2010 To: December 2015
COORDINATOR: Dr. José Luis Pons, CSIC

The HYPER project focuses its activities on new wearable neurorobotic-neuroprosthetic (NR-MNP) systems that will combine biological and artificial structures in order to overcome the major limitations of current rehabilitation solutions for the particular case of Cerebrovascular Accident (CVA), Cerebral Palsy (CP) and Spinal Cord Injury (SCI). The main objectives of the project are to restore motor function in SCI patients through functional compensation and to promote motor control re-learning in patients suffering from CVA and CP by means of an integrated use of neurorobotics and neuroprosthetics. The project also functionally and clinically validated the concept of developing hybrid NR-MNP systems for rehabilitation and functional compensation of motor disorders, under the assist-as-needed paradigm.

The author has a double role in the project as the Virtual Reality Workpackage Coordinator (substituting Dr. Alessandro De Mauro) and Researcher on Assistive Technologies for Neuro-rehabilitation. The most relevant publications from this project are: [DeMauro 2012a], [DeMauro 2012b], [DeMauro 2011a], [DeMauro 2011b], [DeMauro 2010] & [Epelde 2013a].

7.4 EREHAB

PROJECT: **EREHAB Plataforma Ubicua Multidispositivo de Telerehabilitación Personalizada** ETORGAI 2011, ER-2011/00036
FUNDING ENTITIES: Bilbomática, S.A., Baleuko, Ikusi-Angel Iglesias, STT Ingeniería y Sistemas, Teccon Ingenieros S.L., & Vilau Media.
DURATION From: January 2011 To: December 2011
COORDINATOR: Oskar Rueda, Bilbomática S.A.

The main goal of the EREHAB project was to design, develop and validate a joint telerehabilitation service that could be universally deployed. Remote rehabilitation applications had limited deployment at that time. The path to achieve greater user acceptance and adherence was supposed to lay in the provision of solutions tailored to the current needs of the end users and to their real-life context. So, the goal of the project was to devise a new telerehabilitation system that could be adapted to all kind of persons in rehabilitation processes, independently of their age, technical skills or context of use, and to test it with end users.

The author's main role was to conduct research on Human-Computer Interaction. The most relevant publications achieved from project results are: [Epelde 2014a], [Epelde 2013b], & [Epelde 2012a].

7.5 ARGUS

PROJECT: **ARGUS – Assisting personal guidance system for people with visual impairment** FP7-288841 (http://www.projectargus.eu/)
FUNDING ENTITY: European Commission – FP7 – ICT – 2011 - 7
DURATION From: October 2011 To: July 2014
COORDINATOR: Dr. Oihana Otaegui, Vicomtech-IK4

The main goal of the ARGUS project was to develop innovative tools which could help blind and partially sighted people to move around autonomously and confidently. The ARGUS system consisted primarily of a user-friendly portable satellite-based navigation device with acoustic and haptic user interfaces enabling users to obtain a 3D spatial insight of their surrounding environment, and providing continuous assistance to follow a predefined path in urban, rural or natural areas.

The author had a double role in the project as the Technical Manager of the Project and Researcher in Human-Computer Interaction. The main publications achieved in the project are: [Carrasco 2014b], [Carrasco 2013], [Otaegui 2013], [Otaegui 2012a] & [Otaegui 2012b]

7.6 MIND

PROJECT: **MIND – Abordaje Integral de la Enfermedad del Alzheimer** (CENIT-20081013) (http://www.portalmind.es/)
FUNDING ENTITY: Bilbomática y eMedica.
DURATION From: December 2008 To: December 2011
COORDINATOR: Dr. Vicente Belloch, ERESA

The main goal of MIND was to conduct translational research that could contribute to the finding of the mechanisms for the early diagnosis the Alzheimer's Disease. More in detail, Vicomtech was focused in the task of developing a Clinical Decision Support System that could integrate the knowledge coming from several medical specialities in order to provide a diagnosis recommendation for the patient.

Through the subcontract awarded to Vicomtech, the author had two main roles in the project: Manager of the Knowledge Integration and Decision Support Workpackage and Researcher in Artificial Intelligence. The main publications obtained are: [Sanchez 2012], [Sanchez 2011a], [Sanchez 2011b], [Sanin 2012], & [Toro 2012]

7.7 LIFE

PROJECT: **LIFE – Desafío integral al cáncer de mama** (INNPRONTA IPT-20111027) (http://www.proyectolife.es/)
FUNDING ENTITY: Bilbomática.
DURATION From: December 2011 To: December 2014
COORDINATOR: Dr. Vicente Belloch, ERESA

The main goal of the LIFE project was conduct basic research on breast cancer looking for biomarkers on several medical information sources such as medical imaging, genomics and proteomics. Vicomtech-IK4 was in charge of the design and development of a tool that *(i)* could integrate the knowledge coming from the different medical specialties of the Breast Functional Units, and that *(ii)* could reason on top of that in order to provide support in the selection of the most appropriate treatment for each patient with breast cancer

The author took part in the project as a Researcher in Artificial Intelligence. The main publications produced from this project were: [Sanchez 2014] & [Sanchez 2013].

Appendix 2 Thesis most relevant publications

The style of the Thesis is a collection of papers. These original publications are included at the end of the Appendix. In this Appendix we introduce the most relevant publications of the author in direct connection with the Thesis contents. The main contributions and circumstances of each paper are described. According to the main contribution of each publication, the papers have been divided into three categories: *(i)* Universal Accessibility,*(ii)* Decision Support & *(iii)* Assistive Technologies.

8.1 Publications on Universal Accessibility

8.1.1 Universal Remote Console-based next-generation accessible television. Universal Access in the Information Society, 2013. [Epelde 2013a]

The contributions described in this paper were carried out along the I2HOME (FP6-33502) project, except section 4.2.3, the validation of the interactive services, which was carried out in VITAL (FP6-30600) project. This paper tackles the accessibility challenge of television (TV), providing an architecture achieving universally accessibility of current and future TV. This goal is met by the use of the ISO/IEC 24752 ‘‘Universal Remote Console’’ (URC) standard. This standard defines an abstract user interface layer called the ‘‘user interface socket’’ that allows the development of pluggable user interfaces for any type of user and any control device. The URC standard is typically implemented following the Universal Control Hub middleware specifications. There is a significant effort inside the openURC Alliance to provide accurate and updated guidelines and source code to accelerate the mass market deployment of this technology. The integration of this technology in the TV sets, allows to propose two main universal accessibility use cases: (a) for remotely operating the TV set, and (b) for interacting with online services delivered through the TV. Several prototypes of the proposed architecture were implemented to cover the aforementioned two main use cases, and validation with end users was carried out as well. The conclusions of the paper was that the proposed architecture can be easily and unobtrusively integrated in a variety of TV sets and that it provides wide flexibility to meet the particular interaction needs of every possible end user.

8.1.2 Providing universally accessible interactive services through TV sets: Implementation and validation with elderly users. Multimedia Tools and Applications, 2013. [Epelde 2013b]

The contents described in this paper were carried out in VITAL (FP6-33502) project. This paper is a continuation of the previous one [Epelde 2013a]. Here, the focus is on the use case of deploying universally accessible interactive services through the TV sets. The work shares the architecture proposed in [Epelde 2013a], but a deeper analysis is provided about its complete capabilities regarding compatibility with the TV devices and provision of interactive services. Besides, this paper gives special attention to the particular interaction needs of the elderly user as target system users, and specific guidelines have been followed at the time of designing the corresponding user interfaces for them. A prototype which provided videoconference and information services was developed. Finally, the paper reports an extensive validation of the system, which led to satisfying results in terms of usability and improvement of quality of life of the elderly people.

8.2 Publications on Clinical Decision Support

8.2.1 Using set of Experience Knowledge Structure to extend a rule set of clinical decision support system for Alzheimer's disease diagnosis. Cybernetics and Systems, 2012. [Toro 2012]

The research reported in this paper was carried out along the MIND (CENIT-20081013) project. Early diagnosis of Alzheimer's Disease (AD) is still a big challenge. It is widely accepted in the medical community that the integration of knowledge from several medical specialities, such as neurology, neuropsychology, and medical imaging, is required in order to fully understand this disease and its evolution, and to develop sound diagnostic methods. This article presents an experience-based clinical decision support system (ECDSS) for the early diagnosis of AD. The ECDSS integrates and processes experience coming from medical experts of several specialities. The system uses ontologies for knowledge representation, performing semantic reasoning process to infer diagnoses for patients. This system has been extended with the application of Set of Experience Knowledge Structure (SOEKS) and Decisional DNA (DDNA) in order to provide it with the ability to store the experience of the medical experts and to apply it for the discovery of new knowledge. Thanks to the SOEKS and DDNA, experience is represented as formal decision events in an explicit way. Furthermore, this system was implemented and a prototype was developed. The ECDSS was integrated with the ODEI front-end developed by Bilbomática and the whole system was adapted to the case study defined at MIND project.

8.2.2 Decisional DNA: A multi-technology shareable knowledge structure for decisional experience. Neurocomputing, 2012. [Sanin 2012]

This paper was carried out along the MIND (CENIT-20081013) project, and it is a continuation of the previous paper [Toro 2012]. This paper describes an analysis of the capabilities of the Decisional DNA (DDNA) knowledge representation structure when applied to different domains and decisional technologies. It concludes that DDNA can be successfully applied and shared among multiple technologies while providing them with predicting capabilities in the decision making processes. This paper comprises four different technologies to validate the concept. The previous ECDSS described at [Toro 2012] and developed for the MIND project was one of the use cases selected. The results of the study confirmed that the claimed benefits of the DDNA (versatility, dynamicity, shareability, etc.) were also met for the MIND ECDSS.

8.2.3 Bridging challenges of clinical decision support systems with a semantic approach. A case study on breast cancer. Pattern Recognition Letters, 2013. [Sanchez 2013]

The contributions described in this paper were carried out along the LIFE (INNPRONTA IPT-20111027) project. LIFE was the natural continuation of the MIND (CENIT-20081013) project. Analogously, this paper is a continuation of the two previous ones [Toro 2012] & [Sanin 2012]. This work reported in the paper aim is to overcome some of the main technical barriers that impede the wide adoption of the Clinical Decision Support Systems (CDSS) in everyday clinical practice. To do so, this paper proposes a new clinical task model oriented to clinical workflow integration, proposes the uses of semantics in order to fully exploit available medical knowledge and expertise, and finally presents a generic architecture called Semantic CDSS (SCDSS) in order to extend available classical CDSS. Next, a prototype of the proposed SCDSS was developed; it was adapted to the domain of the breast cancer and then integrated in a real clinical environment in collaboration with experts from the hospitals participating in the LIFE project. Finally, an evaluation methodology has been proposed and an evaluation which will last 15 months has been started.

8.2.4 Decisional DNA for modeling and reuse of experiential clinical assessments in breast cancer diagnosis and treatment. Neurocomputing, 2014. [Sanchez 2014]

This paper was conducted along the LIFE (INNPRONTA IPT-20111027) project. Besides, this paper is the continuation of the previous one [Sanchez 2013] carrying out in detail the formalization and integration of the clinical decisions in the CDSS. This step is crucial in order to keep the knowledge repository of the CDSS continuously updated. The identification of state-of-the-art experience acquisition and experience modelling techniques led to the discovery of a (semi-)automatic update process of the underlying knowledge bases and decision criteria of CDSS following a learning paradigm based on previous experiences. For this task, SOEKS and Decisional DNA experiential knowledge representation techniques have been chosen, and on top of them, three algorithms processing clinical experience have been proposed to: (a) provide a weighting of the different decision criteria, (b) obtain their fine-tuning, and (c) achieve the formalization of new decision criteria. . Finally, the paper reports an implementation instance of a CDSS for the domain of breast cancer diagnosis and treatment.

8.3 Publications on Assistive Technologies

8.3.1 Role of cognitive and functional performance in the interactions between elderly people with cognitive decline and an avatar on TV. Universal Access in the Information Society, 2014. [Diaz-Orueta 2014]

The research described in this paper was conducted along the I2HOME (FP6-33502) project. In this paper, the study was focused on the adaptation and tailoring of Avatars to people with mild to high cognitive impairment. More in detail, the experiment was conducted using the Avatar on TV prototype developed in I2HOME, in order to engage in short dialogs and deliver short messages to elderly people with mild to severe Alzheimer's Disease (AD). The goal was to simulate a personal home assistant (the Avatar) who would deliver short and simple instructions or housekeeping messages, such as, "the entry door is open", "the oven is on", "the washing machine has finished the programme". The validation was carried out by INGEMA on a sample of 20 participants with astonishing results. Most subjects were able to understand correctly and follow the instructions given by the Avatar, even in cases of severe dementia. Further analysis of the data by INGEMA showed that participants with better cognitive and functional state, measured by a specific set of neuropsychological and functional tests, significantly performed better fulfilling the TV tasks. Hence, it was concluded that neuropsychological assessment may be used as a useful complementary tool for the assistive technologies adaption for the elderly with different cognitive and functional profiles. Finally, it was considered proven that even people with severe cognitive impairment can successfully interact with IT whenever tailored user interfaces are provided to them.

8.3.2 Universal remote delivery of rehabilitation: Validation with seniors' joint rehabilitation therapy. Cybernetics and Systems, 2014. [Epelde 2014a]

The contributions presented in this paper were carried out in EREHAB (ETORGAI 2011, ER-2011/00036) project. This paper reports additional advances in the research reported in previous three publications [Diaz-Orueta 2014], [Epelde 2013a] & [Epelde 2013b]. In this case, the aim was to develop a joint (articulation) telerehabilitation service towards its universal deployment. Remote rehabilitation applications still have limited deployment. The path to achieve greater user acceptance and adherence lies in the provision of solutions tailored to the current needs of the end users and their real-life context. So, the project goal was to devise a new telerehabilitation system that could be adapted to all kind of persons in rehabilitation processes, independently of their age, technical skills or context of use, and to test it with end users. Again, the URC/UCH architecture was selected to ensure universal access of the patients in rehabilitation processes to the rehabilitation service. Several software clients implementing the UCH were identified and a backend providing several web services was necessary as well. Dedicated user interface and management tools were designed for the rehabilitation specialists working at the hospital or medical centre. A prototype was built to support a validation of the approach conducted by rehabilitation experts of the Hospital Donostia. Both health professionals and patients rated positively the implemented system. The usability evaluation results show the validity of the approach and the acceptance of the developed human−computer interaction paradigm. Moreover, the experimentation identified future work avenues dealing with the automated processing of the data generated by the system in operation.

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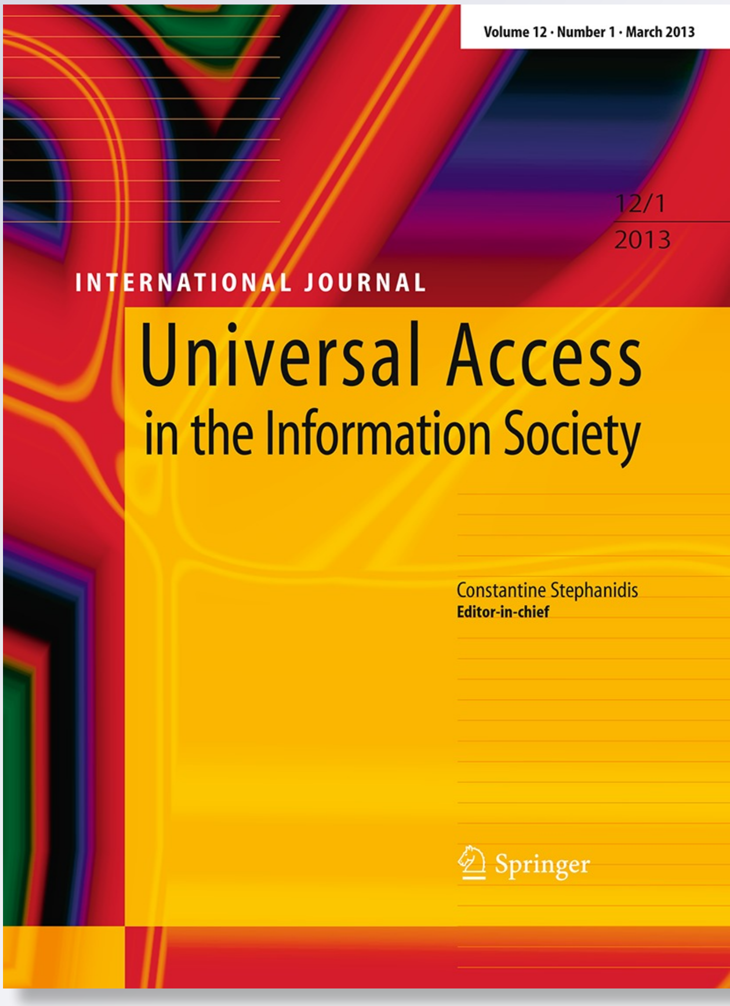

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LONG PAPER

Universal Remote Console-based next-generation accessible television

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Abstract This paper presents a new approach to make current and future television universally accessible. The proposed approach provides a means of universal accessibility both for remotely operating the TV set and for interacting with online services delivered through the TV. This proposal is based on the ISO/IEC 24752 "Universal Remote Console" (URC) standard. This standard defines an abstract user interface layer called the "user interface socket" and allows the development of pluggable (plug-in) user interfaces for any type of user and any control device. The proposed approach lays the foundation for the development of advanced user interfaces that can be interacted within various modalities. Different prototypes have been developed based on this approach and tested with end users. The user tests have shown this approach to be a viable option for the proposed scenarios. Based on the experience gathered with the prototypes, recommendations and implementation options are suggested for commercial adoption.

Keywords Accessible TV · ISO/IEC 24752 · Universal Remote Console—URC · Universal Control Hub—UCH · Multimodal interaction · Pluggable user interfaces

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1 Introduction

The TV set is one of the most common communications device, present in most homes worldwide. Furthermore, watching TV is one of the activities that take up most of people's leisure time [36].

Together with the widespread use of the TV, the TV sets' evolution from the analogue world to the digital world has opened up a new range of possibilities. These possibilities include the option to add new functionality that can be integrated with the TV and at the same time the option of providing universal access to previously existing basic functionality, as well as to future functionality.

With regard to the inclusion of new functionality in the TV, interactive services are cited as the most important of recent advances. Interactive services have been integrated into TVs in many research projects. These types of services can be categorised according to their level of interactivity [26]:

- Broadcast-only services: EPG (Electronic Programme Guide), Local Games, VOD (Video On-Demand), PVR (Personal Video Recorder), etc.
- One-way interactive services: Advertisement direct response, opinion polling, voting, etc.

- Two-way interactive services: TV banking, interactive TV content, email, social networking, etc.

Aside from research developments, reacting to user interest in interactive services, manufacturers started including iTV applications in commercial products. This inclusion has occurred gradually, from set-top boxes and PC-based media centre solutions, to the TV's themselves. The level of interactivity of the services implemented has followed a likely path, from simpler to more complex services, from integrating simple VOD applications to integrating latest social networking applications.

A good example of these developments is the commercial availability of TVs supporting interactive services widgets technology from Yahoo Connected TV [35] or Sony Applicast.

This growing interest in providing interactive services through the TV can also be found in proposals such as HbbTV [17], in which regular broadcasts are complemented by interactive services available on-line, with the aim of providing those services seamlessly on a TV set.

Regarding the TV set's universal access, there have been advances in different areas. In the content accessibility area, the main success has been the transition of accessibility standards from analogue television to digital television. Existing subtitle description standards have been adapted from teletext to the Digital Video Broadcasting (DVB) environment.

Moving on to TV set remote controls, TV remote controls have changed their appearance and advances in usability have been achieved, but the interaction paradigm based on infrared remote control technology has remained unchanged for more than a decade. Effort has been made to make remote controls as user-friendly as possible, but a significant impact on accessibility has yet to be achieved. For many users, remote controls are too complex to use. Some may not see buttons very well, others may not have the dexterity to handle the device or manipulate its buttons without difficulty.

Other users, for example, those with cognitive difficulties, require training on how to use the remote control. Even so, many times they are unable to remember the location of the buttons on the remote control or how to use the TV's On Screen Display (OSD) menus.

Going beyond the remote control, other remote interaction technologies have been researched, such as speech interaction, or the use of different interaction objects such as pillows to make the TV set's remote control accessible to all.

Finally, the provision of universally accessible interactive services on the TV has not been a deeply researched area. Most efforts have been targeted on making EPG use accessible through speech output.

For many people, the integration of online services into a TV set means being able to access online banking, e-health services, having web presence or socialising via social networks, which otherwise would be inaccessible due to a lack of computer skills or other accessibility barriers.

Governmental interest [13] in promoting initiatives to build the Future Internet based on such services, together with the commercial integration of these services into the TV, should not exclude disadvantaged users along the way. Rather than following a "one size fits all" approach, the Future Internet should support different users with heterogeneous needs and preferences through personalised user interfaces and services. Therefore, the future TV should be based on a design approach that allows an easy extension to the TV implementation with the resources required to adapt to each person's specific usage context.

Even if there have been advances in the TV accessibility research area, these have produced specific solutions that solve particular issues, but an approach that would make the TV universally accessible from design is still missing.

Section 2 surveys the current body of work related to the problem presented in the introduction. Next, Sect. 3 introduces the proposed approach to solve this problem. Afterwards, Sect. 4 describes the implementations done to test the proposed approach, together with a summary of the results obtained from the user tests. Section 5 analyses the implementation options of this approach in real-life contexts, and Sect. 6 summarises the paper and draws conclusions.

2 State of the art

2.1 TV accessibility

The Assessment of the Status of eAccessibility in Europe report [12], analysing both the accessibility of broadcast programmes and end-user TV equipment, showed that TV accessibility is still far away from being implemented to its full extent. This report also points out the accessibility opportunities and challenges that the introduction of Digital TV brings. The opportunities include the lower cost and the easier incorporation of accessibility features into a digital system. But at the same time, there is a consideration of a key challenge, related to universal access to new interactive services (e.g., electronic programme guides), provided from the start rather than as an afterthought which has been the case until today.

This survey also highlights the initiatives that different European Member States are carrying out. Even though only a few of them address these challenges in a policy context, many Member States are promoting the development and implementation of automatic media translation (e.g., text-to-speech and vice versa) as well as imposing higher targets and/or quality standards for accessibility services in the digital environment.

The challenge of inclusiveness in a developing technology such as interactive television has already been highlighted by the iTV research community in [15]. This paper suggests that possible solutions should include inclusive (multimodal) design, personalisation and standardisation.

A study with a broader perspective but centred on digital TVs usability and accessibility is presented in [23]. This study analyses the usability and accessibility of the basic remote control of TV and interactive services, together with accessibility in a prior phase, where a product is selected, purchased and installed in the home. This study reports the results and findings from user tests, classified by each class of exclusion.

There are some commercial implementations [25] and firmware developments for Linux-based set-top boxes [19] that go further than subtitles options, through implementing text-to-speech technology and allowing contrast adjustment, but these are specific developments for specific platforms, whose extension would imply being tied to a particular platform.

There have been areas of iTV research more closely related to support activities that have gone further than analysing usability and promote including accessibility consideration from the start of their development process approaches.

In this context, a research paper [7] proposed an affective UI evaluation methodology that takes into consideration the accessibility concerns and TV-specific characteristics (TV medium, TV audience and context of use), ensuring that the developed iTV applications are not only accessible and usable, but they also cope with the established TV experience. A related study [10] presents different qualitative research methods applied to the field of interactive television (iTV) application design and evaluation, suggesting that applying these methods to specific user groups can help in understanding accessibility problems while developing universally accessible iTV applications.

Regarding technological support for the universal access in the TV set, from the authors' point of view three working areas directly related to accessible TV interaction must be tackled: content accessibility, accessible remote controls and the accessibility of interactive services. The state of art in these working areas is presented in the following subsections.

The approach proposed in this paper is based on the Universal Remote Console (URC) framework, which makes a clear separation between the services to be accessed and the UI to be used for accessing and controlling such services.

To aid the reader in understanding our proposed approach, the URC framework is introduced at the end of this section.

2.1.1 *Content accessibility*

This work area covers the efforts of providing means of following regular audiovisual content for people with different disabilities, through alternative synchronised media provided with the original content.

The accessibility services defined as to be included in accessible broadcast content are audio description for the visually impaired, close captioning for the hearing impaired and sign language also for the hearing impaired. Ensuring the availability of these services involves complying with the relevant production, distribution and viewing legislation and standards.

The main efforts in this area have become regulation through standards agencies. AENOR has provided a normative reference on how to create audio-descriptions [2] and subtitles for teletext [1]. With the transition from analogue to digital TV, ETSI has published a standard [11] on how subtitles should be managed in DVB.

DVB offers the possibility to include different content streams for audio, video and data, which allows broadcasting of audio-descriptions, sign language signing or subtitles as additional channels. Thus, the user is able to select the combination of channels to be displayed on their viewing device.

As introduced in the previous section, the amount of accessible TV content produced is still well below 100% in traditional TV broadcasting. Furthermore, there is a substantial challenge to assure content accessibility on a TV content consumption paradigm change, where the user's role is changing from a simple consumer to that of content producers, where the production, distribution and viewing will no longer be in the hands of few parties and fixed set of technologies, which has been the case until now.

2.1.2 *Accessible remote control*

This work area covers the efforts in providing a means of remotely controlling basic TV functionality, such as channel up/down, volume up/down or turning the TV on/off, to all user groups.

Usability advances for different user groups have led to changes in the appearance of the TV remote controls. Some good examples of these remotes are the Weemote [34] and the Falck Vital [14], as shown in Fig. 1.

The research community has driven efforts to extend the capabilities of the remote control. These efforts are

Fig. 1 Example of usable remote controls

classified and numbered in [6]. Some of these approaches that could help making the TV remote control more accessible rely on the use of everyday objects such as pillows [28], gesture recognisers [22], speech interaction and dialogue systems [4], and the use of devices such as mobile phones and PDAs. These efforts target-specific scenarios and the developments cannot be directly applied in future implementations.

2.1.3 Accessible interactive services

This work area covers the effort in providing iTV applications that can be used by everybody.

Most of the work in this area has been related to EPG applications. Some have extended the implementations of text-to-speech capabilities available for the TV set's remote control to EPG applications, while there is an interesting initiative that integrates a paper-based remote concept [3] for navigating through EPG information. As in the TV remote control case, these efforts give specific solutions to particular iTV applications, for a limited number of TV platforms.

After reviewing the state of the art in the TV accessibility topic, the need emerges to elaborate an approach that provides universal accessibility both for remotely operating the TV set and for interacting with online services delivered through the TV.

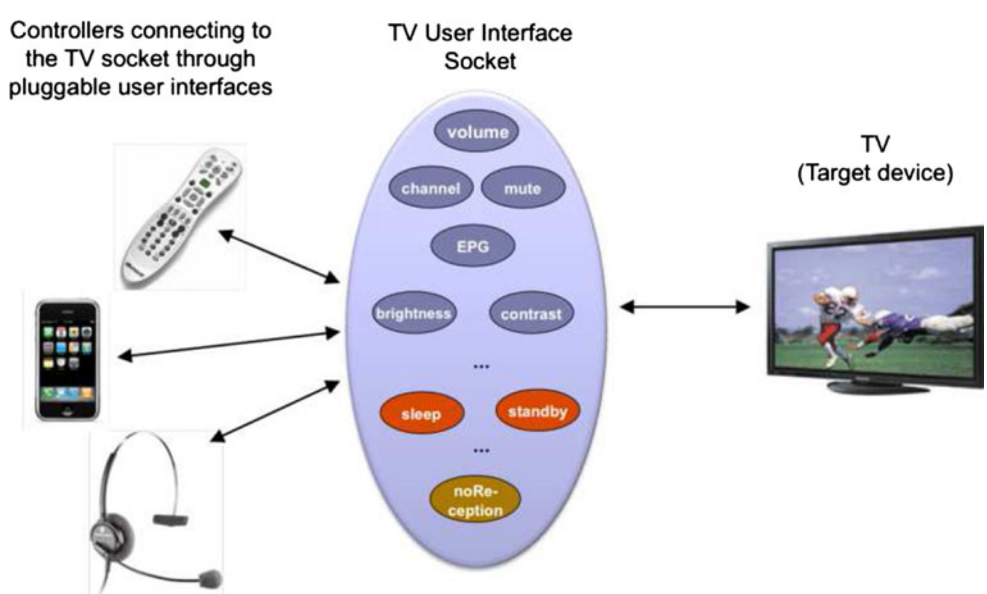
2.2 The URC framework

The Universal Remote Console (URC) framework [20] was published in 2008 as a 5-part international standard (ISO/IEC 24752). It defines a "user interface socket" (or "socket" for short) as the machine-operable access and control point for a target device or service. It can be seen as a user interface "model" that exposes the functions and current state of a target device or service, without specifying how it should be presented to a user. Sometimes this is also referred to as an "abstract user interface" (without specific rendition) as opposed to the "concrete user interface" (that provides a specific rendition of the abstract user interface).

In essence, a user interface socket consists of the following elements:

- *User interface variables* that reflect the current state of the target device or service and that may be modified by the user/controller. For example, in a sample user interface socket for a TV (see Fig. 2), the variable "volume" specifies the current volume setting as a number between 0 and 50. Variables can be of any XML-valid type, such as string, number, boolean, etc. For complex devices or services, variables may hold XML structures (e.g., the content of an EPG table).

Fig. 2 Sample user interface socket for a TV



- *User interface commands* that can be triggered by a user/controller to invoke a specific function that the target device or service provides. For example, in the TV socket, the command "sleep" programs the TV to switch off automatically after a pre-defined period of time, let us say after 60 minutes. A command may have one or more parameters that are to be specified by the user/controller when triggering the command. The "sleep" command could have the switch-off duration as a parameter in order to allow the user to specify their individual "switch-off duration" every time they invoke the command.
- *User interface notifications* that can be raised by a target device/service to notify the user about an event or state. For example, in the TV socket, the notification "noReception" could inform the user that no signal can be currently received. Each notification has a category, which denotes its nature and urgency. Possible categories are information, alert and error.

It is important to note that the user interface socket contains "live" values and triggers only, and no canned labels or icons for the labelling of socket elements (variables, commands, and notifications). Labels and other user interface resources are provided by external "resource sheets." One resource sheet could contain English labels, another one Spanish labels, etc. Also, there could be yet another resource sheet containing icons or audio clips for each of the socket elements. Some users may only want to see a textual label; others may want to have a text label plus icon, yet another group may prefer icons only. Thus, a user interface can be easily localised or personalised just by exchanging the resource sheet, or by adding icons or audio clips from another resource sheet.

As the name suggests, a user interface socket is just one (the abstract) part of a user interface. A concrete user interface implementation is needed, which "plugs" into the socket to "render" the socket, i.e., presents it to the user and allows the user to send input to the socket. The concrete user interface part is called "pluggable user interface." There may be multiple pluggable user interfaces (i.e., multiple renditions) for a user interface socket, varying in many aspects, including their fitness for different controllers. For example, one pluggable user interface for the TV socket may be presented on the TV screen itself, another one on the user's iPhone and a third one may allow voice control of the TV (see Fig. 2).

Pluggable user interfaces allow a high degree of individualisation and personalisation. For example, one pluggable user interface could only expose the most used functions of the TV (so that grandma can easily use it) or include all bells and whistles of the TV (for users who want to see all functions of their TV at once).

The URC technology is an open user interface platform, allowing third parties to create pluggable user interfaces and use them with any target device/service that exposes its functionality through a socket. The framework includes "resource servers" as global market and distribution places for resource sheets and pluggable user interfaces to be shared among the user community.

Today's devices and services do not come with a user interface socket. However, many of them come with some kind of remote controllability, through infrared, wired or wireless communication technologies. It is possible to build a bridge (gateway) between the communication technology implemented by a target device/service and the URC technology. The Universal Control Hub (UCH) is a gateway-oriented architecture for implementing the Universal Remote Console (URC) framework in the digital home [37]. Thus, the UCH is the gateway between any target device/service and any controller, exposing user interface sockets of all connected targets and facilitating pluggable user interfaces that plug into the sockets.

The main features of the UCH are as follows:

- It acts as a bridge between targets and controllers, each with its own communication and control protocol, that otherwise would be unable to talk to one another.
- Standard-based user interface sockets. The UCH is based on the URC framework previously described.
- A variety of user interface protocols. The UCH allows different user interface protocols (DHTML over HTTP, Flash, etc.) to be implemented and used by controllers.
- Globally available resource servers. The UCH can get distributed resources, such as resource sheet, pluggable user interfaces and other run-time components of the UCH from resource servers.

Figure 3 shows the UCH architecture for the URC standard.

In the UCH architecture, a pluggable user interface is represented by a User Interface Protocol Module (UIPM). A UIPM is responsible for presenting one or multiple sockets to the user through a user interface that is rendered on a controller.

The URC-HTTP protocol, as defined by [29], facilitates remote access by a controller to the sockets running in a UCH. This protocol defines the HTTP-based messaging and functions for a controller accessing the sockets on a UCH. The implementation of this protocol is optional for a UCH, but once implemented it offers a standardised and powerful method for advanced clients to access the UCH.

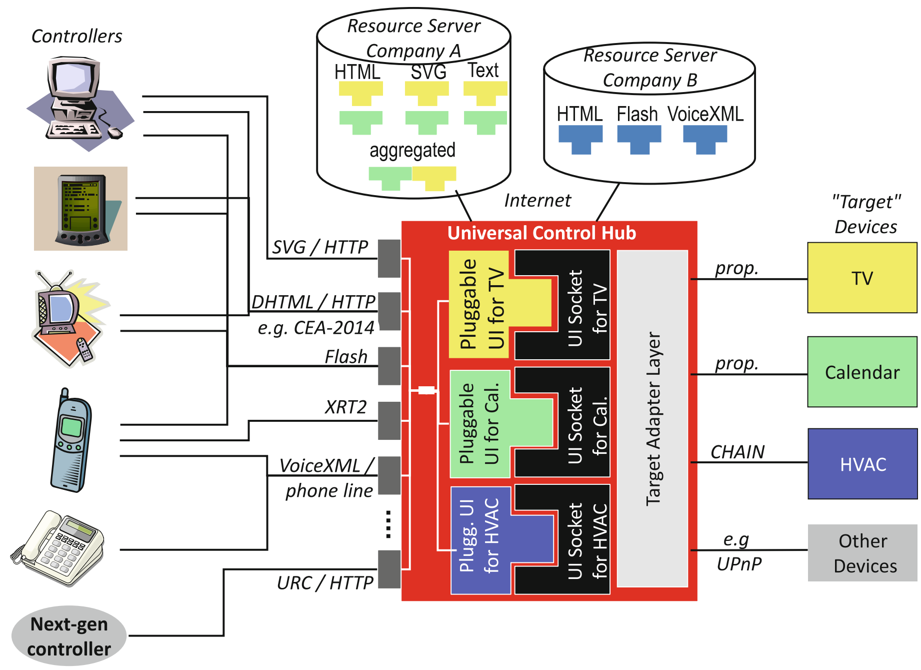


Fig. 3 UCH architecture

3 Proposed approach

This section presents a solution that provides universal accessibility both for remotely operating the TV set and for interacting with online services delivered through the TV.

The novelty of this paper is the exposition of how, by using the UCH architecture, it is possible to achieve both goals at the same time. The next subsection will explain how the TV set's integration is understood from the UCH architecture perspective.

Once the architectural view is explained, the following two subsections present how this technology should be implemented to provide a solution for each of the targeted goals.

3.1 Proposed architecture

In the proposed solution, for each targeted functionality (TV Remote Control and Access to Interactive Services through the TV), the TV set plays a different role. In the case of a TV remote control, the TV is acting as a target to be controlled (TV as target use case), and in the case of the access to interactive services through the TV, the TV acts as a controller which lets the user access the targeted services (TV as controller use case).

Today, TV sets are very heterogeneous (standalone TVs, set-top boxes, media centres, etc.), and these devices can implement a target use case, a controller use case or contain both use cases in the UCH architecture.

Figure 4 shows a TV set that works only as a Target in the UCH architecture. In this case, the TV set is acting as a remotely controllable TV, which can be controlled by a controller to change volume, channel, etc.

Figure 5 outlines a TV set that works only as a Controller in the UCH architecture. In this case, the TV set is acting as a controller, which is able to interact with interactive services through the UCH architecture.

In the case of Fig. 6, the TV set works both as a Controller and as a Target in the UCH architecture. Following an implementation of a mixed (controller + target) use case, it is possible to remotely control the same TV set from the TV set configuration, or alternatively, from a second controller. It is also possible to interact with interactive services that have been integrated into the UCH.

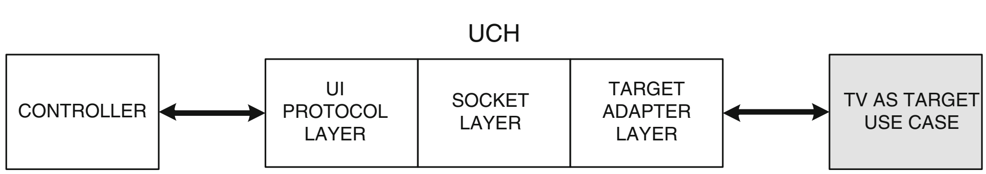


Fig. 4 TV as target use case

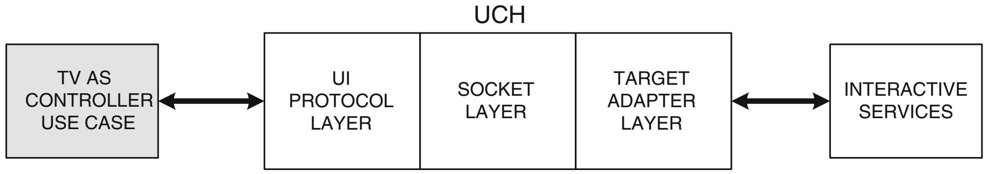


Fig. 5 TV as controller use case

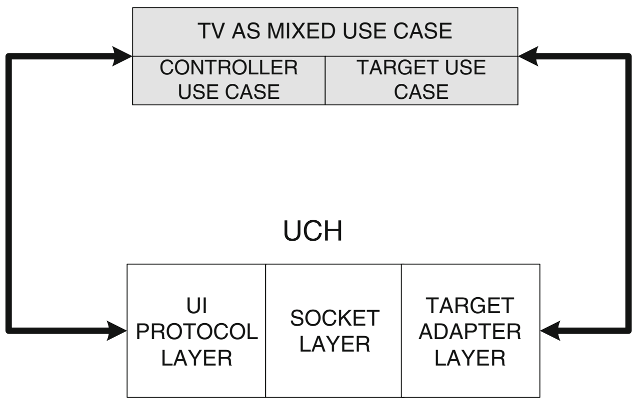


Fig. 6 TV as mixed use case

3.2 TV as target use case: accessible remote control of the TV

The objective of specifying this use case solution is to provide people with the remote control device plus a user interface that best suits them. As said in the introduction, not everyone feels comfortable with the regular IR remote controller, which tend to have smaller buttons and to be more complex. This solution would allow them to use alternative devices like PDAs, tablets, microphones or a combination of such devices.

The main requirement to implement this solution, and to integrate the TV as a UCH's target device, is the remote controllability of the TV set. The requirements to integrate a target to the UCH are described below.

The target device must have an interface for clients to remotely control the complete functionality of the target.

In more detail, there are three categories of requirement on the networking platform of a target:

- Discoverability: A target must be discoverable and identifiable on the home network. This can be implemented as the target advertising a service or the target responding to search messages from the client, or both.
- Controllability: A target must be controllable, i.e., a client must be able to invoke its commands remotely.
- Eventing: A target must send out events to inform a client about its state changes.

These requirements would address the full integration of a TV set, but having remote control via IR is a possible starting point. Later on, a discussion will be presented of the available TV technologies and their possible integration.

The TV set's remote control functionality integration into the UCH architecture is achieved by means of defining the required XML files (UI Socket, Target Description and Target Resource Sheets) and implementing the corresponding code for the target adapter layer requirements (Target Discovery Module and Target Adapter). For more information see [30].

Once a TV set is integrated as a target in the UCH, it is possible both to develop a UCH's User Interface Protocol (UIPM) or to use an existing one. Through the available UIPMs, the different pluggable UIs can remotely control the TV set, using the controller most comfortable for the user.

Also, the UCH can be connected to different resource servers on the Internet that offer UIs and UCH integration modules that may be downloaded and used directly.

Figure 7 outlines a proposal for the TV set's accessible remote control. This figure shows different pluggable user interfaces that can interact with a TV set that has been integrated with the UCH as a target. A resource server object reflects the option of using the pluggable user interfaces and integration modules downloaded directly from the Internet.

More information on the solution proposed for the TV set's accessible remote control can be found in [9].

3.3 TV as controller use case: accessible interactive services on TV

The aim of developing a solution for this use case is that of providing people with interactive services on their preferred device that they use the most during their leisure time. For many people, the integration of online services into a TV set means being able to access online banking, e-health services, having web presence or socialising via social networks, which otherwise would be inaccessible due to a lack of computer skills or other accessibility barriers.

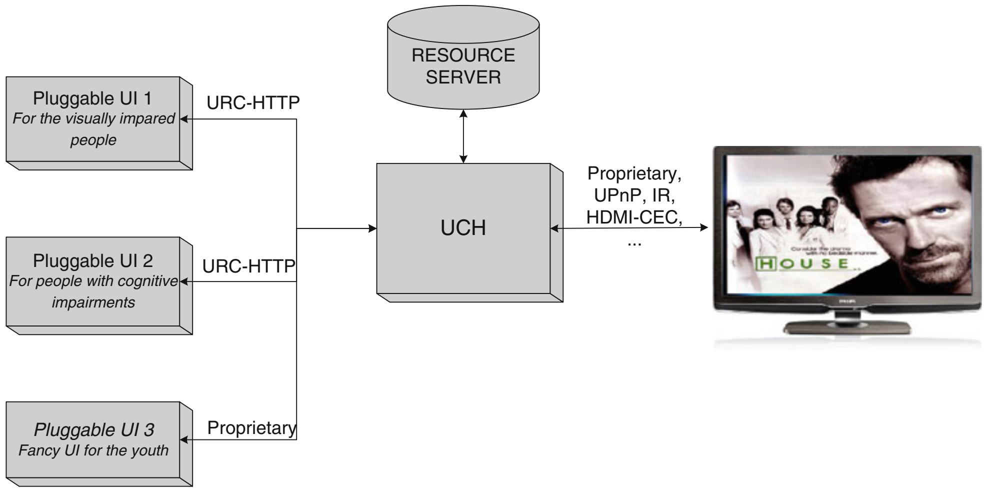


Fig. 7 Proposed solution for the TV set's accessible remote control

The requirements for implementing this solution are that the targeted services are capable of integration with the UCH, which means that they should have an access API or they should be based on web service technology, depending on the openness of the service providers.

In this case, the TV set is playing the role of a controller in the UCH, from an architectural point of view. The requirements for integrating a TV set as a controller in the UCH architecture, and to use it as a pluggable user interface, are that the TV set must implement a bidirectional communication technology and a programmable user interface system.

The services integration into the UCH architecture is achieved by means of defining the required XML files (UI Socket, Target Description, Target Resource Sheets) and implementing the corresponding code for the target adapter layer requirements (Target Discovery Module and Target Adapter) for each interactive service. The interactive services can be running locally or on the Internet. For more information refer to [31].

Through the implementation of a UCH's User Interface Protocol (UIPM), it becomes possible to implement any TV set's compatible communication protocol. Using the UIPM's, the different pluggable UIs can be plugged-in to different TV sets.

After achieving the integration of the services with the UCH and the required UIPM, UIs can be created for any service. This approach also allows the creation of aggregated UIs composed of different services.

At the same time, the UCH can be connected to different resource servers on the Internet that offer UIs and UCH integration modules that may be downloaded and used directly.

Figure 8 outlines the proposed approach to make interactive services accessible to all. This figure shows different target services integrated using their own protocols and accessed from a TV set. The resource server object reflects the option of using the UIs and integration modules downloaded directly from the Internet.

4 Implementation and validation

This section covers the implementations made to validate the proposed approach. As stated previously, a TV set can implement one of the two use cases of the approach, or both. Therefore, the developed implementations are presented and classified in the same sections as the proposed approach.

An interesting outcome of the implementations has been the developer's experience showing the easiness to access the technology, integrate new interactive services, integrate TV set configurations as targets and develop TV set UIs for different UI technologies.

The approach has been implemented in projects such as i2home [18] and Vital [32], following the User Centred Design (UCD) methodology [8], and it has proven to be a good approach to use together with the UCD cycles. The developed UIs have been validated with the targeted users, obtaining encouraging results.

4.1 Tv as target use case: accessible remote control of the TV implementations

4.1.1 Integration of TV sets with the UCH as targets

For the validation of the solution, two different TV sets have been integrated as UCH architecture targets. One of the integrated systems was a PC running Windows Vista Media Center (WMC), and the other one was a Dreambox 7020 set-top box.

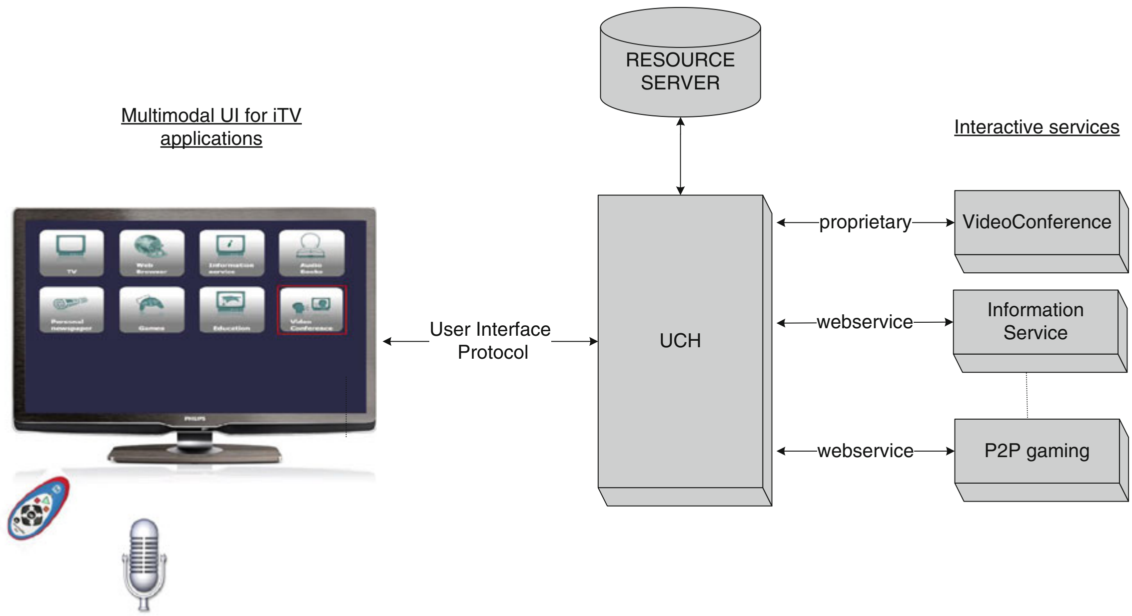


Fig. 8 Proposed solution for the universally accessing interactive services in our personalised TV set

The main reason for selecting these devices has been that they either offer a well-documented API (WMC) or are based on open source code (Dreambox), thus making them easier to integrate. Also, both solutions have IP connectivity, and they fulfil the remote controllability requirements for a target device to be integrated with the UCH architecture (see Sect. 3.2)

A single UI socket has been defined for both TVs, which is the interaction point between a pluggable user interface and a target device, exposing the functionality required to control volume and live TV (Channel selection, Pause-Resume TV). Then, the integration of the targets has been implemented, in the case of WMC including the time shifting functionality.

4.1.2 *Pluggable user interfaces for the TV sets' accessible remote control*

4.1.2.1 Multimodal UI on smartphone The first UI consists of a multimodal (gestures and speech) UI running on a Smartphone. This UI has been developed with young persons with mild cognitive impairments in mind. The typical difficulties faced by this user group are concentration problems and memory deficits.

The main ideas behind this UI have been a large touch screen, a modern mainstream controller (HTC 7500 Advantage PDA) to prevent this user group becoming stigmatised and, finally, a free choice of modalities, or possibly a combination thereof.

The UI is implemented as a client server-architecture based on the ODP platform. This is a platform for implementing multimodal user interfaces based on combinations of any modality. Examples of these modalities are speech, gesturing and mimicking. For more detail, see [27].

Figure 9 shows a depiction of the TV GUI. The bottom row contains artifacts visible in all views of the GUI. There is a back button to the left, a home button to the right and in the middle, current time and the battery status. The middle field activates the speech recogniser. The TV UI has been simplified, and most of the features of a normal TV remote

Fig. 9 Multimodal UI based on gesture and speech interaction running on a PDA controller: HTC 7500 Advantage. The GUI implements the requirements posed by a young person with cognitive impairments

have been removed. The only functionalities left are on/off (top left), volume (bottom), mute (bottom left) and a scrollable 2 × 2 matrix for TV channel overview and selection (central position). All functionalities are accessible via gestures, speech or a combination. Thus, it is possible to switch off the TV by pointing at the on/off button or saying "Switch off (the TV)". Similarly, the volume can be adjusted by gestures or the command "increase (the volume (of the TV))." Great care has been taken to make graphical elements large enough and the interaction simple and intuitive.

Evaluation has been carried out with 10 persons with mild cognitive impairments living in Sweden. The age of 9 test participants was between 22 and 40, and one participant was 50. Each participant was instructed to operate the TV. The tasks consisted of switching on/off the device, changing the volume and switching between different channels. The test result was valuated as good, since all participants successfully completed the test. The result of the evaluations shows a preference for gesture-based interaction since these users find it strange and unnatural to talk to a machine. Additionally, the suggested animation was too fast for the users. For more information, see [24].

4.1.2.2 Accessible DHTML for the visually impaired The second pluggable user interface was developed for people with visual impairments and blind people to remotely control the UCH integrated TV sets. It is based on a DHTML page, which is displayed on a vertically handled Tablet PC. The controller connects to the UCH using the URC-HTTP protocol over a wireless connection. The URC-HTTP protocol is implemented as a JavaScript library [30], and this library is used in the HTML to interact with the TV via the UCH.

The DHTML page is rendered in a web browser. Both Microsoft Internet Explorer and Mozilla Firefox are supported. The developed DHTML page has been correctly tagged. Therefore, it is compatible with screen readers such as Jaws [21].

Figure 10 illustrates the developed accessible DHTML page. This DHTML page was created in compliance with the WCAG 2.0 guidelines [33]. The web page is designed using large buttons and fonts, and the colours can be changed to match the user preferences. Colours and font sizes can be adapted easily to the users' needs by the use of style sheets. This DHTML page even allows for different colour schemes depending on the time of the day, which would be helpful for some of the visually impaired.

The tested tasks consisted of switching on/off the device, changing the volume and switching between different channels.

The tests were performed during two accessibility workshops in Horn Bad Meinberg, Germany. Forty-two

Fig. 10 Tablet PC rendering an accessible DHTML for the visually impaired

elderly persons with their personal care taker (mostly relatives of the disabled person) took part in the workshops.

Each test was carried out on a one-to-one basis by at least two accessibility experts who assisted the participants at any time. Feedback was monitored in individual and round-table discussions.

The majority of the participants were visually impaired. Only some of them were completely blind.

The workshops provided interesting discussions between the parties concerned. The tests led to meaningful and sustainable information that will have an important influence on the accessibility design of the user interfaces.

4.2 Tv as controller use case: accessible interactive services on TV implementations

4.2.1 URC-MCML-based applications on window media center

The first prototype was carried out to validate the TV as controller use case was based on the Windows Media Center (WMC). WMC uses a XML-based markup language called MCML for defining the appearance of the applications together with .NET code for the application logic. A .NET library implementation of URC-HTTP protocol has been used to develop URC-MCML applications. This development was not tested with real users.

Figure 11 shows a screenshot of the URC-MCML UI implementation for remotely controlling a Heating, Ventilating and Air Conditioning (HVAC) device that was already integrated as a target in the UCH architecture, and Fig. 12 shows a URC-MCML UI for receiving reminder notifications. The reminder system is also integrated as a target service to the UCH architecture and has Google calendar synchronisation capabilities.

Fig. 11 URC-MCML UI for remotely controlling a HVAC device

Fig. 12 URC-MCML UI for receiving reminder notifications

4.2.2 Avatar for people with cognitive impairments

A second validation of the TV as controller use case has been done by developing a TV UI system for people with cognitive impairments such as Alzheimer's disease.

Persons suffering from Alzheimer's disease, with a mild stage of progression, typically present cognitive and functional impairments affecting memory, concentration and learning. Furthermore, Alzheimer's usually affects those over 65.

The developed TV UI system is composed of an avatar together with the logic to provide interaction.

This prototype is deployed as a mixed use case TV set since the avatar's TV UI system is deployed together with the WMC target integration introduced previously.

The avatar TV UI system has been validated to provide the notifications of target device or services integrated to the UCH architecture (i.e., home appliances and a reminder system) with very good results. The user of this controller is usually watching the TV set functionality provided by the WMC target, and whenever a notification is generated, the avatar pop ups and establishes a dialogue with the person using the system.

The validation tests were performed at the Matia Foundation IZA Day Care Center, San Sebastian, Spain. An initial neuropsychological screening was carried out first on each candidate user, from which 21 members were selected for the tests. All suffered from Alzheimer's disease with a Global Deterioration Scale (GDS) measure ranging from 3 to 5 (from mild to moderate). The user validations were done on a one-to-one basis.

For the tests, two simple predefined dialogues were executed. These dialogues were triggered by the integrated reminder system. In dialogue 1, the avatar first informed the user that a Basque Handball match was about to start on another channel, asking whether the user wished to watch it or not. At this point, the user pressed a button labelled "Yes" or "No" on the remote control. In dialogue 2, the avatar asked the user to write their name on a piece of paper that was placed beside the chair where they were seated. After a while, the avatar requested confirmation from the user with a "Yes" or "No" type challenge. On each occasion, the test was personalised by introducing the name of the test subject into the system, so that the avatar initially greeted the user using their own name.

From a qualitative point of view, a remarkable result of the tests was how well the group engaged with the avatar. At no point did they exhibit fear, misunderstanding or inconvenience to seeing the avatar on the television, that it had interrupted the TV broadcast or, most importantly, that the avatar spoke to them directly.

From a quantitative perspective, during both dialogues, 100% of the users followed the instructions given by the avatar without difficulty. In dialogue 1, all users were able to respond with their choices. During dialogue 2, when asked by the avatar to write their names, all users fulfilled the task successfully. Finally, when the avatar said goodbye, a majority of the users responded by speaking directly to the avatar.

Figure 13 shows a person interacting with the avatar TV UI system.

More detail on these prototype developments and validations are described in [5].

4.2.3 Interactive services for improving the quality of life of the elderly

Last but not least, a validation of the TV as controller use case focused on elderly users was carried out. More specifically, the focus was on healthy elderly users, with no special impairment. A multimodal TV UI system that was

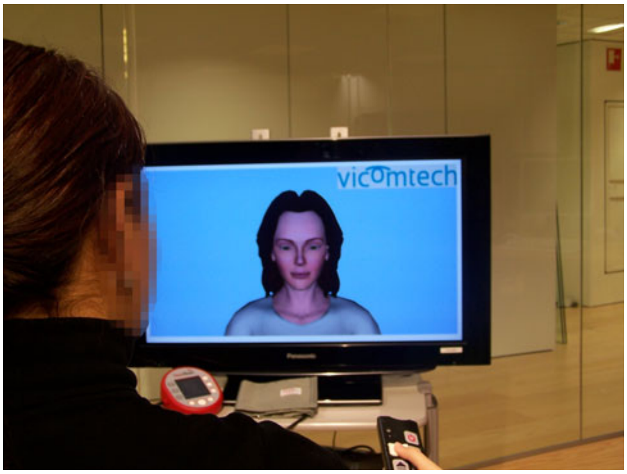


Fig. 13 User interacting with an avatar displayed on a TV set

interacted with a simplified remote control (weemote) or via speech was developed. Only the simplified remote control-based interaction has been validated with the real users.

The aim of this development was to significantly increase the quality of life of the average elderly user. In this sense, the interactive services integrated with UCH and provided through the multimodal TV UI system were videoconference as a social inclusion application, information service as a personalised information provider application, and audio book, P2P gaming (quizzes and chess) and education to enhance their leisure time and their cultural enjoyment.

The validation tests were carried out in parallel in San Sebastian, Spain and in the Durham County Councils, United Kingdom. The sample size was of 30 persons on each site.

To tests the developed TV UI system and the applications, two methods of assessment were used. First, two questionnaires were administered to (1) obtain sociodemographical data, experience with technology and (2) obtain information about TV usage. Second, a semi-structured interview with general questions about the developed system was conducted in order to manage correctly the focus groups. The objectives of the focus groups were to evaluate the usability and accessibility of developed system and to analyse whether the application is interesting for the participants.

The sample was quite heterogeneous concerning education profile and experience with technology.

The result of the tests showed that the users found the system easy to use through the simplified remote and the provided user interface. All the proposed applications were found interesting. Most of the issues found were related to bringing a prototype to a product.

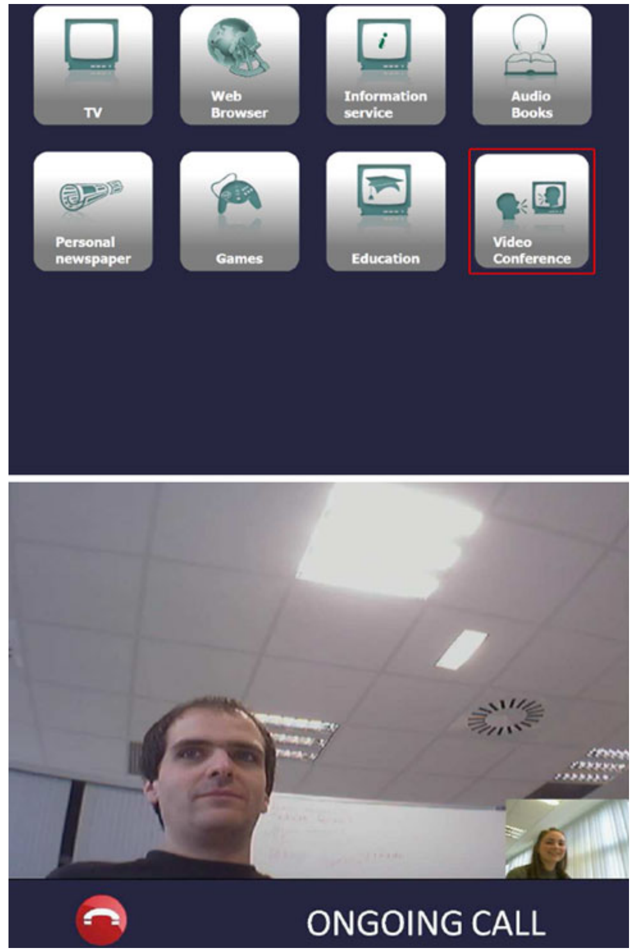


Fig. 14 TV UI system targeted to the elderly

Regarding the products adoption, they would consider it, depending on the cost and easiness to integrate with the devices they already have at home.

Figure 14 shows the main menu of the developed TV UI system, together with an example interface for the videoconference application.

5 Implementation recommendations for mass-market devices

Based on the experience gained in the previous implementations realised to validate the proposed approach, this section discusses how current mass-market devices can be adapted to follow this approach and related recommendations are provided. For new products, the recommendation is to follow the proposed approach from the beginning of their design.

As it has been shown through the implementation and validation developments, the TV set can range from a TV to a set-top box or a PC-based media centre solution.

Next, different options for implementing the UCH in the digital home are analysed, and the available technological options to implement each use case of the approach are analysed.

5.1 UCH implementation

In the digital home, the UCH architecture can be implemented for the accessible TV set scenarios presented in this paper, but it can also provide access to the different devices available in the household, as well as to interactive services (running locally or on the Internet), through the controller that best fits each person's needs.

Therefore, the following three possible hardware options are proposed for hosting the UCH in the digital home:

- Home server for AV purposes.
- Broadband Router.
- UCH in a TV set: If the aim of the implementation is only the accessible TV set scenario this is a feasible option, otherwise the TV must remain switched on. Technically this has already been done for the WMC-based developments and seems to be feasible for the TV, meaning not a PC or a set box implementation, since nowadays many TVs are built on the UCLinux operating system that could allow deployment of a UCH in a TV set.

5.2 TV as target use case

As specified in the proposed approach section a candidate TV set needs to be a remotely controllable target.

Today's TVs can be controlled using one of the following technologies: Infrared, Serial, HDMI-CEC, Firewire, DLNA Renderer profile and IP connectivity using proprietary protocols.

The most widespread communication technology is infrared, but this technology's implementation typically only allows a one-way communication, which allows to operate the TV, but restricts receiving feedback on TV status. With this known disadvantage, it is possible to integrate a TV with the UCH using IR signal, either using an IR transmitter in the machine the UCH runs on, or by using a master controller [16] that has different IR outputs that can be accessed over IP networks. There are IR signal databases of different devices available, so this limited implementation should be possible for most current TVs.

The remainder of the proposed communication technologies offer bidirectional flows, which would help in meeting the requirements for a UCH integrated target. At present, the problem is that none of these communication technologies are extensively implemented in commercial products, and some of them have their own private protocol implementations. This means that an implementation for each communication technology would need to be provided.

Therefore, the recommendation for currently available marketed devices is to either follow a limited IR technology approach, which once done for one TV would be easily extended to other models leveraging IR code databases, or to develop UCH target integrations for mainstream device technologies, as was the case in the performed WMC implementation, thus bringing the technology to a wider range of users.

5.3 TV as controller use case

In the case of the TV set's controller use case, a TV set requires a bidirectional communication technology and a programmable UI system.

As presented in the introduction, reacting to user interest in interactive services, manufacturers have started to include iTV applications in commercial products. This has taken place gradually from set-top boxes and PC-based media centre solutions, to the TVs themselves.

A good example of these developments is the commercial availability of TVs connected to the Internet and supporting widgets technology from Yahoo Connected TV [35] or Sony Applicast.

In the implementation and validation section, solutions have been presented that run on a PC (WMC MCML, Avatar TV UI system, TV UI system for the elderly), which gives a greater opportunity to include accessible technologies. Different modalities have been integrated, like speech and haptics together with virtual characters, to make the interface more natural and accessible to the targeted users.

In these implementations, bidirectional communication is achieved through inter-process communication, if it is implemented in the same machine where the UCH is running, or an IP-based connection, which is the preferred option.

The recommendation for implementing the TV set's controller use case, in order to have everything in one device, is to use a TV that implements the Yahoo Connected TV technology. It supports IP communication and a widget-based UI technology and can be connected to the UCH through the available URC-HTTP JavaScript library. The problem of all-in-one TV device solutions is that they are not usually open platforms, which allow the installation of third party UI system and hinder the integration of assistive products.

Therefore, in order to be able to provide universal access to its fullest extent, the TV set based on a PC or an open source-based set-top box would be the preferred recommendation. In this way it would be possible to use custom

TV UI systems, or use existing fully documented API in cooperation with assistive technologies and create more natural and accessible UIs with speech, gestures or virtual character multimodal interaction.

6 Conclusions

This paper has presented an innovative approach to provide universal access to TV sets. The proposed approach solves two accessibility issues at the same time, which are the accessibility to the TV set's remote control and the access to interactive services on the TV. The proposed implementation options can solve both accessibility issues at the same time or any one of them independently for the same TV set. Furthermore, once the chosen solution is implemented, it is seamless to the user.

The approach is based on the ISO/IEC 24752 Universal Remote Console (URC) standard and its implementation in the UCH architecture. Each accessibility issue's solution is detailed in the paper, identifying the requirements and the development necessary to integrate the solution with the UCH architecture.

The implementations developed to validate the approach have been presented and explained. These developments include the integration of two different TV sets as UCH target devices, together with two accessible pluggable user interfaces to validate the accessible remote control scenario. For the validation of the accessible interactive services on the TV scenario, local and remote interactive services have been integrated with the UCH, and different TV UI systems have been developed for the different target groups.

There is also a third use case for accessible television that should be mentioned. This is the provision of synchronised media in multiple modalities, i.e., captions for hearing impaired users, audio description for vision-impaired users and possibly simple language provision for users with cognitive impairment. Although not part of the current implementation, the URC technology does support this use case by inclusion of streaming variables in the user interface socket, as defined in ISO / IEC 24752. Based on this concept, the user can pick any combination of synchronised streams (video, audio and text) that is most suitable for them.

Additionally, based on the experience gained in the validations, it is believed that the UCH technology is sufficiently mature to be implemented in current mass-market devices and to be considered for integration from the earliest phases of new product development processes. In this sense, various recommendations have been put forward on where the UCH should be implemented and which TV sets to target for integration first.

Finally, the authors' opinion is that this approach will help in providing universal access to TV sets, by means of allowing TV set configurations that include advanced UIs, natural language UIs, assistive technologies and multimodal streaming. This architecture allows the deployment of these alternative user interfaces in a plug-and-play fashion. In this sense, customisable pluggable UIs can be developed by third parties to address the needs of different user groups. This situation opens the door to a new market for UIs. Business models for this new market are still a topic of research, but resource server-based marketplaces may be the best approach. Furthermore, these resource servers cannot only store UIs or their resources, but can also contain UCH integration modules, which help the automation of the installation and the updating of current mass-market devices to support the approach proposed for universal access.

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References

1. AENOR: Subtitling for deaf and hard-of-hearing people. subtitling by teletext. Spanish standard; UNE 153010 UNE 153010, AENOR, 2003
2. AENOR: Audio description for visually impaired people. Guidelines for audio description procedures and for the preparation of audio guides. Spanish standard; UNE 153020 UNE 153020, AENOR, 2005
3. Berglund, A., Berglund, E., Larsson, A., Bang, M.: Paper remote: an augmented television guide and remote control. Univ. Access Inf. Soc. **4**(4), 300–327 (2006)
4. Berglund, A., Johansson, P.: Using speech and dialogue for interactive TV navigation. Univ. Access Inf. Soc. **3**(3–4), 224–238 (2004)
5. Carrasco, E., Epelde, G., Moreno, A., Ortiz, A., Garcia, I., Buiza, C., Urdaneta, E., Etxaniz, A., González, M.F., Arruti, A.: Natural interaction between avatars and persons with alzheimer's disease. In: *ICCHP* '08: Proceedings of the 11th international conference on Computers Helping People with Special Needs, pp. 38–45, Springer, Berlin (2008)
6. Cesar, P., Chorianopoulos, K.: The evolution of TV systems, content, and users toward interactivity. In: *Foundations and Trends in Human–Computer Interaction*, **2**, 373–95 (2009)
7. Chorianopoulos, K., Spinellis, D.: User interface evaluation of interactive TV: a media studies perspective. Univers. Access Inf. Soc. **5**(2), 209–218 (2006)
8. Cooper, A.: *The Inmates Are Running the Asylum*. Sams, 1 edn (1999)
9. Epelde, G., Carrasco, E., Zimmermann, G., Bund, J., Dubielzig, M., Alexandersson, J.: URC based accessible TV. In *EuroITV '09: Proceedings of the seventh european conference on European interactive television conference*, pp. 111–114, ACM, New York, NY, USA (2009)
10. Eronen, L.: Five qualitative research methods to make iTV applications universally accessible. Univers. Access Inf. Soc. **5**(2), 219–238 (2006)

11. ETSI. Subtitling systems: Technical Report EN 300 743 (2006)
12. European Commission: Assessment of the status of eAccessibility in Europe. http://ec.europa.eu/information_society/activities/einclusion/library/studies/meac_study/index_en.htm (2007)
13. European Commission: CORDIS: ICT: Programme : Service and software architectures, infrastructures and engineering (SSAI). http://cordis.europa.eu/fp7/ict/ssai/home_en.html, Dec. 2009
14. Falck Vital: Falck igel—ukjent falck 5117 universal remote control. http://www.falckigel.com/shop/index.aspx?intshopcmd=&group=1450&prod=2669, Dec. 2009
15. Gill, J., Perera, S.: Accessible universal design of interactive digital television. In: *Proceedings of the 1st European Conference on Interactive Television: from Viewers to Actors?*, pp. 83–89, Brighton, UK (2003)
16. Global Cache: Global cache GC-100. http://www.globalcache.com/products/gc-index.html, Mar. 2010
17. HbbTV. http://www.hbbtv.org/, Mar. 2010
18. i2home. Intuitive interaction for everyone with home appliances based on industry standards. http://www.i2home.org/, Dec. 2009
19. Inteco. IDTVOS (INTECO digital television operating system). http://www.inteco.es/TV_Interactiva_en/Accesibilidad_en_TV_en/Decodificador_accesible_en/, Mar. 2010
20. International Organization for Standardization and International Electrotechnical Commission. Information technology—user interfaces—universal remote console (5 parts). International standard; ISO/IEC 24752 ISO/IEC 24752, ISO/IEC, 2008
21. Jaws. JAWS for windows screen reading software, Dec. 2009
22. Kim, S., Ok, J., Kang, H.J., Kim, M., Kim, M.: An interaction and product design of gesture based TV remote control. In *CHI '04: CHI '04 extended abstracts on Human factors in computing systems*, pp. 1548–1548, ACM, New York, NY, USA (2004)
23. Klein, D.J.A., Karger, S.A., Sinclair, K.A.: Digital television for all: A report on usability and accessible design. Technical report, The Generics Group (2003)
24. Neelrath, R., Schulz, C., Pfleger, N., Pfalzgraf, J.S.A., Stein, V., Alexandersson, J.: Homogeneous multimodal access to the digital home for people with cognitive disabilities. In *Proceedings of the second German Congress on Ambient Assisted Living*, Berlin, Germany (2009)
25. Ocean Blue Software. Talking tv. http://www.oceanbluesoftware.co.uk/index.shtml, Mar. 2010
26. Peng, C.: *Digital Television Applications*. Doctoral dissertation, Helsinki University of Technology (2002)
27. Schehl, J., Pfalzgraf, A., Pfleger, N., Steigner, J.: The babbleTunes system: talk to your ipod! In *IMCI '08: Proceedings of the 10th international conference on Multimodal interfaces*, pp. 77–80, ACM, New York, NY, USA (2008)
28. Schiphorst, T., Nack, F., KauwATjoe, M., de Bakker, S., Stock, Aroyo, L., Rosillio, A.P., Schut, H., Jaffe, N.: PillowTalk: can we afford intimacy? In: *TEI '07: Proceedings of the 1st international conference on Tangible and embedded interaction*, pp. 23–30, ACM, New York, NY, USA (2007)
29. URC Consortium. URC-HTTP protocol 2.0. Technical report, Dec. 2009
30. URC Consortium. Webclient JavaScript library, Dec. 2009
31. URC Consortium. URC technical primer 1.0 (DRAFT). Technical report, 2010
32. Vital. Vital assistance for the elderly. http://www.ist-vital.org/, Dec. 2009
33. W3C. Web content accessibility guidelines (WCAG) 2.0. Technical Report WCAG 2.0, W3C, Dec. 2008
34. Weemote. weemote sr. TV remote for adults. http://www.weemote.com/weesrlm.html, Dec. 2009
35. Yahoo! Inc. Yahoo! connected TV: movies, TV shows, internet on demand. http://connectedtv.yahoo.com/, Mar. 2010
36. Zillmann D., Vorderer P. (eds.): Media Entertainment: The Psychology of Its Appeal (Lea's communication series). Lawrence Erlbaum, UK
37. Zimmermann, G., Vanderheiden, G.: The universal control hub: An open platform for remote user interfaces in the digital home. In: Jacko, J.A., (eds.), *Human-Computer Interaction*, vol. 4551 of *LNCS*, pp. 1040–1049, Springer, Berlin (2007)

Providing universally accessible interactive services through TV sets: implementation and validation with elderly users

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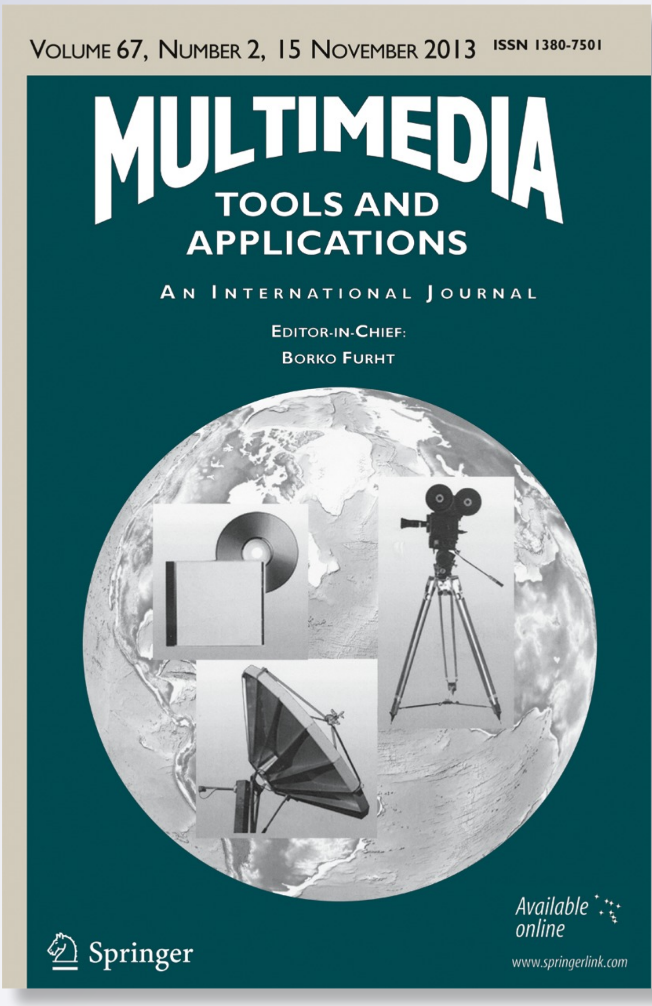

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Providing universally accessible interactive services through TV sets: implementation and validation with elderly users

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Abstract One of the challenges that Ambient Intelligence (AmI) faces is the provision of a usable interaction concept to its users, especially for those with a weak technical background. In this paper, we describe a new approach to integrate interactive services provided by an AmI environment with the television set, which is one of the most widely used interaction client in the home environment. The approach supports the integration of different TV set configurations, guaranteeing the possibility to develop universally accessible solutions. An implementation of

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this approach has been carried out as a multimodal/multi-purpose natural human computer interface for elderly people, by creating adapted graphical user interfaces and navigation menus together with multimodal interaction (simplified TV remote control and voice interaction). In addition, this user interface can also be suited to other user groups. We have tested a prototype that adapts the videoconference and the information service with a group of 83 users. The results from the user tests show that the group found the prototype to be both satisfactory and efficient to use.

Keywords Inclusive TV · Universal remote console · Multimodal interaction · Interactive TV · Interactive services · Universal access · Elderly users

1 Introduction

As part of the Ambient Intelligence vision, the environment has to seamlessly support the users in carrying out routine activities. The activities can range from home automation tasks to keeping up with friends in social networks. These tasks can be understood as services provided by an entity, integrated in the home environment itself and interacted through a certain kind of User Interface (UI). For the purpose of the research presented here, they will be generalised as interactive services.

Watching TV is one of the activities that take up most of people's leisure time [54], regardless of their technical skills and knowledge. Consequently, the TV has become a broadly extended electronic appliance, with a relevant place at home, and its remote control has become a common interaction device for most people. The TV is evolving and converging with computers rapidly. In fact, a TV set is a computer, with a particular interaction paradigm and a particular content consumption setting.

Therefore, the use of the TV as the most suitable controller UI to provide services adapted to each user in an AmI environment is very sensible. In this context, providing interactive services adapted to the user on the familiar device that is most frequently used by them in their spare time provides an interesting topic of research.

For many users, the integration of these services into a TV set provides the means for being able to access online banking, e-health services, socialising via available social networks or making use of the services provided by their environment that otherwise would be inaccessible due to a lack of computer skills. The current trends of moving physically provided services into the cloud to save money in personal costs and to improve benefit margins, sharpens the need of providing interactive services in an accessible way to all. Otherwise, these user groups could be at risk of exclusion from the digital society.

Up to now, the majority of research carried out on inclusive TV has attempted to provide techniques for the interactive television (iTV) service's lifecycle development (requirements gathering, design, implementation and evaluation), or to make the remote control of the TV accessible to groups of users with specific disabilities. Regarding the accessible interactive services on TV challenge, there are specific implementations coming from generic iTV research area, which are mostly electronic program guide (EPG) related. One of the results of providing specific solutions to specific user group's problems, instead of using an intermediary open user interface platform, is that developed service adaptations are not reusable.

It is interesting that the greatest efforts to develop natural interfaces for the TV set come from the interactive television area. In recent years, the iTV research community has progressed through the integration of interactive services within the TV. There is also an industrial commitment, to include such interactive functionalities in commercial products that have already been brought to market. However, most research and industrial developments have been targeted to the mainstream user, generally ignoring the accessibility barriers experienced by people with disabilities and elderly people. An approach to easily integrate interactive services with the TV, based on inclusive design, and one that would give universal access to the different user groups is still missing.

In this sense, the main contribution of this paper is a new approach to integrate all kind of interactive services (locally or remotely provided) with the TV set in a way that would allow personalising the UI to the needs of each user group.

After this brief introduction, in Section 2 we have surveyed the current body of work related to the problem presented in the introduction. The next section introduces our approach to solve this problem. Following this in section 4 the details of the approach's implementation done for the elderly users are given. Section 5 explains the evaluation method followed in the user tests and in section 6, we present the observed results. In section 7 we summarise the paper and draw our conclusions. Finally, Section 8 depicts the future working lines that will tackle the existing improvable points and opportunities of the approach.

2 TV accessibility and related work

European Commission's "Assessment of the Status of eAccessibility in Europe" report, analysing both the accessibility of broadcast programs and end-user TV equipments, shows that TV accessibility is still far away from being implemented to its fullest extent. This report also highlights the accessibility opportunities and challenges that the introduction of digital TV brings. The main challenge of not excluding people from accessing any digital TV's services has been underlined by the iTV research community at [21].

Given the political pressure to confront the poor design of accessibility and usability of interactive TV services and client devices, research to enhance the universal access has increasingly improved the state of art of this technology.

From our point of view there are two main working areas directly related to making the TV interaction experience accessible, which are: content accessibility and access to the digital TV. The state of art of these working areas is presented in the following sections.

2.1 Content accessibility

This working area covers the initiatives that seek to provide alternative content means, which are synchronised with the original content, so that people with different disabilities can consume audio-visual content in an accessible way. This audio-visual content corresponds to the broadcasted TV content and to the iTV applications' media content.

The accessibility services defined for providing accessible broadcast content are: audio-description for the visually impaired, subtitles for the hearing impaired and sign language interpretation for the hearing impaired. To ensure the availability of these services, it is necessary that all stakeholders comply with the legislation and the standards of production, distribution and display of such content.

The main efforts in this area have been made in the standardisation through regulatory agencies of the creation of the alternative content. AENOR provides a standard reference on the creation of audio-description [48] and another standard reference on the creation of teletext subtitles [47]. With the transition from analogue to digital television, ETSI has published a standard [17] on how the subtitles should be managed in the Digital Video Broadcasting (DVB) technology.

It is remarkable, the ability of the DVB technology to transmit content composed of different streams of audio, video and data, which enables the distribution of the audio-description, the sign language signing or the subtitles as additional channels. Thus, the user can select the combination of content streams to be rendered on their client device.

In the content accessibility research area, different approaches have tried to present solutions to adapt the content to the different user groups by making use of the multimedia framework provided by the MPEG-21 standard. Yang et al. [52] proposes an adaptation system based on the MPEG-21 standard, focused on visual disabilities (people with colour blindness). Opposed to specific efforts like this, Vlachogiannis et al. [50] propose a content adaptation framework, also based on the MPEG-21 standard, that is not limited to one specific disability and that can adapt pre-authored content to the specifics of each user.

As introduced in the previous section, the amount of accessible TV content produced is still well below 100% in traditional TV broadcasting. Due to the legislation change in many countries obligating to broadcast a higher level of accessible content, several initiatives like creating signed language through virtual characters, automatic captioning or translation of subtitles have been launched to fully or partially automate the production of accessible content.

There is also a major challenge to ensure content accessibility in the current paradigm shift of TV content consumption, since the user is moving from being a mere consumer to produce content in an environment, where production, distribution and render are no longer in the hands of few parties and fixed set of technologies, as has been so far.

2.2 Access to the digital TV

Access to the digital TV is comprised by the purchase, installation, setup and use stages. In this sense, a report on usability and accessible design of the TV [26] analysed the following usage stages:

- Choosing and purchasing the Set-top box (STB).
- Installing the STB.
- Tuning the STB.
- Setting the TV so that the DTV channel is convenient to access.
- Finding out what is on and selecting the desired channel, either by using the interactive on-screen guide, or by random surfing.
- Using subtitles, accessing additional settings, navigating the menu structure.
- Accessing interactive content (e.g. Teletext, BBCi).

The focus of this paper is on the accessibility of the user's interaction with the TV, so the information related to the product's acquisition and installation will be left out. Therefore, the remainder of this section is divided into the accessible remote control of the TV and the accessible interactive services on TV.

The emphasis of the related work is concentrated in the accessible interactive services subsection, since it is our contribution's specific research area.

2.2.1 Accessible remote control

The accessible remote control topic covers the efforts of providing a means of remotely controlling basic TV functionalities such as channel up/down, volume up/down or turning the TV on/off, to all user groups.

The difficulties associated with the use of conventional handsets (unclear labels, insufficient tactile feedback, poor position and size of buttons) by the different user groups are well known. Usability advances for different user groups have led to changes in the appearance of the TV remote controls. As introduced by Rice et al. [38], the usability improvement process has to be done taking care of the difficulties of simplifying the remote control, and getting it right, since as Carmichael notes in [10], fewer buttons may reduce demands on memory, but it can increase the workload when attempting to match more functions to fewer buttons.

The research community has also driven efforts to develop new remote control paradigms. These efforts are listed and classified by Cesar et al. [13]. Some of the work that could help making the TV remote control more accessible is the use of objects such as pillows, gesture recognisers, speech interaction and dialogue systems [6], and the use of devices such as mobile phones and PDAs. A notable work [40], proposes to use a PDA with 3D visualisation based interaction paradigm, which enables the direct manipulation of physical environments, such as those composed by TV sets, where the user can control these devices or even drag and drop a presentation from a PDA to a TV set. Furthermore, thanks to its UPnP network based architectural approach [41], it facilitates the user with a direct access to the physical environment that the user may want to control without having to know about IDs or IP numbers of specific devices. Another interesting alternative introduced by Kim et al. at [25] is the interaction through a gesture based TV remote control. Nowadays, is becoming common to find commercially available high end remotes with gyroscopes or microphones, and game console controllers like the Nintendo Wiimote or Microsoft Kinect that makes us think that these new paradigms of remote control could simplify some user's life in the future. Researchers are already investigating the use of these types of controllers in pointer based [49] or gesture based interactions with the TV set. Figure 1 shows possible alternatives that could help ensuring the accessibility of the remote control of the TV.

The TV experience is usually shared among different users, traditionally limited to watching broadcasted programmes. With the digitalisation of the TV technology and the introduction of iTV applications, a new challenge has appeared to enable the multi-user interaction of iTV services. Different studies [49, 51], have analysed the multi-user interaction of TV sets, and have provided advanced solutions to allow the interaction with more than one remote control at the same time.

Fig. 1 Possible alternatives that could help improving TV sets' remote control accessibility

The presented initiatives either target specific use-case scenarios and specific developments for specific TV models, so the developments cannot be easily integrated in future implementations or do not provide user interface adaptation features regarding accessibility in their approaches. In this sense, Epelde et al. [18] proposed an approach to make TV sets' remote control accessible from design and to provide the ability to plug-in different UIs developed for different controller technologies, such as those previously described.

2.2.2 Accessible interactive services on TV

In recent years, several research projects have focused on the integration of interactive services into TVs. This type of services can be categorised according to their level of interactivity [34]:

- Broadcast-only services: Electronic program guides (EPG), Local games, Video on Demand, Personal Video Recording …
- One-way interactive services: Advertisement direct response, opinion polling, voting …
- Two-way interactive services: TV banking, interactive TV content, email, social networking …

Apart from research projects, reacting to user interest in interactive services, manufacturers began including iTV applications in commercial products. This grew gradually from Set-top boxes and PC based Media Center solutions, to the TV's themselves. The level of interactivity of the implemented services has followed a similar path, with successively more complex services being introduced.

With the advances in computation power, user interface technology has evolved from a simple on-screen display (OSD) to modern widget technology to improve the usability and user acceptance. A good example of these developments is the commercial availability of TVs supporting advanced user interface technology like Yahoo Connected TV, Google TV, Philips Net TV or Sony Applicast.

This growing interest in providing interactive services through the TV can also be found in recent approval standards such as HbbTV [46], in which regular broadcasts are complemented by interactive services available on-line, with the aim of providing those services seamlessly on a TV set.

Once introduced a generic view of the interactive services on TV's evolution, the study will focus on research related to the usability and the accessibility of the interactive services on TV. In this sense, the initiatives are analysed from a product's lifecycle point of view. Firstly, research on specific user groups' requirement gathering is introduced, secondly, accessible iTV application design methodologies are analysed, next the implementations efforts to make iTV applications accessible are studied and finally iTV evaluation techniques that assess accessibility are discussed.

With regard to user requirement gathering methodologies and studies, Rice et al. presented an approach centred on elderly users [38], where possible iTV applications are presented at theatrical sessions which allow audiences to empathise with the characters, and questioning their actions, they can think about the role of this technology. Once their needs, feelings and requirements about the applications are gathered, the author proposes to follow up with paper prototyping and brainstorming sessions to understand how older people perceived using the targeted applications.

A related study [19], introduces various qualitative research methods applied to the field of design and evaluation of iTV applications, suggesting that the application of these methods to the adaptation of applications to specific user groups, can help understanding their accessibility problems, while developing universally accessible interactive TV applications.

Following ethnographic methods, Obrist et al. [33] and Bernhaupt et al. [7] present studies, which investigate media consumption with TV as the focal point.

Continuing with design and development methodologies, Springett et al. [43], present a methodology to develop accessible iTV applications. This methodology divides the application's tasks into simpler tasks and the capacities needed to fulfill each task. To define the needed capacities, the authors evaluate each task with users, checking if they have any problem to carry out the defined task and they annotate the capacities needed to fulfill the task. In a following phase, they evaluate prototypes with users and they inspire creative thinking and gather suggestions by using checklists that challenge the participant to think about questions and ideas that they may not have considered.

A notable guide [10] offers detailed information on the appropriate design of digital services deployed on TV for the older people in relation to their sensory and cognitive abilities and the demands the system may place on them. For example, the importance of clear visual/spatial navigational support, such as suitable highlighting and lowlighting, is referenced as being important to relieve working memory load, minimise errors, and help guide attention through operations on screen.

Regarding the implementation of accessibility solutions for specific services, most of the work to date has been related to EPG applications. Some have extended the implemented text to speech capabilities for the basic TV interaction activities to EPG applications. There is an initiative that integrates a paper based remote for interacting with the EPG application [5]. Carmichael et al. [11] developed a virtual assistant, providing a new mean of interaction between the viewers and the content and functions of the EPG.

With the explosion on the use of Internet based services, the development of TV based interactive services like the social networks, telemedicine or telerehabilitation has grown substantially, mostly focused on the mainstream users, but work is still missing on the provision of these services to less favourable user groups in an accessible way on their TV sets.

Concerning the available iTV platform implementations, the commercially available platforms like Yahoo Connected TV or Google TV are based in closed middleware implementations that cannot be easily extended to enable the interaction through more accessible or more advanced user interface technologies.

With regard to the work in the implementation of the adaptation of the graphical user interfaces to fit elderly users' needs, Rice and Alm proposed and evaluated four prototype layouts (carousel interface, flipper interface, transparency interface, standard iTV interface) and navigational strategies of communications systems [38]. The authors underline the need of developing user interfaces, which follow a continuity concept, meaning that the users can relate them to concepts of their real life.

In the context of the iTV applications evaluation, a research work [14] has proposed an affective UI evaluation methodology that takes into account usability and accessibility requirements as well as the specific characteristics of the TV consumption context, which is a step forward on providing accessible iTV UIs, making sure that the resulting UI competes with the established TV experience.

Rice [37] presented the difficulties that visually disabled users face while consuming iTV services. This work makes emphasis in parameters like screen size, font size and colour, icons' identification and screen layout. The main conclusion derived from the study is that the best way to approach the problem situation is personalisation, due to diverging requirements. A related study by Springett et al. [42], examines the applicability of the W3C web accessibility guidelines to interactive television focused in the visually impaired. Regarding the elderly users, up to now, few studies have evaluated the design of iTV applications for older people, beyond the usability evaluation of existing services [32].

From the literature review, we conclude that techniques exist from the iTV service's lifecycle development point of view (requirements gathering, design, implementation and evaluation). Additionally, there are specific implementations coming from the generic iTV research area, mostly EPG related, that provide accessibility solutions. Also, the availability of commercial iTV platforms targeted at mainstream users, shows the path of near future iTV services' usage scenario.

But in our opinion, it is necessary to define an approach that would allow the integration of services with different TV sets to meet different user needs. In order to guarantee the openness and the adaptability of the evolved scenario, an abstract user interface based approach is needed. The provision of an approach like this can foster the development of accessible TV interactive services' solutions, ensure the reusability of different modules and provide means of fast prototyping of new services or new TV set configurations (with new interactions technologies), to fill the existing gap of studies and solutions on TV accessible interactive services research area. Figure 2 presents the evolution from the actual scenario to an abstract user interface based evolved scenario.

3 Universally accessible interactive services on TV

3.1 User interface personalisation technologies

The three main concepts regarding the user interface personalisation are the possibility to choose the interaction device, the interaction technology (multimodality option) and the personalisation of the user interface presentation.

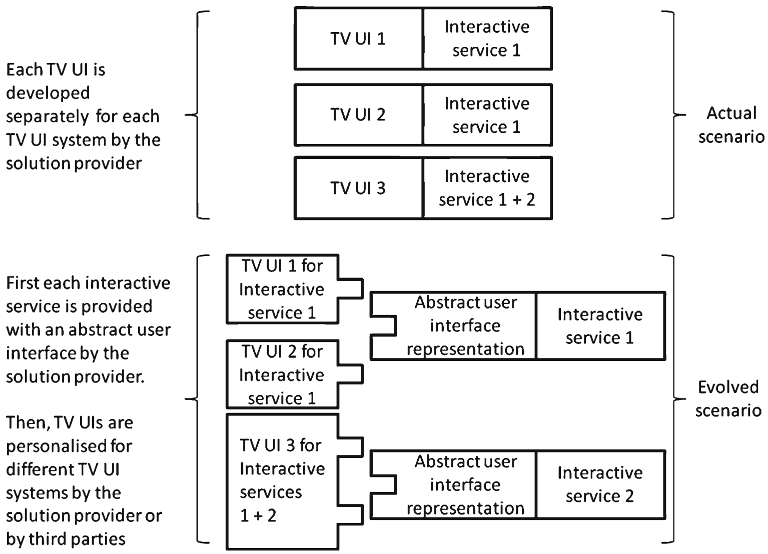

Fig. 2 Actual iTV applications development in contrast to an evolved scenario which allows the integration of services with different TV sets to meet different user needs

Traditionally, the user interface personalisation has been achieved by developing a different application per each different configuration need. In the Web world, style sheets technology based solutions (Cascading Style Sheets–CSS [8] or Extensible Stylesheet Language Formatting Objects–XSL-FO [4]) have been developed, which allow modifying the presentation of the user interface for different users and different interaction devices.

The main benefits of the style sheet technologies come from the separation of the structure and the content of the presentation's document. This technology allows more precise control (outside the tagging) over the spacing between characters, text alignment, the position of objects in a web page, the audio and voice output, text type characteristics, etc.

Moreover, the abstract user interface technologies like User Interface Markup Language (UIML) [1], Extensible Interface Markup Language (XIML) [36], XForms [9] and Universal Remote Console (URC) [24], allow changing the complete user interface to meet each person's needs and preferences. These technologies permit to fulfill the main three concepts related to user interface personalisation introduced earlier in this section (possibility to choose the interaction device, the multimodality options and the personalisation of the user interface presentation). Furthermore, it provides these properties, without needing to develop a different application per each different configuration need, without having to limit the applications to be only of web type and being able to implement multimodal interfaces.

A reference study [45], analyses four abstract user interface technologies (UIML, XIML, XForms, URC) for a scenario where the abstract user interface technologies enable any user to access and control any compatible device or service in the environment, using any personal controller device. For the proposed scenario and for the abstract user interface representations being evaluated, the study defines the following properties as desirable: the applicability to any target and any context of use; personalisation; flexibility, extensibility and simplicity. These properties are specified as the following specific technical requirements that a language for abstract user interface representation must meet:

- Separation of data from presentation.
- Explicit machine interpretable representation of the target's user interface elements, commands, dependencies, relations and semantics.
- Flexibility in the inclusion of alternate resources and compatibility with concrete user interfaces.
- Support for different interaction styles.
- Support for remote control.

UIML and XIML are not well suited for the proposed scenario particularly with respect to separation of data from presentation and flexibility in resource substitution. XForms is a W3C recommendation with narrower scope but powerful representation capabilities. It focuses on gathering input provided by the user. Some information display facilities are also included in XForms, but in general these are provided by a surrounding XHTML context or other host markup language in which the form is embedded (e.g. SVG, VoiceXML). In this sense, it requires the presence of a suitable host language and framework to fulfill the requirements of supporting different interaction styles and providing flexibility in the inclusion of alternate resources. URC has broad scope and includes a framework for the delivery of context-of-use specific and abstract user interface resources in addition to the abstract language.

The Guide project [22] is based on the PERSONA UI framework [44]. The Persona UI framework uses Xforms technology for the dialogs that an iTV service is going to present to the user, together with content-specific adaptation parameters. These adaptation parameters are later on enriched by a so called Dialog Manager, which adds information related to user and context profile. Finally, the system chooses the input/output interaction handler (I/O handler) that fits each user profile best. Based on the modality and layout neutral representation given by the Xforms representation and the adaptation parameters, the selected I/O handler realises the transformation needed to adapt the content to each user. The Guide project adds two innovative concepts to the Persona UI framework, which are the user simulation at design time and the UI adaptation during runtime through continuous evaluation of the context.

In contrast to the transformation approach followed in the Persona UI framework, the URC framework proposes a plug-in approach. This plug-in approach relies on a standardised interface definition, which allows the creation of pluggable user interfaces, also by third parties. Compared to the transformation approach, the development of a pluggable user interface is much simpler than an I/O handler. In the first case, the concrete user interfaces development is targeted at UI designers and developers, while in the second case an expert in the Persona UI framework is needed. Additionally, the resource server concept included in the URC framework enables the deployment and the update of UIs through repositories on the Internet.

Regarding the user simulation at design time and the UI adaptation during runtime, both are clearly applicable to the URC framework, and would help enrich the generic user interfaces generated by the URC framework, but always taking in mind that UIs developed specifically for specific users and involving real user's in the development process will have as a result UIs that fit better those users' needs.

Our proposed approach targets a similar scenario to the one studied at [45], where different TV set interaction paradigms enable any user to access different services, either local or remote to different users. So in this sense, we have decided to use the URC abstract user interface representation for our solution's technological base. To aid the reader in understanding our proposed approach, the URC framework is introduced in the following section.

Next, Table 1 compares the eligible iTV frameworks found in the state of art, regarding the desirable characteristics for providing universally accessible interactive services through TV sets.

3.1.1 The URC framework

The Universal Remote Console (URC) framework [24] was published in 2008 as an international standard composed of 5 parts (ISO/IEC 24752). The standard's main concept is defined as a "user interface socket" (or "socket" for short), which is an interaction point between a pluggable user interface and the device or service which is aimed to be remotely

Table 1 Comparison of available iTV frameworks regarding desirable characteristic for the provision of universally accessible interactive services through TV sets

	Yahoo connected TV, Google TV	Guide-persona approach	Our approach (URC based)
Allow different multimodal TV set configurations (adapted interaction)	No. Only works with commercially available compatible clients.	Yes	Yes
Integration of environment or internet provided services	Only Internet based ones.	Yes	Yes
Third party developed specific UI pluggability	No. Only complete applications can be downloaded.	No	Yes
Deployment–update of UIs through repositories on the internet	No	No	Yes

controlled. In the context of the URC framework, user interfaces are either generic or specific. The generic user interfaces are based on the automatic generation of user interfaces directly from the description of the socket. Moreover, the specific user interfaces are developed based on the knowledge acquired from the detailed description of the socket.

The URC technology is a platform for open user interface allowing third parties to create pluggable user interfaces and to use them with any device or service that exposes its functionality through a socket. The framework includes "resource server" as global markets for all types of user interfaces and resources needed to interact with applications and services that are made available to the user community.

In addition, the Universal Control Hub (UCH) is an implementation of the Universal Remote Console (URC) as a gateway, initially developed in the framework of the digital home [55]. The UCH architecture is shown in Fig. 3.

The main features of the UCH are:

- It acts as a gateway between the target devices and services and the client controllers, each with its own form of communication and control protocol. Without a gateway, the different parts would not be able to talk to each other.
- The user interface socket is based on standards: The UCH is based on the URC framework previously described.
- It provides the option to use different user interface protocols: The UCH enables different user interface protocols' (HTTP through DHTML, Flash, etc.) implementations and use by the client controllers.
- Globally available resource servers: The UCH can get resources, such as, target adapters, target discovery modules and user interfaces in a distributed manner.

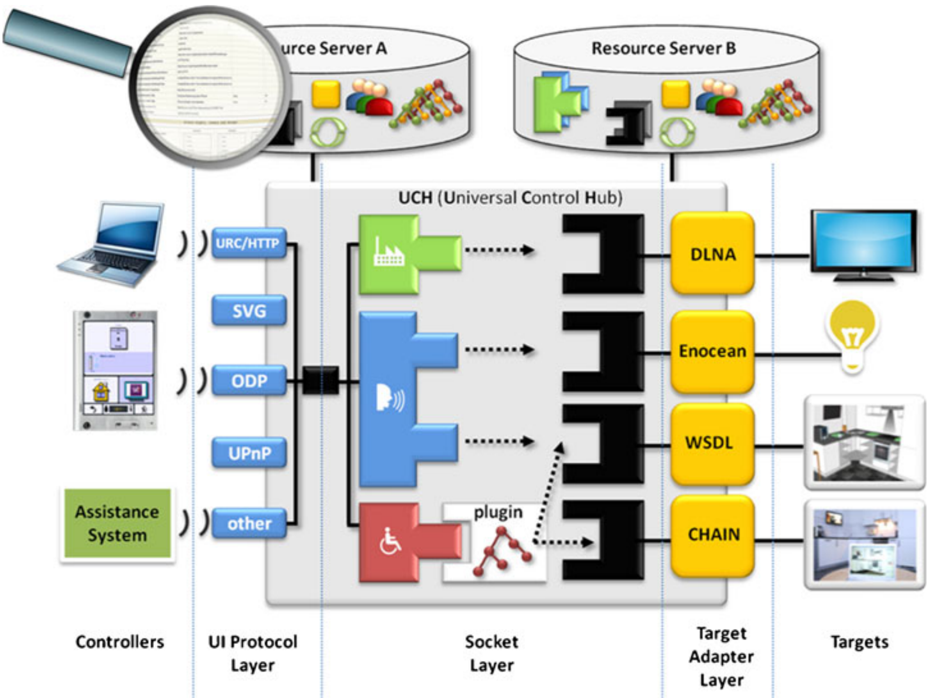

Fig. 3 The Universal Control Hub Architecture

In the UCH architecture, a User Interface Protocol Module (UIPM) is the responsible for presenting one or more sockets' functionalities to the user through a user interface that is rendered in a controller. Controllers and their software aware of this architecture, may want to access directly the socket of the target device or service and its atomic resources, to create an appropriate user interface based on the socket elements and their values.

Finally, the URC-HTTP protocol, which is a user interface protocol, provides remote controllers with direct access to the sockets that are running in the UCH. This protocol defines the messaging over HTTP and the functions for a controller to access the sockets of a UCH. The implementation of this protocol in the UCH is optional, but once implemented, provides a standardised and powerful way for controllers to access the UCH.

3.2 Our approach

In this paper we present an approach that proposes the use of the URC framework in the form of a gateway-oriented architecture, UCH, to provide accessible interactive services to any TV set.

We adopted the URC Framework because it makes a clear separation between the service we want to access and the UI we want to use for accessing it. This way, we are able to provide accessible interactive services on any TV set. The TV sets that are used in this approach have to fulfill the following requirements: they must implement a communication technology and a programmable user interface system. These TV sets can implement varying levels of accessibility features, depending on the user's requirements, and they may have different form factors, ranging from a TV, to a Set-top box, or a PC based media center solution.

Regarding the services to be integrated, they can have different levels of openness: they may have proprietary access protocols, defined access APIs or web service specifications.

The services' integration into the UCH architecture is achieved by means of defining the required XML files (UI Socket, Target Description, Target Resource Sheets) and implementing the corresponding code for the target adapter layer requirements (Target Discovery Module and Target Adapter) for each interactive service.

Through the implementation of a UCH's User Interface Protocol Manager (UIPM) we can implement any TV set's compatible communication protocol. Using the UIPMs we have the ability to plug-in the different pluggable UIs to TV sets.

After achieving the integration of the services with the UCH and the required UIPM, we are able to create UIs for any service. The approach also allows the creation of aggregated UIs composed of different services. At the same time, the UCH can be connected to different resource servers on the Internet that offer UIs and UCH integration modules that may be downloaded and used directly.

The Fig. 4 outlines our approach to provide accessible interactive services in TV sets. This figure shows different target services integrated using their own protocols and that are accessed from different TV sets. The resource server object reflects the option of using the UIs and integration modules downloaded directly from the Internet.

The UCH implementation can be embedded into a consumer broadband router, into the TV itself, or with a more powerful UCH that has extended functionality, such as a dedicated PC.

Finally, as this approach is an open and standardised approach, it's remarkable that in addition to the presented Internet based or locally provided interactive services, it can also be used to interact with devices in different environments. In this sense, the i2home project [27] provided the URC ecosystem with adaptation modules for several devices in the home environment. Shortly, we can say that our approach, being based on a standard, guarantees the validity of the approach in time.

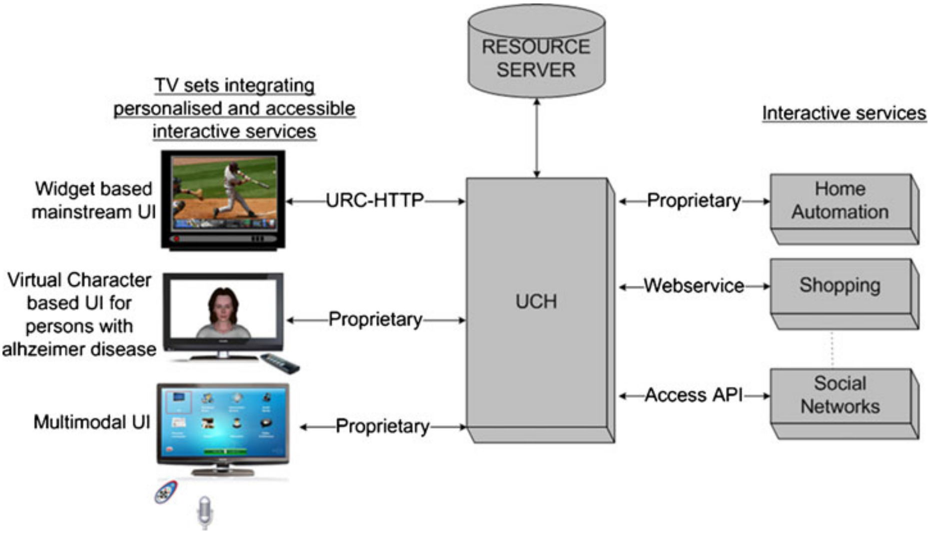

Fig. 4 Provision of universally accessible interactive services in TV sets

4 Implementation

We focused our approach's implementation on elderly users who are 60 years or older, with normal cognitive aging, and have an active life. With this idea in mind, we integrated those services that best fit the improvement to their quality of life, integrating them with mainstream society, and introducing them to new technologies through familiar interfaces.

The current elderly generations as well as less technical inclined people, adopt easier and with lesser rejection the traditional interaction mean of TV. On the contrary, the new services deployed on the traditional TV do not correspond with the elderly users' mental model (coming from the classic TV), which makes them get lost. It is necessary to develop advanced multimodal user interfaces [31], but that use classical interaction resources so that the different user groups, and specially the elderly user is able to understand how to operate the provided applications.

The following services have been integrated to the UCH: videoconference as a social inclusion application, information service as a personalised information provider application, and audio book, educational content and p2p gaming (quizzes, chess) to enhance their leisure time and their cultural enjoyment.

Concerning the specific needs of the seniors related to iTV platform's user interface, the requirements and the guidelines defined for the development and the extension of the implemented platform are introduced in a condensed version in subsection 4.1.

With regard to the targeted TV set's UI, a multimodal interaction has been developed together with a simple and easy to navigate graphical user interface. The multimodal interaction includes both a simplified remote control and speech interaction modalities. The dialog system technology used in the implementation is explained in subsection 4.2.

The TV set's UI system is composed of a main menu with access to the different applications and the interfaces of the corresponding applications.

For the discussion of the evaluation and its results we will concentrate in the videoconference and the information service. In this way, these applications are explained in more detail in the subsections 4.3 and 4.4.

From the implementer's perspective what is remarkable is the easiness to integrate already existing modules like the dialog system or the introduced services, and the simplicity to develop user interface instances of the selected TV UI solution, for new services or devices from different environments.

4.1 Elderly user needs and followed design guidelines

4.1.1 Visual domain needs

Among the elderly, the impairment of visual functions is a process of normal ageing. Ageing process implies a decrease of visual functions [16], including a reduction of visual acuity, sensibility to contrast (when trying to determine brightness differences) and loss of the ability to detect fine details.

4.1.2 Adopted visual domain design guidelines

As it has been presented, changes in vision that occur with age can make it more difficult to read computer or TV screens. Considering the previously described features of elderly people in visual domain, the following recommendations are adopted for the design of user interfaces in the targeted platform:

Use of icons/graphics:

- Concepts in application screens must be presented using an adequate combination of text, graphics and when considered appropriate audio.
- Graphics should be relevant and not for decoration.
- Icons should be simple and meaningful.
- Animation should be reduced to the minimum as necessary, to minimise users' distraction.

Use of text, font type and size:

- Fonts in the application screens must be resizable.
- Condensed letters should be avoided.
- Take into account text presentation in TV terminals is poorer than in PC monitors.
- Upper case only fonts are preferred in application messages and text. Upper case fonts are easier to read. Italics are not recommended since italics text is easily degraded in TV terminals.
- Boldface can be used to emphasise important texts or to increase the readability.

Use of colours:

- Following different authors' guidelines for interface design [28], background screens should not be pure white or change rapidly in brightness between screens. High contrast between the foreground and background should exist.
- Colour must be used to attract the attention of the users to the most important elements of an application screen (i.e. the currently selected element). The contrast is the most important factor to keep in mind when considering colours to be implemented in the applications.
- Take into account the colour performance of TV and PC terminals is absolutely different.

Screen titles:

- Every application screen must have a text title identifying the purpose of the screen.
- Every application screen must offer a help option to the user.

4.1.3 Auditory domain needs

Auditory functions in the elderly may include the presence of tinnitus, which is characterised by continuous sounds in the ear (buzzing, softly singings or little bells), and can be caused by small abnormalities in blood flow reaching the ear [39]. Presbicusis, also known as the loss of ability to discriminate between medium and high frequency sounds, can mask peripherical sounds and difficult the detection of a concomitant tinnitus.

Overall, the declines described above, together with excessive accumulations of ear wax, make it difficult for older people to deal with their daily tasks in some way. Sometimes words are hard to understand, another person's speech may sound slurred or mumbled, especially with background noise, certain sounds can be annoying or loud, and TV shows, concerts or parties may be less enjoyable because of hearing difficulties.

4.1.4 Adopted auditory domain design guidelines

Use of audio feedback:

- Background noise should be minimised.
- For each possible state of an application, the user can be informed as to where they are in the interaction and which actions are possible at this point.
- Audio feedback must be used with great care since it can become annoying and frustrating when it is too insisting. It might also affect the privacy of the users since other persons in the same room may get access to private information.
- Speech rates should be kept to 140 words per minute or less [20]. Artificial (synthesised) speech messages that do not closely imitate natural speech should be avoided.
- For acoustic signals to attract attention, a frequency between 300 Hz and 3,000 Hz should be used [20]. Moreover, older adults miss attention getting sounds with peaks over 2,500 Hz [23].

4.1.5 Cognitive domain needs

In normal ageing, some functions stay stable: Automatic and over learned responses, remote memory, semantic memory (memory for the meaning of words and concepts) and verbal reasoning and comprehension.

In contrast, some other functions decline: Decrease in information processing speed, including slower reactions, and slower reasoning and thinking capacity and they may experience a decline in working memory [23], defined as "the temporary storage and manipulation of information that is assumed to be necessary for a wide range of complex cognitive abilities" [3], in other words, the capacity for maintaining some information and mentally operate with it at the same time.

According to Zajicek et al. [53], 82% of their elderly users were unable to build useful conceptual models of the workings of the Web. Their confidence in making the decisions needed for the construction of conceptual models was low and they became confused and frustrated. In this sense, information and UI navigation should be provided in an easy way to master and should seek to increase users' confidence, avoiding unexpected behaviours.

4.1.6 Adopted cognitive domain design guidelines

- Language used should be simple and clear, avoiding irrelevant information on the screen.
- Important information should be highlighted and concentrated mainly on the centre of the screen.
- Screen layout, navigation and terminology used should be simple, clear and consistent.
- Ample time should be provided to read information. Time critical processes must be avoided. Feedback information must be also adapted to the expected slow responsiveness of the users.
- When a critical action has been selected by the user (i.e. exit an application), the system must always clearly notify this circumstance to the user and must request his explicit confirmation.
- Web-based interfaces must provide backward and forward navigation.
- Whenever possible, processes must be sequential and one way.
- The presence of parallel or simultaneous tasks must be avoided at all cost.
- It must also be avoided the use of complex navigation structures composed of multiple tree-like levels.
- The demand on working memory should be reduced by supporting recognition rather than recall and providing fewer choices to the user.
- Use new objects with new appearances for new interface behaviours, to avoid interference with the user's previous knowledge.
- The same actions must be implemented using exactly the same procedures in all applications.

4.1.7 Motor domain needs

Within the aging, different joint diseases together with different bone fractures occur more frequently. These diseases significantly restrict movement in joints and increase the pain in the realisation of daily live tasks. People with these pathologies, make slower movements and the lack of precision of movements, limits their dexterity to realise those daily tasks and to interact with mainstream technology through provided controls.

4.1.8 Adopted motor domain design guidelines

- For users with different forms of motor dysfunctions, the graphical interface should be made less sensitive to erratic hand movements.
- The slowness and lack of precision of movements associated to the pathologies described above could affect the use of scroll bars or image maps.
- The enlargement of interface does not only have implications for the visual domain. Allowing the user to adapt the size of user interface elements as much as they want, the need for fine-motor coordination can be reduced.
- The remote controller must be extremely simple and must have as few keys as possible.
- The size of the remote must be adequate to its planned use by the target users.
- The remote must have big, individual, well separated keys.
- The design of the remote must be ergonomic, must adapt to the shape of the hand and must have volume.
- Every key must present a drawing representing its function on its surface.

4.2 Dialog system

We conceive the multimodal dialog system as a scalable and modular unit, which provides voice control over the applications integrated in the targeted platform. The core component of the multimodal dialog system is constituted by the Ontology-based Dialog Platform framework (ODP). It provides an open architecture for building multimodal, task-oriented user interfaces that is in concordance with large parts in W3C's multimodal architecture proposal [30].

The ODP framework itself is built up on blocks (see Fig. 5) which stand for the basic dialogue system modules:

- The Extended Typed Feature Structures (eTFS) represents a data representation format which unifies the properties of RDF/RDFS (Resource Description Framework [29], and typed feature structures [12]). The encoding of the internal data as eTFS is accordant to the approach of ontology design in general, such that we use an < object > tag in order to denote a complex object of a certain type.
- PATE[1] [35] provides a framework that supports the development of applications for multimodal dialogue systems. PATE's architecture is centred on the idea of three separated data storage facilities: (i) the goal stack, (ii) the working memory, and (iii) the long-term memory. The working memory is responsible for the activated instances so-called Working Memory Elements (WMEs), which are accessible for processing, i.e., rule applications. The long-term memory is responsible for the persistent storage for all instances of the type hierarchy the system has in the background. The purpose of the goal-stack is to represent the focus of attention within the process of the system [2]. The placing of WMEs between the three data storage parts is organised by the activation value, which changes in the processing flow and the effects taken by rule applications.
- The Ontology-based Middleware Platform for Multimodal Dialogue Systems (OBM) is a middleware platform and application-programming framework for building multimodal dialogue systems. It is based on the eTFS API for system-wide data representation and PATE for implementing rule-based message routing. The OBM core functions as a server component that ties all modules and services together and maintains their interoperability. At run-time the server is responsible for managing the deployment of system modules.

As to enable voice interaction for the applications, the technical challenge was to first integrate the ODP framework into the UCH and second to provide the TV with the abstract presentation encoding the graphical content. In order to achieve a consistent context within the dialog system with respect to what is happening on the target side (e.g. Information Service Target) and on the User Interface side (TV), the internal state of the dialog system has to keep track and administrate the actions taken place at both ends. As we can see in Fig. 6, the ODP docks by means of the two different services at the UIPM Layer that speaks the URC-HTTP protocol, i.e., receiving and posting socket modifications from/to the targets and the protocol that can be interpreted by the TV client:

- **The Function Modeler Service** supplies the ODP with the information returned by the target that are converted into TFS objects and serve the Information State Module to update its own state.
- **The Presentation Planner Service** implements a service that invokes event handling on the UIPM. The TV client exclusively processes rendering information, which is made ready by the UIPM. Also, in case the context information is not fully covered

[1] PATE stands for A Production Rule System based on Typed Feature Structures.

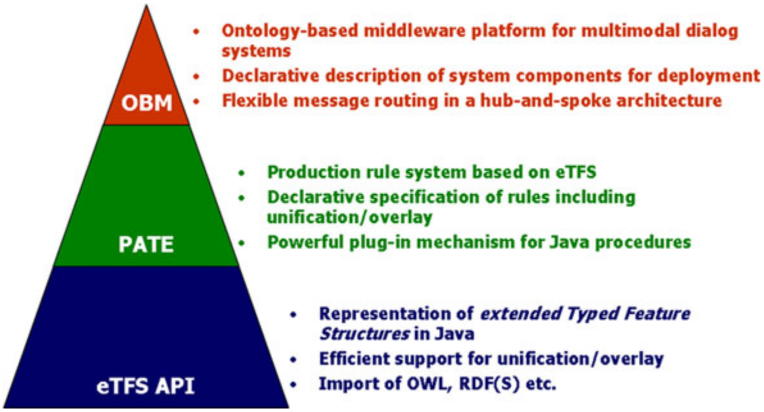

Fig. 5 The core building blocks of the ODP framework

by the information retrieved from the target, the dialog system uses the rendering information as complementary input.

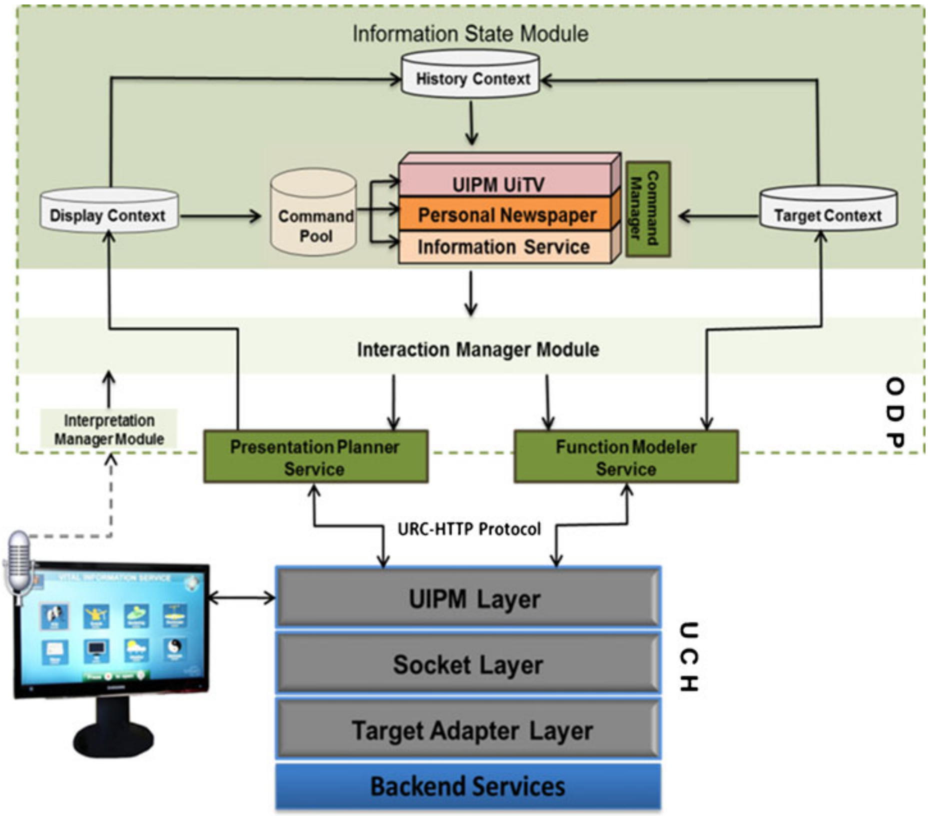

Fig. 6 The data flow in the dialogue system's architecture demonstrates how the Information State Module together with its building blocks is synchronised via two channels dedicated to the input coming from the User Interface (TV) and the backend services

Besides the services, which are dealing with the communication to the TV and the backend services, different tasks within the multimodal dialog platform along the speech processing are allocated across multiple modules (see Fig. 6):

- **The Interpretation Manager** carries out natural language interpretation. For that purpose it processes the word lattice reflecting the user's vocal utterance with its semantic interpretation of the utterance. In particular, the natural language understanding component interprets the recognised spoken input of the user and converts it into instances of the ontology.
- **The Information State** stores and manages the ontology-based representation of all targets that represents the appropriate services on the backend side. Additionally, the Information State administrates and makes available a coherent representation of the displayed graphical content. The synchronisation between the internal state of the dialog system and the backend components together with the content on the screen builds the basis for enabling access to multimodal interactive services. Depending on the state configuration, the Command Manager of the Information State Module retrieves the required command assigned to manipulate the states of the backend services or/and the graphical user interface (GUI).
- **The Interaction Manager** has the task to propagate these commands and invoke the adapters that are able to speak the language of the URC-HTTP protocol, hence takes care of the information exchange with the target layer (backend services) and the presentation layer (TV). Typically when the user utters commands specific to the presentation layer, i.e., "*Go to the Main Menu*", first an ontological concept SwitchApplication is instantiated and then the interaction manager invokes the presentation planner to build and send the appropriate message to the UIPM.

Within the context of the tested prototype we can change between two input modalities and allow the user to alternate between voice interaction and the remote control. Possible utterances by the user are described by a grammar, maintained in a W3C standard compliant format. However, not only predefined speech input is accepted; the framework allows for loading new grammar entities on the fly. This is useful in the context of dynamic concept names (e.g. the title of a movie), which are created using information available from the web at runtime.

4.3 Videoconference service

The main motivation for choosing to integrate the videoconference was that one of the biggest problems that the elderly suffer from is loneliness. To overcome this problem, connectivity applications are thought to improve the quality of their ageing. Using these connectivity applications the elderly can keep in touch with their family or friends and make their life happier and more entertained.

Even if there are mainstream solutions in the market that integrate videoconference on a TV set like the Skype based solution, we felt that providing this functionality through a personalised and accessible UI, could improve the elderly's interest and adoption of this service. The videoconference service has been provided through the integration of the open source Ekiga software as a target service to the UCH.

The developed videoconference application's user interface for our TV UI system is composed of three interfaces. The first interface "Call Contacts" visualises user's contacts and allows establishing a call with one of the contacts by pressing OK in the simplified remote. The second interface "Incoming Call" appears in the foreground when a new call arrives. This interface is composed of a picture of the caller contact and the options to take or reject the call.

The users can choose one of the options by pressing on the left and right arrow keys on the simplified remote and they can run their option by pressing OK. The third interface "Ongoing Call" shows the video streams of the call and has a hang-up button that is activated by pressing OK in the simplified remote.

The videoconference service makes use of the platform's contact management service. These contacts can be easily managed on a PC through a user interface developed for the contact database's UI Socket.

Figure 7 shows the screenshots of the main menu and the three interfaces developed for the videoconference service.

4.4 Information service

An important concern we wanted to address was how to make the acquisition of information in the web easy to master. We believed that an application with such features integrated into the platform was of special interest for the elderly. To this end, we decided to avoid the use of web browsers, direct access to search engines (instead, the information service invokes a query on behalf of the user), and even hide the fact that the user accesses the Internet at all. In order to accomplish transparency of the content for the elderly, we encapsulate the knowledge about the web site into the project's ontology. Using this approach "web-surfing" is substituted by browsing through an ontology tree.

Here, the ontology defines the conceptual relations in the domain. Furthermore, it assigns web pages to concepts and specifies the rules to extract the documents. In a second step, the ontology provides a description of content related to specific web pages. User preferences

Fig. 7 Screenshots of the main menu and the three interfaces (call contacts, incoming call and ongoing call) developed for the videoconference service

and interests of a specific user help to further restrict the space of concepts. Learning of users' interests is done by statistical evaluation of previous user behaviour. Combining a probability approach and a vector space model, a personal recommendation service provides interesting documents which are instances of the favoured concepts in the ontology tree. For instance two instantiated concepts that have been established by the users' preferences are:

- **TV**: A personalised guide to the daily TV programme. The user can browse through all programmes split into categories (e.g. movies, sports, series, music and more). This category is displayed as the sixth category in the information service's menu interface in Fig. 8.
- **Wellness**: Information about a healthy life style, suggestions for staying in good shape, news about advanced techniques in medicine and so on; see the last category in the information service's menu interface in Fig. 8.

In the following sections, the validation with users of the introduced services is presented. Firstly, the evaluation methodology is introduced, and later, the results of the user tests are discussed.

5 Evaluation method

The development of the platform was done following the User centred design approach. Following this approach, the platform was evaluated at the end of each iteration and the results of the first evaluations served as an input for the next iteration's developments.

Fig. 8 On the top, a screenshot of the start page of the Information Service is displayed. Preselected topic areas are distinguished by big icons and ordered by users' preference that may change after usage. Below, two screenshots of the navigation through the content are shown

For the initial user test the platform was tested in labs by 10 users in Spain and by 30 users in the United Kingdom. The tests included interaction with the initial prototypes, together with personal interviews and focus groups to capture the user's experience and to compile the input for the upcoming development period.

For the final test of the platform, the system was tested by 16 users at homes in the United Kingdom and by 4 users at home in Spain for a period of 3–4 weeks. The platform's final prototype was also tested in elder associations in Spain with a meaningful amount of users. The reporting that is detailed in the following subsection is concentrated in the final evaluation of the platform done in the north of Spain in different older people associations, where the system was shown and discussed with an amount of users large enough to enable the performance of subsequent quantitative statistical analyses.

5.1 Participants

The sample recruited for the final evaluation of platform was composed of 83 participants. After the revision of the answered questionnaire and subsequent refinement of the data, the final sample from whom the results have been compiled, was composed of 47 participants, 13 male and 34 female, with an age ranging from 52 to 89 (x=71.11; sd = 7.12) from the town of Zarautz (n=23) and the city of San Sebastian (n=24), in the North of Spain. All users were attending elder associations in their respective locations. They had been living in their current location a mean of 46.58 years (sd = 19.04), which identifies them as stable participants in their respective communities. Only 27.7% had no studies, while 46.8% had completed primary studies, 8.5% secondary studies, 12.8% had technical studies and a small 4.3% had completed university studies. They had been active workers throughout their lives, with a mean working life of 36.08 years (sd = 12.22). 51.1% of the people from the sample were married, while 38.3% were widows.

5.2 Technical set up

Two laptops with a headset, a simplified remote control, and their corresponding signal receptors were set in a room where the demonstration would take place on a group basis, connecting the main computer running the platform to a slide projector. One evaluator and one observer explained the whole procedure to the users in each testing site, gathered as a group in the room. They were administered a consent form, thus showing their acceptance to participate in the evaluation session. Afterwards, they were given the a questionnaire, which included the following sections: 1) sociodemographical data; 2) quality of family and social contacts; 3) leisure activities; 4) satisfaction with life, and 5) specific evaluation of the platform's services (here, questions about the system in general and individual applications in particular were asked).

Figure 9 shows the technical set up of the evaluation sessions.

5.3 Tests steps

After an approximate time of 30 min to fulfill sections 1 to 4 from the questionnaire, the main menu was presented, and a brief explanation of its usage was given to the participants. Users were required to give written answers to questions related to the main menu as well as to provide specific verbal feedback to what they were seeing on the screen and consulting the staff at any time. The same procedure was followed for each application (from video-conference to information service), thus showing the interface and the functioning (via a

Fig. 9 Photograph showing the technical set up of the evaluations in an elderly association

simplified remote control) of each application. A demonstration of the interaction via voice (in English) was done. After all the services were presented, users were asked to discuss aloud any additional comments or feedback they would like to add. Then, the questionnaires were collected and users were thanked for their participation.

6 Results

6.1 Overall impression about the system and main menu

The opinions about the system were very divided among those not having a clear statement, those thinking that it was a good application, and those reporting from the beginning that "*this application may isolate people… it might isolate them in their homes*". However, a majority of 68.2% thought it would be helpful in improving their social relationships, 71.4% thought it would help them to keep closer contact to their relatives, 73.7% thought it would help them to get closer with friends and 84.2% were confident in the idea that it would improve their quality of life.

Regarding the main menu interface, most of the sample (53.3%) found it pleasant or very pleasant, not being tiring for the eyes. All of them considered the interface was readable, with appropriate font size and colour. The voice control demonstration worked well and participants were impressed. They expressed concerns regarding the use of headsets, the provision of the technology in other languages and the accuracy of the voice interaction with elderly users.

A table summarising the results from the evaluation with users is included in Table 2.

6.2 Videoconference service

The layout of the videoconference was described as pleasant by 48% of the sample (48% said it was neutral, neither pleasant nor unpleasant). When they saw the way it worked on the demonstration session, 81.3% thought it was a useful application, and 50% would regularly use it (the others would rather continue with the regular phone). 54.5% would use it to talk to family, and 36.4% to both family and friends. It was a very well rated application ("*it helps you keep in touch easier… it brings you closer to your relatives… in this way, I can see them*").

Table 2 Summary of evaluation results

Overall impression about the system
68.2% found it helpful in improving their social relationships
84.2% were confident it would improve their quality of life
53.3% of the sample found the main menu interface pleasant
Videoconference service
48% found the layout as pleasant (48% were neutral)
81.3% thought was a useful application, 50% would regularly use it
Information service
50% described the layout as pleasant
87.5% considered it was useful, 50% would regularly use it

Some of the participants were familiar with this form of communication through Skype on a PC. However, it was considered an advantage that the videoconference system allowed being using the TV set for other purposes (watching a film, etc.) while it run in the background; the user could be just watching the TV and, in case of receiving an incoming call, the call would pop-up on the TV screen. This simplicity of use was highly appreciated by the users.

Moreover, some of the opinions stated by the users were related to their perception of the videoconference service. More specifically, there was a significant relationship between feeling happy with the frequency of family contacts and perceiving videoconference as a device that could improve their quality of life ($\chi^2(3) = 12.058$, p<..01), thus resulting in 63.15% of users (who were already happy because they met their relatives as much as they wanted to) who thought that videoconference would improve their quality of life. In addition, 66.66% of the users who had social relationships mainly outside home were the ones who precisely described videoconference as a device that could improve their social relationships ($\chi^2(1) = 4.421$, p<..05). These results suggest that a device like this, rather than improving quality of life of those with less social relationships, is more likely to be accepted by those who can perceive it as a complement to their already existing successful social network.

6.3 Information service

50% described the layout as pleasant. After being exposed to its use, 87.5% considered it was useful, but only 50% would use it regularly. They liked the fact that local content was available but stressed that the content would have to be updated regularly in order for it to be useful. Many stated that they would continue with regular newspaper, and this kind of technologies may be good "*for younger people*". Some complained that the layout contrast was no good and that fonts should be made bigger, but they were told that this may be adjusted when using it on a TV set.

More detail on the evaluation and result of the applications developed to validate our approach can be found at [15].

7 Conclusions

In this paper we have presented a new approach to integrate all kinds of interactive services with the TV set in a way that allows personalising the UI to the needs of each user group.

The proposed approach is based on the ISO/IEC 24752 Universal Remote Console (URC) standard and its implementation in the UCH architecture.

Our proposal for an "ordinary" TV user interface is based on the contributions provided by the interactive TV research. This approach allows access to interactive services from common TV sets, through the provision of personalised plug and play user interfaces that are rendered on the TV set. Following this approach permits an easy integration of new accessible services into our TV sets, including the services locally provided by intelligent environments. At the same time, this approach allows the consumption of these interactive services in new TV set configurations with their corresponding interaction paradigms. These interaction paradigms include advanced UIs, natural language UIs, assistive technologies, and multimodal UIs.

Moreover, having the required modules available on a resource server on the Internet, allows us to deploy and update our systems easily and opens a new market for service integrators and UIs developers.

The provision of an approach like this fosters the development of accessible TV interactive services' solutions and provides a means of fast prototyping of new services or new TV set configurations (with new interactions technologies) thus filling the existing gap of studies and solutions on accessible interactive services in TV research. The provided approach is a great tool, to be used in collaboration with the iTV application lifecycle methodologies introduced Section 2.

The UCH implementation can be embedded into a consumer broadband router, into the TV itself, or with a more powerful UCH that has extended functionality such as a dedicated PC. Additionally, the ongoing initiatives to provide the web services with native URC interface as well as providing a URC interface directly on devices in the environment, can reduce the implementation complexity of the URC solution, making it simpler to embed in devices like the TV in the future.

An implementation of this approach has been carried out focused on the elderly. Services targeted on improving the elderly people's quality of life were integrated. With regard to the targeted TV set's pluggable UI, a multimodal interaction has been developed together with a simple and easy to navigate graphical user interface.

The user tests showed that the developed UI was well accepted and they thought that the developed concept could improve their social relationship and their quality of life, especially for those who already perceived themselves as having an adequate social network and had close contact with their relatives.

From the implementers perspective what is remarkable is the easiness to integrate existing modules like the dialog system or the presented services and the simplicity to develop user interface instances of the selected TV UI solution for new services or devices from different environments.

8 Future work

There are aspects of the presented paper that require further work, firstly to enhance the concrete TV UI solutions developed following the presented approach and secondly, to evolve the presented approach and facilitate the work required to personalise the UIs to the different user groups and thirdly, to simplify the task of selecting and installing new services and their corresponding UIs by non technical end users.

The application of the presented approach in the development of UIs for interactive services on TV, enables and simplifies the provision of universally accessible interactive services on TV. But the mere application of the approach, does not guarantee that the resulting TV UI configuration will be accessible to the target user group for which it has been designed. In this sense, it is planned to analyse the available methodologies to develop and validate accessible UIs for TV sets, in order to provide an adapted methodology to be run in combination with the presented approach, to ensure that the developed UIs are usable and accessible by their target users.

As part of the validation process of the developed UIs, in terms of the user tests, it is likely that the experience with a meaningful sample of individual home trials would have enriched the specific feedback already obtained from the group-based user trials; participants did not show any reluctance to openly show their opinion on the solution shown to them, but a deeper experience and the gain of skills could have been derived from a home trial with a bigger sample and a larger period of testing time. Still, results and feedback provided by the participants showed to be very useful for future developments from a user-oriented perspective.

For the future, the way to proceed in the user validation topic, is to target statistically significant home trials in addition to group based trials, since apart from specific feedback gathered from the group based trials, it will allow to evaluate the evolution of the quality of life of the users and a more realistic user experience in their daily environment. The home trials with non-mainstream users have to be carefully designed and carried out, considering the budget restrictions and taking in mind how economically and socially costly is to involve non-biased users (people which have not previously tested similar prototypes) and to configure and maintain the user trials at home.

Regarding the approach's implementation for the elderly presented in this paper, the users expressed concerns regarding the use of headsets, the provision of the technology in other languages and the accuracy of the voice interaction with elderly users. To overcome these issues, it is foreseen to research the use of other audio input paradigms (e.g., remote control with an integrated microphone) as well as including other language options to the system and integrating the most successful approaches for voice recognition of the elderly.

Additionally, to facilitate the work required in developing and adapting the UIs defined for the interactive services, the study and evaluation of hybrid approaches among pluggable UI and UI generation approaches is foreseen. The objective is to reach a consensus between fully personalised pluggable UIs and fully parameterised transformations modules. Hybrid approaches that define pluggable UIs for specific target user groups that through some adaptation parameters allow fine-tuning the UI to the specifics of each user and their context will be researched.

Finally, with the increasing number of available services provided through the Internet, the need of guiding the users (especially the ones with technological difficulties) in the installation process of new services will require the integration of the presented approach with semantic annotation technologies applied to the services, providing a simple way to search and find services to the end user. At the same time, the number of downloadable UI and resource options is increasing exponentially. The use of semantic annotation technologies applied to UI resources, together with the development of matchmaking algorithms, will enable the identification and adaptation of the best fitting UIs for the previously selected service or compound of services.

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References

1. Abrams M, Phanouiou C, Batongbacal A et al (1999) UIML: an appliance-independent XML user interface language. Comput Netw 31:1695–1708
2. Anderson JR, Lebiere C (1998) The atomic components of thought. Lawrence Erlbaum Associates, Mahwah
3. Baddeley A (2003) Working memory and language: an overview. J Commun Disord 36:189–208
4. Berglund A (2006) Extensible Stylesheet Language (XSL) version 1.1. W3C. Technical Report
5. Berglund A, Berglund E, Larsson A, Bang M (2006) Paper remote: an augmented television guide and remote control. Univ Access Inf Soc 4:300–327
6. Berglund A, Johansson P (2004) Using speech and dialogue for interactive TV navigation. Univ Access Inf Soc 3:224–238
7. Bernhaupt R, Obrist M, Weiss A et al (2008) Trends in the living room and beyond: results from ethnographic studies using creative and playful probing. Comput Entertain 6:1–23
8. Bos B, Çelik T, Hickson I, Wium Lie H (2011) Cascading style sheets level 2 revision 1 (CSS 2.1) specification. W3C. Technical Report
9. Boyer JM (2009) XForms 1.1. W3C. Technical report
10. Carmichael A (1999) Style guide for the design of interactive television for elderly users. Technical Report
11. Carmichael A, Petrie H, Hamilton F, Freeman J (2003) The vista project *: broadening access to digital TV electronic programme guides. PsychNology J 1:229–241
12. Carpenter B (1992) The logic of typed feature structures. Cambridge University Press, Cambridge
13. Cesar P, Chorianopoulos K (2009) The evolution of TV systems, content, and users toward interactivity. Found Trends HCI. doi:10.1561/1100000008
14. Chorianopoulos K, Spinellis D (2006) User interface evaluation of interactive TV: a media studies perspective. Univ Access Inf Soc 5:209–218
15. Díaz U, Etxaniz A, Urdaneta E, et al. (2011) A TV platform to improve older people's quality of life: lessons learned from the evaluation of the VITAL project with Spanish elderly users. In Proceedings of the 4th International Conference on PErvasive Technologies Related to Assistive Environments (PETRA 2011), Crete, Greece
16. Echt KV (2002) Designing web-based health information for older adults. Visual considerations and design directives. In: Morrell RW (ed) Older adults, health information, and the World Wide Web. Lawrence Erlbaum Associates, Mahwah, pp 61–68
17. EN 300 743 (2006) Subtitling systems. ETSI, Sophia Antipolis Cedex
18. Epelde G, Carrasco E, Zimmermann G, et al. (2009) URC based accessible TV. In Proceedings of the 7th European conference on Interactive Television (EuroITV 2009), Leuven, Belgium. 111–114
19. Eronen L (2006) Five qualitative research methods to make iTV applications universally accessible. Univ Access Inf Soc 5:219–238
20. Fisk AD, Rogers W, Charness N et al (2004) Designing for older adults. Principles and creative human factor approaches. CRC Press LLC, Boca Raton
21. Gill J, Perera S (2003) Accessible universal design of interactive digital television. In: Proceedings of the 1st European Conference on Interactive Television (EuroITV 2003), Brighton, UK. 83–89
22. Hamisu P, Heinrich G, Jung C, et al. (2011) Accessible UI design and multimodal interaction through hybrid TV platforms: towards a virtual-user centered design framework. In Proceedings of the 6th International Conference on Universal Access in Human-Computer Interaction: Users Diversity. (UAHCI 2011), Orlando, FL, USA. 32–41
23. Hawthorn D (2000) Possible implications of aging for interface designers. Interact Comput 12:507–528
24. International Organization for Standardization (2008) ISO/IEC 24752:2008–information technology–user interfaces–universal remote console (5 parts). ISO/IEC, Geneva
25. Kim SH, Ok J, Kang H, et al. (2004) An interaction and product design of gesture based TV remote control. In CHI'04 extended abstracts on Human factors in computing systems, Vienna, Austria. 1548–1548
26. Klein DJA, Karger SA, Sinclair KA (2003) Digital television for all: a report on usability and accessible design. Technical Report
27. Klima M, Macik M, Urdaneta E et al (2009) User interfaces for the digital home on the basis of open industrial standards. In: Mikulecky P, Liskova T, Cech P, Bures V (eds) Ambient intelligence perspectives. Selected papers from the first international ambient intelligence forum 2008. IOS, Amsterdam, pp 144–152
28. Kurniawan S, Zaphiris P (2005) Research-derived web design guidelines for older people. In Proceedings of the 7th international ACM SIGACCESS conference on Computers and accessibility (Assets 2005), Baltimore, MD, USA. 129–135

29. Manola F, Miller E (2004) RDF primer.W3C. Technical Report
30. McGuinness DL, van Harmelen F (2004) OWL web ontology language overview. W3C. Technical report
31. Obrenovic Z, Abascal J, Starcevic D (2007) Universal accessibility as a multimodal design issue. Commun ACM 50:83–88
32. Obrist M, Bernhaupt R, Beck E, Tscheligi M (2007) Focusing on elderly: an iTV usability evaluation study with eye-tracking. In Proceedings of the 5th European Conference on Interactive Television (EuroITV 2007), Amsterdam, The Netherlands. 66–75
33. Obrist M, Bernhaupt R, Tscheligi M (2008) Interactive TV for the home: an ethnographic study on users' requirements and experiences. Int J Hum Comput Interact 24:174–196
34. Peng C (2002) Digital television applications, PhD-thesis, Helsinki University of Technology
35. Pfleger N, Schehl J (2006) Development of advanced dialog systems with PATE. In Proceedings of the International Conference on Spoken Language Processing (Interspeech 2006/ICSLP), Pittsburgh, PA, USA. 1778–1781
36. Puerta A, Eisenstein J (2002) XIML: a common representation for interaction data. In Proceedings of the 7th international conference on Intelligent user interfaces (IUI 2002), San Francisco, CA, USA, 214–215
37. Rice MD (2004) Personalisation of interactive television for visually impaired viewers. In Proceedings for the 2nd Cambridge Workshop on Universal Assistive Technology, Cambridge University, UK. 45–48
38. Rice M, Alm N (2008) Designing new interfaces for digital interactive television usable by older adults. Comput Entertain 6:1–20
39. Segal ES (1996) Common medical problems in geriatric patients. In: Carstensen LL, Edelstein BA, Dornbrand L (eds) The practical handbook of clinical gerontology. Sage, London, pp 451–467
40. Shirehjini AAN (2004) A novel interaction metaphor for personal environment control: direct manipulation of physical environment based on 3D visualization. Comput Graph 28:667–675
41. Shirehjini AAN (2005) A generic UPnP architecture for ambient intelligence meeting rooms and a control point allowing for integrated 2D and 3D interaction. In Proceedings of the 2005 joint conference on Smart objects and ambient intelligence, Grenoble, FRANCE. 207–212
42. Springett MV, Griffiths RN (2007) Accessibility of interactive television for users with low vision: learning from the web. In Proceedings of the 5th European conference on Interactive TV: a shared experience (EuroITV 2007), Amsterdam, The Netherlands. 76–85
43. Springett MV, Griffiths RN (2008) Innovation for inclusive design: an approach to exploring the iDTV design space. In: Proceeding of the 1st international conference on Designing interactive user experiences for TV and video (uxtv 2008), Silicon Valley, CA, USA. 49–58
44. Tazari MR (2010) An open distributed framework for adaptive user interaction in ambient intelligence. In Proceedings of the First International Joint Conference on Ambient Intelligence. (AMI 2010), Malaga, Spain. 227–238
45. Trewin S, Zimmermann G, Vanderheiden G (2004) Abstract representations as a basis for usable user interfaces. Interact Comput 16:477–506
46. TS 102 796–V1.1.1 (2010) Hybrid broadcast broadband TV. ETSI, Sophia Antipolis Cedex
47. UNE 153010:2003 (2003) Subtitling for deaf and hard-of-hearing people. Subtitling by teletext. AENOR, Barcelona
48. UNE 153020:2005 (2005) Audio description for visually impaired people. Guidelines for audio description procedures and for the preparation of audio guides. AENOR, Barcelona
49. Vatavu RD (2011) Point and click mediated interactions for large home entertainment displays. Multimed Tool Appl. doi:10.1007/s11042-010-0698-5
50. Vlachogiannis E, Gavalas D, Tsekouras G, Anagnostopoulos C (2011) Accessible interactive television using the MPEG-21 standard. Univ Access Inf Soc 10:151–163
51. Wang S, Chung T, Yan K (2011) A new territory of multi-user variable remote control for interactive TV. Multimed Tool Appl 51:1013–1034
52. Yang S, Ro YM, Nam J, Hong J (2004) Improving visual accessibility for color vision deficiency based on MPEG-21. ETRI J 26:195–202
53. Zajicek M, Hall S (2000) Solutions for elderly visually impaired people using the internet. In Proceedings of Human Computer Interaction 2000 Conference (HCI2000), Sunderland, United Kingdom. 299–307

54. Zillmann D, Vorderer P (2000) Media entertainment: the psychology of its appeal. Lawrence Erlbaum Associates, Mahwah
55. Zimmermann G, Vanderheiden G (2007) The universal control hub: an open platform for remote user interfaces in the digital home. In Proceedings of the 12th international conference on Human-computer interaction: interaction platforms and techniques (HCI 2007), Beijing, China. 1040–1049

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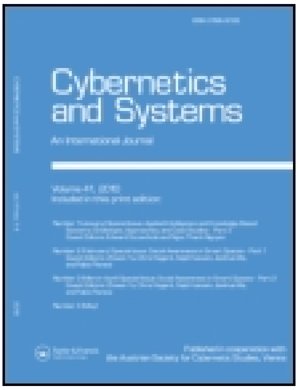

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USING SET OF EXPERIENCE KNOWLEDGE STRUCTURE TO EXTEND A RULE SET OF CLINICAL DECISION SUPPORT SYSTEM FOR ALZHEIMER'S DISEASE DIAGNOSIS

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Using Set of Experience Knowledge Structure to Extend a Rule Set of Clinical Decision Support System for Alzheimer's Disease Diagnosis

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In this article we present an experience-based clinical decision support system (CDSS) for the diagnosis of Alzheimer's disease, which enables the discovery of new knowledge in the system and the generation of new rules that drive reasoning. In order to evolve an initial set of production rules given by medical experts we make use of the Set of Experience Knowledge Structure (SOEKS). An illustrative case of our system is also presented.

KEYWORDS Alzheimer's disease, clinical decision support system, set of experience knowledge structure, user experience

INTRODUCTION

Interest in making clinical decision support systems (CDSSs) for the diagnosis of Alzheimer's disease (AD) is great, because it is the leading cause of dementia in developed countries (Monien et al. 2009). Early diagnosis of

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AD is commonly carried out through analysis of the results of different medical tests, which are multidisciplinary by nature, such as neurological, neuropsychological, and neuroimaging tests (Monien et al. 2009). During this process, a large number of parameters are generated and making a proper diagnosis becomes a knowledge handling problem. In addition, recent advances in early diagnosis of AD date the initial stages even 15 years before the first clinically recognizable symptoms become visible (Monien et al. 2009) and there is still no known cause for AD. Therefore, there is a need for the medical and scientific community to discover which parameters are most relevant and which are not with regard to an early diagnosis.

CDSSs help physicians overcome knowledge handling problems. They are active knowledge resources that use patient clinical data to generate case-specific advice (Liu et al. 2006). During diagnosis processes, CDSSs analyze data from those medical tests and present results to physicians so they can make decisions more easily and efficiently and obtain a proper diagnosis.

In this article we present a CDSS that (i) supports physicians during diagnosis of AD and (ii) offers tools needed to fulfill the aforementioned need to discover relevant parameters for this diagnosis. In fact, this CDSS is based on the experience acquired or learned from the user, and it enables the discovery of new knowledge in the system and the generation of new rules that drive reasoning.

This CDSS is an evolution of the system proposed by Sanchez et al. (2011) that consists of a knowledge-based approach based on semantic technologies for knowledge representation and a set of static production rules provided by domain experts. This static rule set drives the reasoning process that leads to a diagnosis; in other words, it is the criteria for the diagnosis.

According to the aforementioned need to find the relevant criteria for diagnosis of AD, the system presented in this article discovers new knowledge from this set of rules. In this way, new rules are generated based on experience.

There are several approaches that can be used to endow the proposed system with the ability of adapting and discovering rules when special conditions are encountered, such as fuzzy logic or neuronal networks, among others. We propose the use of the set of experience knowledge structure (SOEKS) and decisional DNA (DDNA; Sanin and Szczerbicki 2005, 2008, 2009) in their Web Ontology Language (OWL) form (Sanin et al. 2007) as a novel way of attaining this behavior. These elements will allow the system to capture previous experiences and discover new knowledge using bio-inspired techniques and the reasoning capabilities offered by ontologies.

This article is arranged as follows: in the next section we present some background concepts about CDSS, semantic technologies, and SOEKS, which will be referenced throughout the article. Following, we present the experience-based CDSS. Then, we present the application of SOEKS and the process of the evolution of the rules or generation of new ones with it.

Next, we introduce a case study that uses the aforementioned experience-based CDSS for the evolution of the initial rule set. Finally, we discuss our conclusions and future work.

BACKGROUND CONCEPTS

In this section we present a short overview of the relevant concepts that are discussed in the following sections.

Clinical Decision Support Systems

Classical CDSS share some common limitations that have not been entirely overcome yet (Wright and Sittig 2008). Firstly, the representation of knowledge is static, limiting the type of knowledge that can be represented. Additionally, CDSS definition is specified only through explicit information enumeration (i.e., case-based systems) and, thus, arguably no discovery of new knowledge is directly supported (Sanchez et al. 2011). Secondly, knowledge sources are often heterogeneous and disperse, which increases the complexity of CDSS. Third, criteria for diagnosis are by nature highly changeable due to the high frequency of new findings and advances and should be updated often. Hence, the maintainability of the system could be a critical problem. Lastly, terminological interoperability is also an important matter that classical approaches in CDSS do not solve appropriately (Wright and Sittig 2008). Two different CDSSs may not understand each other, even if their domain and purpose is the same, because they can adopt different terminologies or, in extreme cases, due to the inertia related to monolithic and legacy system architectures.

In the literature, several architectures for CDSS have been presented (Michalowski et al. 2005; Hussain et al. 2007). According to Wright and Sittig (2008), the evolution of architectures for CDSS has followed four phases: standalone CDSS, CDSS integrated to clinical systems, standards-based systems, and service models. The main challenges addressed by these architectures deal with (a) the integration of CDSS into clinical workflows and systems and (b) the transference of successful interventions from one system to another (Wright and Sittig 2008).

Semantic Technologies Applied to Clinical Decision Support Systems

Knowledge engineering (KE) techniques can efficiently deal with the aforementioned problems such as terminological interoperability, system maintainability, and source heterogeneity and disparity. More precisely, semantic technologies have been described in the literature as a promising approach to solve knowledge handling and decision support in the medical domain (Gnanambal and Thangaraj 2010; Lindgren 2011).

In particular, ontologies are very promising. Gruber defined ontologies in the computer science domain as the explicit specification of a conceptualization (Gruber 1995). Ontologies can fulfill the needs for organized and standardized terminologies and reusability efficiently at a structural level (Houshiaryan et al. 2005). They also deliver interesting benefits when used for reasoning and inferring new knowledge (Yu and Jonnalagadda 2006); for instance, the fast query systems presented by Toro et al. (2008).

Among the most widely used ontologies within the medical domain are the Semantic Web Application in Neuromedicine (SWAN; Ciccarese et al. 2008) and the Systematized Nomenclature of Medicine Clinical Terms (SNOMED CT; Nyström et al. 2010).

Set of Experience Knowledge Structure and Decisional DNA

Knowledge has been an important asset for individuals, organizations, and society throughout the ages. Decision makers, in general, base their current decisions on lessons learned from previous similar situations (Sanin and Szczerbicki 2005); however, much of the experience held by individuals is not properly capitalized on due to inappropriate knowledge representation or administration. This leads to decision reprocessing, inadequate response times, and lack of flexibility to adapt when new environmental conditions are found.

In order to represent and reuse experience in an adequate form, Sanin and Szczerbicki (2005, 2008) proposed the concepts of the SOEKS and DDNA. SOEKS is a knowledge representation designed to store formal decision events in an explicit way and is based on four basic elements that are considered to be crucial in decision-making actions. These elements are variables (V), functions (F), constraints (C), and rules (R).

Variables are used to represent knowledge in an attribute-value form, following the traditional approach for knowledge representation. Given that the set of F, C, and R of SOEKS are different ways of relating knowledge variables, it is safe to say that the latter are the central component of the entire knowledge structure. Functions describe associations between a dependent variable and a set of input variables; therefore, SOEKS uses functions as a way to establish links among variables and to construct multi-objective goals (i.e., multiple functions). Similarly, constraints are functions that act as a way to limit possibilities, restrict the set of possible solutions, and control the performance of the system with respect to its goals. Finally, rules are used to represent inferences and correlate actions with the conditions under which they should be executed. Rules are relationships that operate in the universe of variables and express the connection between a condition and a consequence in the form if–then–else.

SOEKS is the basis for the creation of DDNA, which is a structure capable of capturing decisional fingerprints of an individual or organization. The name *decisional DNA* is an allegory to human DNA because of its structure and the ability that if offers to store experience within itself. Let us illustrate this metaphor: the four elements that comprise a SOEKS can be compared to the four basic nucleotides of human DNA, and they are also connected in a way that resembles a human gene. A gene guides hereditary responses in living organisms, and analogously a SOEKS guides responses in decision-making processes. A group of SOEKS of the same "type" (i.e., knowledge category) comprise a decisional chromosome, which stores decisional "strategies" for a specific category. Therefore, having several SOEKS chromosomes is equivalent to having a complete DDNA strand of an organization containing different inference strategies. SOEKS and DDNA have been successfully applied in industrial environments, specifically for maintenance purposes, in conjunction with augmented reality (AR) techniques (Toro et al. 2007), and in the fields of finances and energy research (Sanin et al. 2009).

EXPERIENCE-BASED CLINICAL DECISION SUPPORT SYSTEM FOR THE DIAGNOSIS OF ALZHEIMER'S DISEASE

In this section, we propose an experience-based CDSS for the diagnosis of AD. The experience of the physician using our system is stored in it and with this experience the system is able to (i) make explicit the implicit knowledge contained in the system and (ii) generate new criteria to drive reasoning.

The proposed system is the evolution of a previous work presented by Sanchez et al. (2011) in which a knowledge-based CDSS for the diagnosis of AD was presented. The system was based on ontologies for knowledge representation and a semantic reasoning process that inferred diagnoses for patients. The semantic reasoning was driven by a static set of production rules provided by AD experts. The previous system has been extended with the application of SOEKS to provide it with the ability to evolve the rule set and discover new rules.

The architecture of the CDSS presented consists of five layers (Figure 1): a data layer, a translation layer, an ontology and reasoning layer, an experience layer, and an application layer.

Heterogeneous and spatially disperse databases (DBs) store the data that feed the experience-based CDSS presented in this article. These DBs, which can be provided and maintained by different organizations, are all accessible to our system and they form the data layer of the architecture. The translation layer performs an alignment between data in the DB of the data layer to knowledge that is stored in the ontology and reasoning layer; each DB is related to a translation module in the translation layer. In this way, DB do not need to be aligned in between or intercommunicate directly; they remain

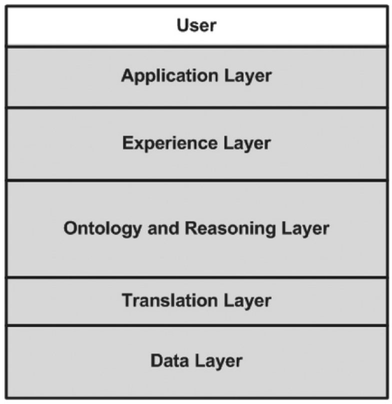

FIGURE 1 Proposed architecture for the CDSS.

decentralized. The ontology and reasoning layer contains the knowledge of the system and performs reasoning processes for clinical decision support. Figure 2 shows the structure of the ontology and reasoning layer.

Ontologies were chosen as the knowledge containers of the system. In particular, three different ontologies model this domain of diagnosis of AD: the Mind ontology (Sanchez et al. 2011) and the supporting ontologies SWAN (Ciccarese et al. 2008) and SNOMED CT (Nyström et al. 2010). Firstly, SWAN links and endorses the criteria of the system with the hypotheses and publications that are being held by the medical and scientific community, and the contents of our system can be validated and verified to be current and updated. Secondly, SNOMED CT is used for standardization purposes. Lastly, the Mind ontology contains the tests carried out on patients diagnosed with probable AD, such as neuropsychological, neurological, radiological,

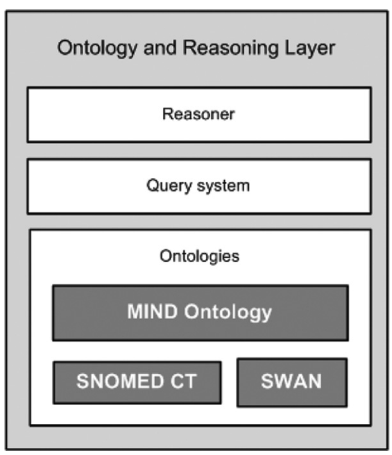

FIGURE 2 Proposed structure of the ontology and reasoning layer.

metabolomical, and genetic tests. It is mapped to both SWAN and SNOMED CT.

The intrinsic semantics embedded in the ontologies can lead to the discovery of new knowledge, such as diagnoses from implicit knowledge or new connections in the model when queried and inferred using production rules and description logic (DL) reasoners. Our domain experts have generated a set of production rules that drive the semantic reasoning (Sanchez et al. 2011). They follow an if–then–else structure and the syntax is inspired in RuleML recommendation with minor changes given basically for usability reasons. Each rule has been endorsed by the corresponding bibliographic source (by means of the mapping to SWAN) and has also been weighted depending on its importance within the rule hierarchy. This importance was set by the criteria of our domain experts. Figure 3 depicts a production rule example.

The experience layer above is based on SOEKS and DDNA. It stores the experience of the user (the methodology and criteria used for the diagnosis process) in forms that represent the formal decision events in an explicit way. This experience is then applied, and new knowledge and new rules that drive the diagnosis are discovered by the system. In this way, not only are diagnoses suggested to physicians but new or modified rules to achieve those diagnoses are also supplied. In the next section the evolution process of the rule set with the use of SOEKS and DDNA is explained in detail.

Finally, the application layer deals with the interaction between the user and the system. A graphical user interface (GUI) gathers the inputs given by users and presents the results to physicians to provide support for decision making. Figure 4 depicts the diagnosis inferred by the system and presented to physicians.


```
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<RuleSet>
    <LoadRule>
        <RuleID>HUVR_1</RuleID>
        <Rule>if (( CLASS InformacionClinicaNeurologica with the PROPERTY InformacionClinicaNeurologica_E
        <weight>1</weight>
        <AccordingTo>
            <classes>
                <class>JournalArticle</class>
            </classes>
            <contributionAuthors>
                <contributionAuthor>Rafael Blesa</contributionAuthor>
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FIGURE 3 Production rule example.

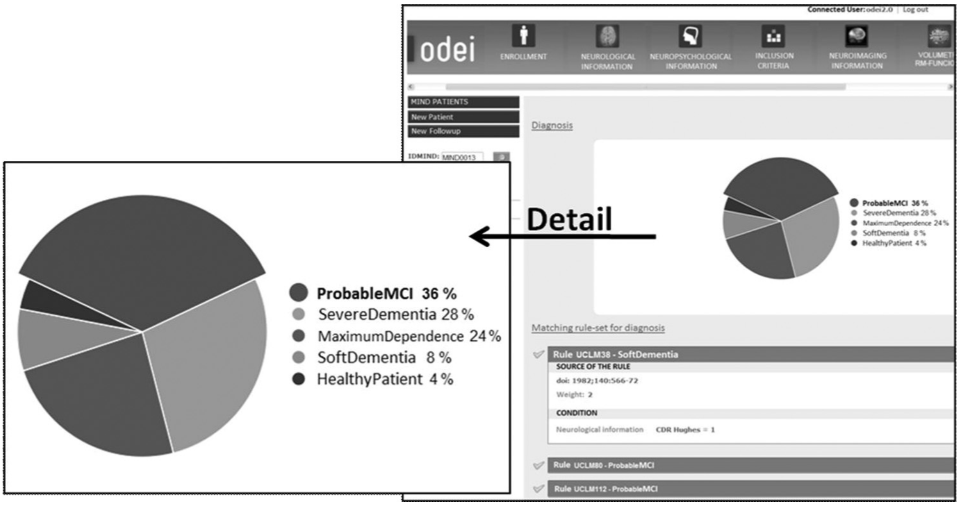

FIGURE 4 Suggested diagnosis from the system (partial view).

EVOLVING THE SET OF RULES USING SOEKS

As a type of decision maker, medical experts base their current decisions on lessons learned from previous similar situations, which in the context of Alzheimer's diagnosis are represented by studies performed on several groups of patients in different contexts. In spite of the wide range of scenarios considered by medical studies, the rules and conditions that are derived from them may prove to be insufficient, too general, or simply not relevant in scenarios with very particular characteristics. This situation clearly illustrates the need for an automated solution capable of determining adaptability in the set of rules of the diagnosis system, with the purpose of increasing the accuracy and effectiveness of the diagnoses made by medical experts. We propose the use of DDNA and SOEKS in their OWL form (Sanin et al. 2007) as a novel way of attaining this behavior.

The proposed integration takes existing decisions made by experts stored in the system and feeds them into SOEKS/DDNA ontology. Each decision is translated into its corresponding SOEKS equivalent, and then the system is able to infer new rules in three categories:

- Fine-tuned rules: a combination of existing rules to generate a new one.
- Deprecated rules: rules that are deemed not to be relevant anymore based on previous experiences.
- Original rules: rules discovered by the system that were not apparent to the experts.

In order to successfully accomplish the extension described previously, some considerations have to be taken into account. First of all, rules in the ontology and reasoning layer are defined by experts; in other words, they are heuristics representing the experience of several medical practitioners, which means that they are decisions. Secondly, for the knowledge stored in the ontologies of the system, several restrictions on the possible values that the variables can take have been defined but mathematical functions that relate the different variables in an independent/dependent form have not.

For the aforementioned considerations, the different SOEKS that are created based on this existing decisions (i.e., heuristics) are considered a special type of SOEKS. A SOEKS resulting from the parsing process will not have any functions or rules; instead, each heuristic represents an experience, which is comprised at this stage of variables and constraints. This approach reflects the decision-making process performed by the medical staff in a more precise way, based on rules derived from scientific studies, where each rule is a decision drawn upon experience.

CASE STUDY

The implementation of the proposed experience-based CDSS is being developed as part of the Spanish MIND project (http://www.portalmind.es), which follows a multidisciplinary approach for the early detection of AD. Clinical trials have been performed on more than 350 patients in three hospitals in Valencia, Spain, with the intention of gathering information about the early diagnosis of MCI patients evolving to AD. The CDSS described in this article is a technological tool that supports the work of physicians during the clinical trials. This section describes the current implementation of the system, which uses the Protégé OWL Application Programming Interface (API) as the mechanism to create and manipulate OWL-DL ontologies. In addition, an outline of the future implementation of the SOEKS/DDNA integration and rule discovery process is presented; however, the details of the inference procedure required to execute such a process are outside the scope of this article.

Initially, the system requires data from the different trials performed on the patients. Such data are gathered via a Web-based system called ODEI. When new data are loaded, the Mind ontology is instantiated using the information provided by users through ODEI's user interface. Then, a semantic reasoning process based on the initial set of production rules is executed with the objective of inferring diagnoses. An evaluation of the inferred diagnoses and decisions on the appropriate course of action are made by the physicians; their final decisions are loaded to the SOEKS/DDNA ontology.

As described in the previous section, a translation and inference process between the SOEKS/DDNA ontology is required. However, performing such translation process on a one-on-one basis every time a record is inserted is not practical; it is time consuming with a large number of concurrent users and may lead to inaccurate results when the system is "learning" (i.e., has little or no experiences in its initial state). This last issue is due to the fact that an accurate inference requires the evaluation of similar elements or situations; therefore, numerous experiences are preferred in order to execute the automated inference process.

Consequently, a microbatch approach is proposed, similar to those used in data warehouses, that allows processing a reasonable amount of data without the heavy workload of large batch processes or the inherent infrastructure complexity required for real-time or near real-time processing. Additionally, processing small batches of knowledge allows the system to deliver better inference results even when the system is still learning. According to these ideas, the batch process to load the SOEKS/DDNA ontology has two main steps: (1) translate knowledge between ontologies and (2) execute the inference process. As mentioned previously, the details regarding step 2 are outside the scope of this article.

The translation process will use a parser in charge of reading the knowledge from the Mind ontology, extracting the details of all OWL classes, individuals, and attributes and inserting them into the SOEKS/DDNA ontology using the SOEKS API. This API is a Java-based library that provides the means to create, manipulate, and import/export SOEKS in XML or OWL formats; the API was developed by the Knowledge Engineering Research Team (KERT) from the University of Newcastle, Australia.[1] The parser will comprise three main submodules: one to extract classes, one for variables, and one to extract constraints. Each module will create an image in memory of the SOEKS that is being processed, which is written to the SOEKS/DDNA ontology once the extraction is finished. To illustrate the functionality of the modules, we use an example production rule. It is assumed that the variables and restrictions in the following example are already stored in the Mind ontology:

```
IF((CLASS NeuropsychologicalInformation WITH THE PROPERTY
NeuropsychologicalInformation_FAQPfeffer GREATER THAN 5)) AND (CLASS
NeuropsychologicalInformation WITH THE PROPERTY NeuropsychologicalInformation_GDS SMALLER
THAN 6) THEN (( CLASS Diagnosis WITH THE PROPERTY Diagnosis_ReasonedDiagnosis EQUALS TO
ProbableAlzheimer ) AND (CLASS Diagnosis WITH THE PROPERTY Diagnosis_ReasonedRisk EQUALS
TO Low))
```

In the first place, the class module reads every class in the Mind ontology and translates them into individual SOEKS. In the example, we have

[1]Visit http://www.newcastle.edu.au/school/engineering/research/KERT/ for more information.

the classes NeurophsycologicalInformation and Diagnosis; as a result, two SOEKS instances (i.e., two experiences) are created as follows:

```
SOEKS NeurophsycologicalInformation =new SOEKS();
Category cat=new Category();
cat.setArea("Neuro Psychological Information");
NeurophsycologicalInformation.setCategory(cat);

SOEKS Diagnosis =new SOEKS();
cat.setArea("Diagnosis");
Diagnosis.setCategory(cat);
```

Each of these experiences has different variables. For the NeurophsycologicalInformation class, the variables are FAQPfeffer and GDS, and for the Diagnosis class, the variables are ReasonedDiagnosis and ReasonedRisk; therefore, the variable module will create two variables as shown below:

```
Variable FAQPfeffer =new Variable("FAQPfeffer",
                                    Variable.VARIABLE_TYPE_NUMERICAL,

                                     causeValue,effectValue,unitType,true);

Variable GDS =new Variable("GDS ",
                                      Variable.VARIABLE_TYPE_NUMERICAL,

                                     causeValue,effectValue,unitType,true);
Variable ReasonedDiagnosis =new Variable("ReasonedDiagnosis",

                                     Variable.VARIABLE_TYPE_CATEGORICAL,

                                     causeValue,effectValue,unitType,true);
Variable ReasonedRisk =new Variable("ReasonedRisk",

                                     Variable.VARIABLE_TYPE_CATEGORICAL,

                                     causeValue,effectValue,unitType,true);
```

The previous code fragment illustrates the process of creating SOEKS variables in memory. Each variable is assigned a name, a type (numerical or categorical), cause-and-effect values, the unit of measurement, and a flag to indicate if it is internal or external. The cause-and-effect values represent the variable in its current and desired states, respectively; the unit of measurement of the variable being processed is defined by the experts; and the internal/external flag indicates whether the variable can be controlled by the decision maker or not.

Once the SOEKS and its variables are created, the constraints module will read the OWL properties and constraints for every variable and construct the constraints elements in memory. For example, according to the production rule, FAQPfeffer is greater than 5; therefore, a constraint based on this knowledge should look like this:

```
Constraint FAQ_Constraint=new Constraint();
               FAQ_Constraint.value(5);
               FAQ_Constraint.symbol(">");
               FAQ_Constraint.variable(FAQPfeffer);
```

This process is repeated for every constraint and variable in the system. The last step before inserting the experience into the SOEKS/DDNA ontology is to link all of the elements of each SOEKS together. To do this, we will create a set of variables and a set of constraints that will be added the individual experiences. The following code fragment illustrates the process with the NeuropsychologicalInformation SOEKS.

```
VariableSet varSet=new VariableSet();
varSet.add(FAQPfeffer);
varSet.add(GDS);
NeurophsycologicalInformation.setSetOfVariables(varSet);

ConstraintSet consSet=new ConstraintSet();
consSet.add(FAQ_Constraint);
NeurophsycologicalInformation.setSetOfConstraints(consSet);
```

Finally, the translation process will write the SOEKS to an OWL-DL ontology. This is done by simply calling the soeksToOWL( ) method provided by the SOEKS API. After all of the experiences in the batch are translated using the ideas described before, the inference process is executed to discover new rules according to the categories described in the previous section. Then, assuming the existence of more knowledge in the system, under specific conditions and after validation against other experiences, the inference process might be able to determine that the values obtained from the Folstein test and the probabilities of suffering from AD are related. As a result, the original rule discovered by the system could be as follows (assuming the existence of other experiences in the system):

```
IF ((CLASS NeuropsychologicalInformation WITH THE PROPERTY
NeuropsychologicalInformation_MMSEfolstein SMALLER THAN 16 )
THEN ( CLASS Diagnosis WITH THE PROPERTY Diagnosis_ReasonedDiagnosis EQUALS TO
ProbableAlzheimer)
```

As a result of the extension of the system with the experience layer using SOEKS and DDNA the system is able to discover new knowledge and rules using bio-inspired techniques and the reasoning capabilities offered by ontologies. By using these methods, the system acts as an advisor for physicians and supports their decisions.

CONCLUSIONS AND FUTURE WORK

In this article we presented an experience-based CDSS for the diagnosis of AD that enables the discovery of new knowledge and new rules in the system. The process that leads to this discovery has also been presented and discussed, as well as a case study of the system.

This system supports physicians during diagnosis processes, but it is also a research tool that could help them determine the most relevant parameters for the diagnosis of AD and its cause.

The system proposed in this article is arguably very promising, because it does not rely only on the criteria given by the domain experts providing the rule set but also relies on the experience of the domain experts that are using the system. With this experience, some of the rules may be modified or some other may be generated in order to have a more accurate rule set.

SOEKS has been shown to be a valid technology for the discovery of new rules. As future work we are working on the extension of the SOEKS to not only discover new rules but to make decisions based on previous ones. We will also work on the measurement of the quality of the captured and generated experience.

The use of SOEKS and DDNA in this project is a contribution in the field of decision support systems that takes existing elements from rule-based and expert systems to create an intelligent experience-based system.

The CDSS presented in this article could also be extended to cover other areas in the domain of AD, such as drug discovery, as well as extended to other purposes, such as treatment or patient monitoring. It could also be applied to other domains—for example, cancer or sclerosis—where the discovery of new knowledge, and especially new rules, plays a fundamental role.

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REFERENCES

Ciccarese, P., Wu, E., Wong, G., Ocana, M., and Kinoshita, J. "The SWAN Biomedical Discourse Ontology." *Journal of Biomedical Informatics* 41 (2008): 739–51.

Gnanambal, S. and Thangaraj, M. "Research Directions in Semantic Web on Healthcare." *Journal of Computer Science* 1 (2010): 449–53.

Gruber, T. R. "Toward Principles for the Design of Ontologies Used for Knowledge Sharing." *International Journal of Human–Computer Studies* 43, nos. 5–6 (1995): 907–28.

Houshiaryan, K., Kim, H. S., Kim, H. H., Tung, T., Kim, I. K., Kwak, Y. S., and Cho, H. "Customized Ontology-Based Intelligent Medical Terminology Tool." In *Proceedings of 7th International Workshop on Enterprise Networking and Computing in Healthcare Industry*, edited by H. K. Choi, 320–24. Piscataway, NJ: IEEE, 2005.

Hussain, S., Abidi, S. R., and Abidi, S. S. R. "Semantic Web Framework for Knowledge-Centric Clinical Decision Support Systems." *Artificial Intelligence in Medicine* 4594 (2007): 451–5.

Lindgren, H. "Towards Personalized Decision Support in the Dementia Domain Based on Clinical Practice Guidelines." *User Modeling and User-Adapted Interaction* 21, nos. 4–5 (2011): 1–30.

Liu, J., Wyatt, J. C., and Altman, D. G. "Decision Tools in Health Care: Focus on the Problem, Not the Solution." *BMC Medical Informatics and Decision Making* 6, no. 4 (2006).

Michalowski, W., Slowinski, R., Wilk, S., Farion, K. J., Pike, J., and Rubin, S. "Design and Development of a Mobile System for Supporting Emergency Triage." *Methods of Information in Medicine* 44, no. 1 (2005): 14–24.

MIND Consortium, 2009. Home page of the MIND project. Available at: http://www.portalmind.es (accessed 1 February 2012).

Monien, B., Apostolova, L., and Bitan, G. "Early Diagnostics and Therapeutics for Alzheimer's Disease—How Early Can We Get There?" *Expert Review of Neurotherapeutics* 6 (2009): 1293–1306.

Nyström, M., Vikström, A., Nilsson, G. H., Ahlfeldt, H., and Orman, H. "Enriching a Primary Health Care Version of ICD-10 Using SNOMED CT Mapping." *Journal of Biomedical Semantics* 1, no. 7 (2010).

Protégé, 2012. Protégé OWL API. Available at: http://protege.stanford.edu/plugins/owl/opi/ (accessed 1 February 2012).

Sanchez, E., Toro, C., Carrasco, E., Bonachela, P., Parra, C., Bueno, G., and Guijarro, F. "A Knowledge-Based Clinical Decision Support System for the Diagnosis of Alzheimer Disease." Paper presented at the 13th IEEE International Conference on e-Health Networking, Application & Services (Healthcom 2011), 13–15 June 2011, 355–61, Columbia, MO.

Sanin, C., Mancilla-Amaya, L., Szczerbicki, E., and Cayford Howell, P. "Application of a Multi-Domain Knowledge Structure: The Decisional DNA." In *Intelligent Systems for Knowledge Management*, vol. 252, edited by N. T. Nguyen and E. Szczerbicki, 65–86. Berlin: Springer, 2009.

Sanin, C. and Szczerbicki, E. "Set of Experience: A Knowledge Structure for Formal Decision Events." *Foundations of Control and Management Sciences* 3 (2005): 95–113.

Sanin, C. and Szczerbicki, E. "Decisional DNA and the Smart Knowledge Management System: A Process of Transforming Information into Knowledge." In *Techniques and Tools for the Design and Implementation of*

Enterprise Information Systems, edited by A. Gunasekaran, 149–75. New York: IGI Global, 2008.

Sanin, C. and Szczerbicki, E. "Experience-Based Knowledge Representation: SOEKS." *Cybernetics and Systems* 40, no. 2 (2009): 99–122.

Sanin, C., Szczerbicki, E. and Toro, C. "An OWL Ontology of Set of Experience Knowledge Structure." *Journal of Universal Computer Science* 13, no. 2 (2007): 209–23.

Toro, C., Sanin, C., Szczerbicki, E., and Posada, J. "Reflexive Ontologies: Enhancing Ontologies with Self-Contained Queries." *Cybernetics and Systems* 39 (2008): 171–89.

Toro, C., Sanin, C., Vaquero, J., Posada, J., and Szczerbicki, E. "Knowledge Based Industrial Maintenance Using Portable Devices and Augmented Reality." In *Knowledge-Based Intelligent Information and Engineering Systems. 11th International Conference, KES 2007, XVII Italian Workshop on Neural Networks*, edited by B. Apolloni, R. J. Howlett and L. Jain, 295–302. Berlin: Springer, 2007.

Wright, A. and Sittig, D. F. "A Four-Phase Model of the Evolution of Clinical Decision Support Architectures." *International Journal of Medical Informatics* 77, no. 10 (2008): 641–9.

Yu, W. D. and Jonnalagadda, S. R. "Semantic Web and Mining in Healthcare." In *Proceedings of the 11th IEEE International Conference on e-Health Networking, Applications and Services*, 17–19 August 2006, 198–201, New Delhi, India.

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Decisional DNA: A multi-technology shareable knowledge structure for decisional experience

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ABSTRACT

Knowledge representation and engineering techniques are becoming useful and popular components of hybrid integrated systems used to solve complicated practical problems in different disciplines. These techniques offer features such as: learning from experience, handling noisy and incomplete data, helping with decision making, and predicting capabilities. In this paper, we present a multi-domain knowledge representation structure called Decisional DNA that can be implemented and shared for the exploitation of embedded knowledge in multiple technologies. Decisional DNA, as a knowledge representation structure, offers great possibilities on gathering explicit knowledge of formal decision events as well as a tool for decision making processes. Its applicability is shown in this paper when applied to different decisional technologies. The main advantages of using the Decisional DNA rely on: (i) versatility and dynamicity of the knowledge structure, (ii) storage of day-to-day explicit experience in a single structure, (iii) transportability and shareability of the knowledge, and (iv) predicting capabilities based on the collected experience. Thus, after analysis and results, we conclude that the Decisional DNA, as a unique multi-domain structure, can be applied and shared among multiple technologies while enhancing them with predicting capabilities and facilitating knowledge engineering processes inside decision making systems.

1. Introduction

Now-a-days, engineering systems are established on evolving paradigms; knowledge and users' experience take a big role in today's applications as we have now the computational potential of modeling such paradigms. The term knowledge engineering (KE) has been defined as a discipline that aims to offering solutions for complex problems by the means of integrating knowledge into computer systems [1]. It involves the use and application of several computer science domains such as artificial intelligence, knowledge representation, databases, and decision support systems, among others. Knowledge engineering technologies make use of the synergism of hybrid systems to produce better, powerful, more efficient and effective computer systems. Among the features associated with knowledge engineering systems are human intelligence capabilities such as learning, reasoning and forecasting from current knowledge or experience. From an application point of view, different research projects have been presented by the scientific community involving knowledge representation and decision making technologies to extend the user's understanding; however, to our acquaintance, most of these approaches miss the potential of using knowledge based theories that might enhance the user's experience and at the same time creating his/her decisional fingerprints.

In our case, we propose experience as the main and most appropriate source of knowledge and its use leads to useful systems with improved performance. Multiple applications perform decisions, and most of the decisions are taken in a structured and formal way, this is what we call formal decision events. All these formal decision events are usually disregarded once the decision is made, or even worst, if the system is queried again, the decision has to be repeated. What to do with the experience gained on taking such decisions relies on our proposed knowledge representation structure. We propose the Decisional DNA as a unique and single structure for capturing, storing, improving and reusing decisional experience. Besides, we make use of the Set of Experience (SOE) as part of the Decisional DNA which allows the acquisition and storage of formal decision events in a knowledge-explicit form. It comprises variables, functions, constraints and rules associated in a DNA shape allowing the construction of the Decisional DNA of an organization. Having a powerful knowledge

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structure such as the Set of Experience Knowledge Structure (SOEKS) within the Decisional DNA can enrich and develop any decisional system based upon previous experience.

This paper presents the Decisional DNA as a multi-domain knowledge structure that provides additional support by constructing a decisional repository, i.e., decisional fingerprints. Additionally, such decisional repository, since it is multi-technology applicable, can be shared and distributed enhancing the user's decisional experience. We present its application into four technologies: Decisional DNA Ontology-based knowledge Structure, Reflexive Ontologies, Embedded Systems, and Decision Support Medical Systems. We have chosen these technologies due to their noticeable advantages of being wide spread technologies that are developing the Artificial Intelligence (AI) scientific field. This paper is organized as follows: In Section 2, an overview of the conceptual basis is presented. In Section 3, we introduce four technologies implementing the Decisional DNA knowledge structure. And in Sections 4 and 5, we present our conclusions and lines for future work.

2. Conceptual basis and background

Humanity has always being accompanied by knowledge. Both have grown together to construct what we understand now as society and civilization. Hence, humankind has been trying to make knowledge part of its assets. Knowledge seems to be a valuable possession of incalculable worth and it has been considered as the only true source of a nation's economic and military strength as well as, the key source of competitive advantage of a company [2]. Thus, humankind in general and, more specifically, managers have turned to knowledge administration. They want technologies that facilitate control of all forms of knowledge because such technologies can be considered as the key for the success or failure of an organization, and subsequently, knowledge society. Knowledge itself appears as a human being attribute and can be defined as [3]: *(i)* theoretical or practical expertise and skills gained by a person through experience or education, or *(ii)* familiarity gained by experience of a fact or situation.

One theory suggests that situation assessments are the base for experienced decision-makers when taking decisions [4]. Decision-makers principally use experience for their decisions, i.e., when a decision event emerges, managers select actions that have worked well in previous similar situations. Then, in a brain process that is not well understood yet, managers extract the most significant characteristics from the current circumstances, and relate them to similar situations and actions that have worked well in the past. Therefore, this theory suggests that any mechanism that supports the process of storing previous decisions would improve the decision maker's job; and as such, it is related to a process of storing knowledge and experience.

Since this paper tackles problems in the engineering and computer fields, we concentrate on the concept knowledge engineering (KE). According to Feigenbaum [1], "Knowledge Engineering (KE) is an engineering discipline that involves integrating Knowledge into computer systems in order to solve complex problems normally requiring a high level of human expertise". Two main movements surround KE, they are: the transfer movement and the modeling movement. The transfer movement aims for techniques to transfer human knowledge into the artificial intelligent systems. The modeling movement aims for modeling the knowledge and problem solving techniques of the domain expert into the artificial intelligent system. Our research concentrates on the modeling trend which requires the areas of knowledge representation (KR) and knowledge modeling. Therefore, KE [5] depends on computer science in general, trying to mimic knowledge in a certain domain and within the scope of an artificial system. This definition involves not only the need for specific technologies, but also the need to overcome related implementation issues.

From a mechanistic point of view, reasoning in machines is a computational process. This computational process, to be feasible, definitely needs systemic techniques and data structures, and in consequence, several techniques have been developed trying to represent and acquire knowledge. These kinds of technologies try to collect and administer knowledge in some manner. Although these technologies work with decision-making in some way, they lack of keeping structured knowledge of the formal decision events they participate on [6]; they do not use their experience. We formally define a *Formal Decision Event as a choice [decision] made or a commitment to act that was the result [consequence] of a series of repeatable actions performed in a structured manner.*

For us, any technology able to capture and store formal decision events as explicit knowledge will improve the decision-making process. Such technology will help by reducing decision time, as well as avoiding repetition and duplication in the process.

Unfortunately, computers are not as clever as to form internal representations of the world, and even simpler, representations of just formal decision events. Instead of gathering knowledge for themselves, computers must rely on people to place knowledge directly into their memories. This problem suggests deciding on ways to represent information and knowledge inside computers.

A Knowledge Representation (KR) is fundamentally a replacement, a substitute for the thing itself. KR is an element of intelligent reasoning, a medium for organizing information to facilitate making inferences and recommendations, and a set of ontological commitments, i.e., an answer of how to interpret the world [7]. KR has been involved in several science fields; however, its main roots come from three specific areas: logic, rules, and frames. They appear as the most generalized techniques, and symbolize the kinds of things that are important in the world; even though developed systems can use exclusively one of the techniques, their hybridization is a common element. Logic implicates understanding the world in terms of individual entities and associations between them. Rule-based systems view the world in terms of attribute-object-value and the rules that connect them. Frames, on the other hand, comprise thinking about the world in terms of prototypical concepts. Hence, each of these representation techniques supplies its own view of what is important to focus on, and suggests that anything out of this focus may be ignored [7]. Recent advances in the field of KR have converged on constructing a Semantic Web, an extension of the current World Wide Web, looking for publishing information in a form that is easily inferable to both humans and machines. Current progresses have led to the standardization of the Web Ontology Language (OWL) by the World Wide Web Consortium (W3C). OWL provides the means for specifying and defining ontologies, that is, collections of descriptions of concepts in a domain (classes), properties of classes, and limitations on properties. OWL can be seen as an extension from the frame based approach to knowledge representation, and a division of logic called Description Logics (DL) [8].

These KR techniques have been implemented with different data structures creating a universe of knowledge as big as the number of applications researchers and IT companies have developed. These technologies have been developed to make useful huge quantities of stored information by modeling knowledge in some way; however, none of them keep an explicit record of the decision events they participate on. Hence, it is necessary to define a multi-domain shareable knowledge structure able to be adaptable and versatile as to capture all these different decision events from the day-to-day operation, to store proper characteristics of the experience acquired, to keep this experience as explicit knowledge, and to allow it for multiple technologies to be used, analyzed, and categorized.

This paper presents four technologies that use Decisional DNA (and the Set of Experience Knowledge Structure – SOEKS – within it) as the knowledge representation. Decisional DNA is offered as a solution to be utilized for the aims mentioned above. Decisional DNA and SOEKS certainly improve KE and the quality of decision-making by advancing the notion of administering knowledge in the current decision making environment.

2.1. Set of experience knowledge structure (SOEKS) and Decisional DNA

In living species, Deoxyribonucleic Acid (DNA) is a nucleic acid found in cells that carries genetic information, and is the molecular basis of heredity. DNA is made from a combination of four basic elements called nucleotides. These nucleotides are Adenine (A), Thymine (T), Guanine (G) and Cytosine (C). Their combination allows for the different characteristics of each individual, and becomes as one of the highlighted uniqueness of this kind of structure. One part of the long strand comprises a gene. A gene is a portion of a DNA molecule, which guides the operation of one particular component of an organism. Genes give orders to a living organism about how to respond to different stimuli. Finally, a set of genes makes a chromosome, and multiple chromosomes make the whole genetic code of an individual [9]. DNA demonstrates unique aspects as a data structure [10]. Information about the living organism is kept to be passed on to future generations, as well as being the basis of new elements in the organism which are evaluated in terms of performance. DNA stores information for the survival of the species, and improvement in the evolutionary chain.

In our research and taking experience as one of the most valuable ways to acquire knowledge, we rely on computers as in important mean to capture it. However, computers must depend on human beings to enter knowledge directly into them. Thus, the problem is how to adequately, efficiently, and effectively represent information and knowledge inside a computer.

Based upon the DNA concept and using it as a metaphor, we developed the Set of Experience Knowledge Structure (SOEKS) as a form to keep FDE in an explicit way [6]. It is a model based upon existing and available knowledge, which must adjust to the decision event it is built from (i.e., it is a dynamic structure that relies on the information offered by a FDE). Four basic components surround decision-making events and FDE, and are stored in a combined dynamic structure that comprises the SOE (Fig. 1); they are: *variables V, functions F, constraints C,* and *rules R*.

Variables usually involve representing knowledge using an attribute-value language (i.e., by a vector of variables and values) [11]. This is a traditional approach from the origin of knowledge representation, and is the starting point for the SOEKS. Variables that intervene in the process of decision-making are the first component of the SOE. These variables are the center root of the structure, because they are the source of the other components.

Based on the idea of Malhotra [12] who states that "to grasp the meaning of a thing, an event, or a situation is to see it in its relations to other things" (p. 51), variables are related among them in the shape of functions. Functions describe associations between a dependent variable and a set of input variables; moreover, functions can be applied for reasoning optimal states, because they come out from the goals of the decision event. Therefore, the SOE uses functions, its second component, and establishes links among the variables constructing multi-objective goals, that is, multiple functions that restrict experience on decision-making by the elements of a universe of relationships.

According to Theory of Constraints (TOC), Goldratt [13] maintains that any system has at least one constraint; otherwise, its performance would be infinite. Thus, constraints are another way of relationships among the variables; in fact, they are functions as well, but they have a different purpose. A constraint, as the third component of SOEKS, is a limitation of possibilities, a restriction of the feasible solutions in a decision problem, and a factor that limits the performance of a system with respect to its goals.

Finally, rules are suitable for representing inferences, or for associating actions with conditions under which the actions should be done. Rules, the fourth component of SOEKS, are another form of expressing relationships among variables. They are conditional relationships that operate in the universe of variables. Rules are relationships between a condition and a consequence connected by the statements IF-THEN-ELSE.

As stated above, SOE is a Knowledge Structure that is able to store and act as a repository of decisional experiences based upon FDE; therefore, functions and operations acting upon such knowledge structure are commonly operated actions performed on traditional computer-based structures. Many of these operations are based upon the specific technology that is applying the SOEKS, for instance, in [14], Sanin and Szczerbicki used SOE in combination with Genetic Algorithms (GA) techniques and therefore, the SOEKS absorbed GA operations such as finding individual fitness, mutations and crossover. Another example takes SOEKS to be implemented on Reflexive Ontologies (RO) [15]; in such case, Toro et al. create a SOEKS RO-based which uses RO operations, allowing SOEs to be operated by Union, Intersection and other set operations. Summarizing, SOEKS as a knowledge structure absorbs operations depending on the technology that applies it.

Furthermore, the SOEKS takes other important features of DNA. Firstly, the combination of the four nucleotides of DNA gives uniqueness to itself, just as the combination of the four components of the SOE offer distinctiveness. Moreover, the four elements of a SOE are connected among themselves imitating part

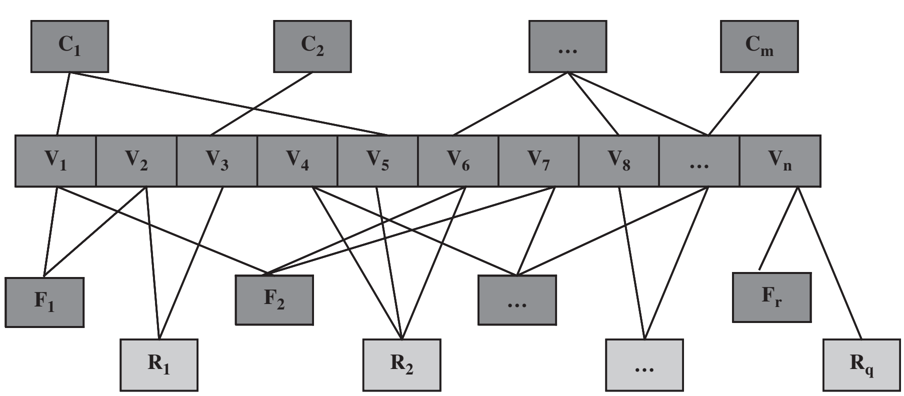

Fig. 1. Set of Experience Knowledge Structure (SOEKS).

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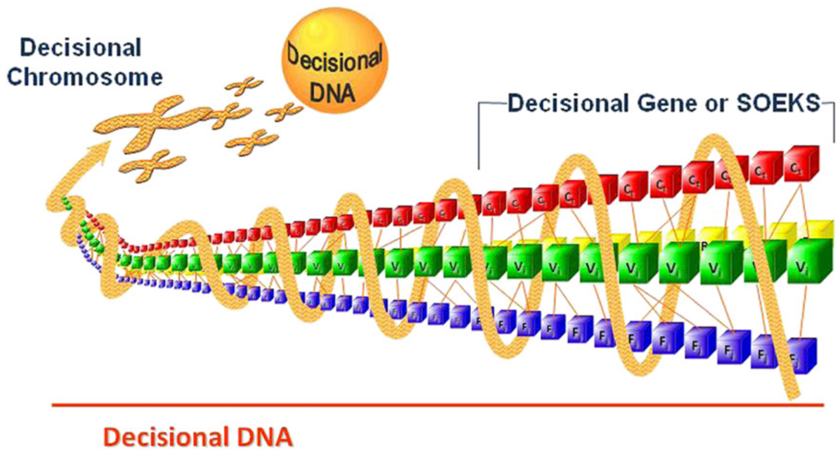

Fig. 2. SOEKS and Decisional DNA.

of a long strand of DNA, that is, a gene. Thus, a gene can be assimilated to a SOE, and in the same way as a gene produces a phenotype, a SOE produces a value of decision in terms of the elements it contains. Such value of decision can be called the efficiency or the phenotype value of the SOE [6]; in other words, the SOEKS, itself, stores an answer to a query presented. Each SOE can be categorized, and acts as a gene in DNA. A gene guides hereditary responses in living organisms. As an analogy, a SOE guides the responses of certain areas of decision making; in our case, a decisional gene.

A unique SOE cannot rule a whole system, even in a specific area or category. Therefore, more Sets of Experience should be acquired and constructed. The day-to-day operation provides many decisions (or FDE), and the result of this is a collection of many different SOE. A group of SOE of the same category comprises a decisional chromosome, as DNA does with genes. This decisional chromosome stores decisional "strategies" for a category. In this case, each module of chromosomes forms an entire inference tool, and provides a schematic view for knowledge inside an organization. Subsequently, having a diverse group of SOE chromosomes is like having the Decisional DNA of an organization, because what has been collected is a series of inference strategies related to such enterprise (Fig. 2).

In conclusion, the SOEKS is a compound of variables, functions, constraints and rules, which are uniquely combined to represent a FDE. Multiple SOE can be collected, classified, and organized according to their efficiency, grouping them into decisional chromosomes. Chromosomes are groups of SOE that can accumulate decisional strategies for a specific area of decision making. Finally, sets of chromosomes comprise what is called the Decisional DNA of the organization [6]. Furthermore, the Decisional DNA can be used in platforms to support decision-making, and new decisions can be made based on it. In this text a concise idea of the SOEKS and the Decisional DNA was offered, for further information [6] should be reviewed.

3. Constructing Decisional DNA

Applications involved in decision making produce myriads of FDE, i.e., decisional experience, their results are, in most cases, analyzed and stored; however, such decisional experience is commonly disregarded, not shared, and put behind [16–19]. Little of this collected experience survives, and in some cases, over time, it becomes inaccessible due to poor knowledge engineering practices or due to technology changes in software, hardware or storage media. Knowledge and experience are lost indicating that there is a clear deficiency on experience collection and reuse. We suggest that some of the reasons are:

(a) the nonexistence of a common knowledge–experience structure able to collect multi-domain and multi-technology formal decision events, and
(b) the nonexistence of a technology able to capture, store, improve, retrieve and reuse such collected experience.

Through our project, we proposed three important elements:

(i) a knowledge structure able to store and maintain experiential knowledge, that is, the Decisional DNA and the SOEKS,
(ii) a solution for collecting experience that can be applied to multiple technologies from different domains, that is, a multi-technology knowledge structure, and
(iii) a way to automate decision making by using such experience, that is, retrieve collected experience by answering a query presented.

In this paper, we introduce the reader to the three above mentioned elements throughout four different technologies: Decisional DNA Ontology-based knowledge Structure, Reflexive Ontologies, Embedded Systems – Interactive TV (iTV), and Decision Support Medical Systems for Alzheimer diagnosis. Nevertheless, we would like to add that Decisional DNA is not limited to these technologies and advances are being made with it in several areas. To our knowledge, multiagents systems, web engineering, and robotics are some additional technologies that are currently using Decisional DNA.

3.1. *Decisional DNA ontology-based knowledge structure and Reflexive Ontologies (RO)*

This section introduces our approach to model and apply Decisional DNA knowledge structure from an ontology perspective. In order to obtain such ontology, Decisional DNA XML-based was taken as the starting point. For a better understanding of Decisional DNA XML-based, the reader should refer to [20]. Afterward, an ontology model process was performed using the Protégé editor [21].

Reflexivity addresses the property of an abstract structure of a knowledge base (in this case, an ontology and its instances) to "know about itself". When an abstract knowledge structure is able to maintain, in a persistent manner, every query performed on it, and store those queries as individuals of a class that extends the original ontology, it is said that such ontology is reflexive.

Thus, Toro et al. [15] proposed the following definition for a Reflexive Ontology: "A Reflexive Ontology is a description of the concepts and the relations of such concepts in a specific domain, enhanced by an explicit self contained set of queries over the instances". Therefore, any RO is an abstract knowledge structure with a set of structured contents and relationships, and all the mathematical concepts of a set can be applied to it as a way of formalization and handling. A RO is, basically, an ontology that has been extended with the concept of reflexivity and must fulfill the properties of: query retrieval (storing every query performed), integrity update (updating structural changes in the query retrieval system), autopoietic behavior (capacity of self creation), support for logical operators (mechanisms of set handling), and self reasoning over the query set (capacity of performing logical operations over the query system). The advantage of implementing RO relies on the following main aspects: Speed on the query process, incremental nature, and self containment of the knowledge structure in a single file.

The purpose of this case study is to exemplify how the SOEKS-OWL is converted into a Reflexive Ontology by the use of the ReflexiveQueryStorer class and the changes it generates in such ontology; therefore, we start from a point where a SOEKS-OWL has been already instantiated with real values. Next step comprises the adaptation of the Reflexive Query Storer class with some initial values such as the path of the ontology, options of saving the reflexive structure and the query instances, and the type of query to be performed. For explanation purposes, three queries are included in this case study. The first query is defined in the code as: `public static String SIMPLE_RFLEXIVE_QUERY=''CLASS variable with the PROPERTY var_name EQUALS to X1'';` notice that this is a value type query. Such query is written in a human readable form, but in other terms, it means "retrieve all the variables of the ontology that have the variable name X1".

The execution of the code offers information about the type of query executed and the successful saving of the Reflexive Ontology Structure (created for first time) as well as the query executed with results. Following, the results can be seen as a query successfully executed with the new instance in the SOEKS-OWL transformed into a Reflexive Ontology (Fig. 3):

```
START
  Testing Simple query : CLASS variable with the
PROPERTY var_name EQUALS to X1
  ... saving successful.
  File modification saved with 0 errors.
  END
```

The next example includes a data type query: `public static String SIMPLE_RFLEXIVE_QUERY=''CLASS term with the PROPERTY withVariable EQUALS to X2_1`; or in other words it means "`retrieve all the terms in the ontology that involve the variable with name X2_1`". Its results are as follows (Fig. 4):

```
START
  Testing Simple query : CLASS term with the PROP-
ERTY withVariable EQUALS to X2_1
  ... saving successful.
  File modification saved with 0 errors.
  END
```

In these results can be seen that the term_2 and term_4 are valid for the query; in other words, those terms contain the X2_1 variable. One of the features of the Reflexive Ontologies is that when a new query comes, it is not necessary to perform it again, if it was already done. Finally, RO also allows performing complex queries which comprise autopoietic behavior and support for logical operations, and example is shown below.

```
START
  Testing Complex query : CLASS simfactor with the
PROPERTY hasSterm EQUALS to term_1 AND CLASS sim-
factor with the PROPERTY hasSterm EQUALS to term_2
  CLASS simfactor with the PROPERTY hasSterm EQUALS
to term_1 AND
  CLASS simfactor with the PROPERTY hasSterm EQUALS
to term_2
  Sub queries in query 2
  ... saving successful.
  File modification saved with 0 errors.
  END
```

As it has been shown, the Reflexive Ontolgy transformation includes the creation of a new class inside the ontology, in this case the SOEKS-OWL. Additionally, when different simple or complex queries (data type or value type) are executed, they are inserted as instances in the new Reflexive Ontolgy; this change facilitates the application of similarity elements among the Sets of Experience and it will allow an extended logic handling over the SOEKS as it comprises the self reasoning over the query set property of the RO.

A RO Decisional DNA-based model, once instanced, can be accessed through different queries, which would be developed according to similarity parameters [22] and users' requirements.

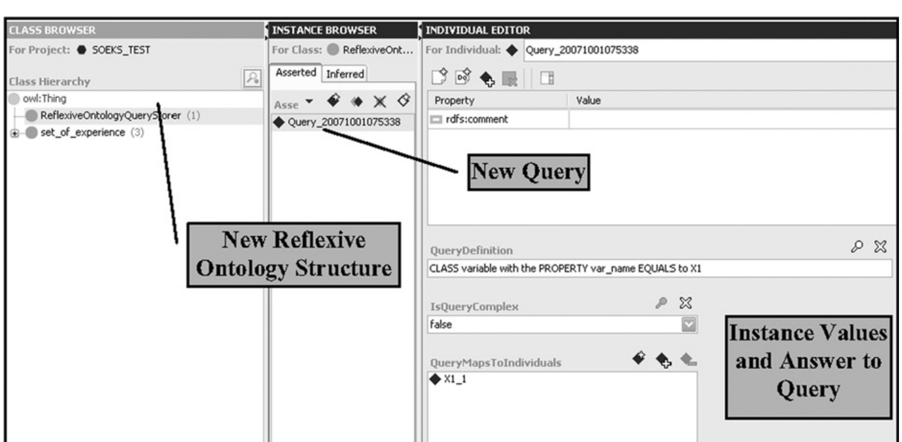

Fig. 3. SOEKS-OWL transformed into a Reflexive Ontology with its new elements.

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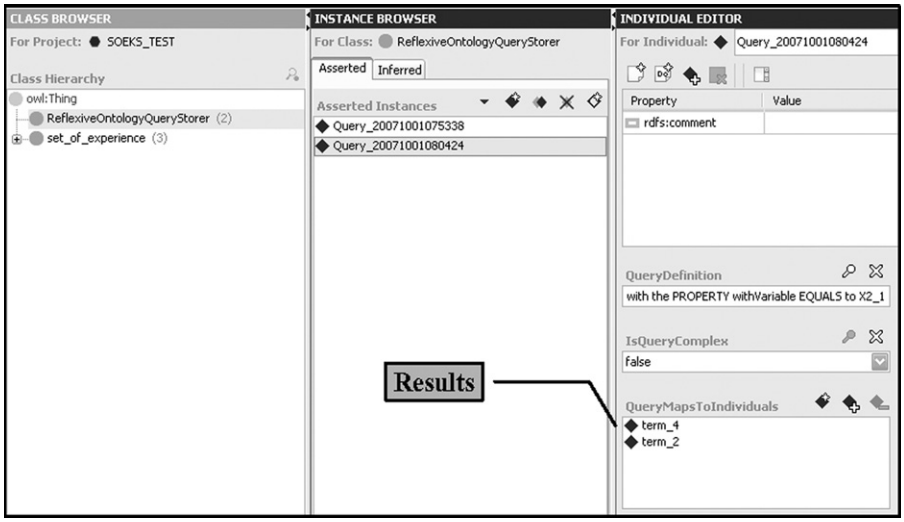

Fig. 4. SOEKS-OWL with a data type query executed.

A powerful representation, querying and inference capabilities are exploited in several ways. For instance, the ability to perform advanced queries on large sets of information with an optimal response time was exploited by means of Reflexive Ontologies (RO) [15,23].

As expressed by Nguyen [24], knowledge of a group is more appropriate than the individual knowledge; therefore, having an ontology-based repository ready to be feed with Decisional DNA produced by members of a decisional community is the beginning of a new way of sharing knowledge. The decisional community would share decisions among its members allowing decision-maker users to improve their day-to-day operation by querying such repository, and along with this interaction, the decisional community would increase and improve the Decisional DNA available for being shared.

3.2. Decisional DNA-based embedded systems

Embedded systems are computer systems created to implement one or a few dedicated functions [25] such as the control system in an elevator or the ABS (anti-lock braking systems) in a car. They are usually embedded as part of a complete system. Now-a-days, any device that includes a computer, but it is not a general-purpose computer itself, can be regarded as an embedded system [26]. ES range from household appliances like microwave ovens and washing machines, to industrial applications like automatic production lines and network switches; from portable devices such as MP3 players to very big equipments like nuclear power plants. Recent advances in microelectronics, IC (integrated circuit), communications, computing, software and other information technologies are influencing ES to be increasingly powerful and popular than ever. Such technologies are enabling ES to be built as what is required to meet all kinds of demands from our daily life [27].

In addition to embedded operating systems, software/firmware and middleware technologies for ES are making notable progress as well. Thanks to improvements on software, hardware and embedded operating systems, it is now possible to apply more mature approaches onto ES, like using regular Java, C or C++ compiler on the ES itself, making applications portability an easier job [27].

Knowledge-based embedded systems are the new trend on Embedded Systems (ES) and they can make our world increasingly intelligent and convenient. However, due to lack of standardized solutions and development platforms, it is very hard to share knowledge among different knowledge-based systems. Therefore, we present Decisional DNA-based embedded systems as an alternative for knowledge-based developments in this area which can potentially be applied on various systems and enable them with acquisition, reusing, evolving and sharing knowledge.

In order to use Decisional DNA on embedded systems, a series of required features were defined; they involved a transformation on the traditional Decisional DNA in order to make it a viable alternative for ES. Decisional DNA was then adapted to make it *adaptable and cross-platform portable* (not a problem since the Decisional DNA API is already written in Java), *Compact* and, *Configurable*.

3.2.1. Interactive TV Decisional DNA-based software architecture

Interactive television (also known as iTV) is an evolutionary integration of the Internet and Digital TV (DTV) [28]. It contains a number of novel smart technologies and enables viewers to interact with television services and content. The most exciting thing about an interactive TV is the ability to run applications that have been downloaded as part of the broadcast stream. For the user (viewer), this is what really makes a significant difference between a basic Digital TV box and an interactive TV system. In order to support and enable interactive applications, the receiver is required to support not only the implementation of APIs (Application Programming Interface) needed to run the applications, but also the infrastructure needed to inform the receiver what applications are available and how to run them.

Decisional DNA, as a domain-independent, flexible and standard knowledge repository, can not only capture and store experiential knowledge in an explicit and formal way, but can also be easily applied to various domains to support decision-making and standard knowledge sharing and communication among these systems [6] [29]. In this paper, we present an approach that integrates Decisional DNA with iTV to capture and reuse viewers' TV watching experiences. We have demonstrated this approach in order to test the usability and suitability of Decisional DNA in ES.

Decisional DNA iTV consists of the User Interface, the System I/O (input/output), the Integrator, the Prognoser, the Convertor and the Decisional DNA Repository (Fig. 5).

User Interface: The User Interface is developed to interact with the user/viewer. In particular, the user can control, set and

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configure the system, select services, give feedback, and interact with the service providers by using the User Interface.

System I/O: The System I/O allows the Decisional DNA iTV platform communicating with its domain of operation. The System I/O tells the iTV which service is selected, for example, what movie should play or what feedback was given, etc. Additionally, it is able to access and retrieve the media stream, viewers' feedback, system time, and service information from its domain.

Integrator: The Integrator is where the scenario data is gathered and organized. In our case, we link each decisional experience with a certain scenario describing the circumstances under which the experience is collected, such as the system time, name of a selected service, user input, and other service information. The Integrator organizes the scenario data and sends them to the Prognoser for further processing.

Prognoser: The Prognoser is in charge of sorting, analyzing, organizing, creating and retrieving collected experience. It sorts data received from the Integrator to further analyze and organize it according to system configurations. Finally, it interacts with the Decisional DNA Repository and the XML Parser in order to store and reuse experience depending on the purpose of different tasks.

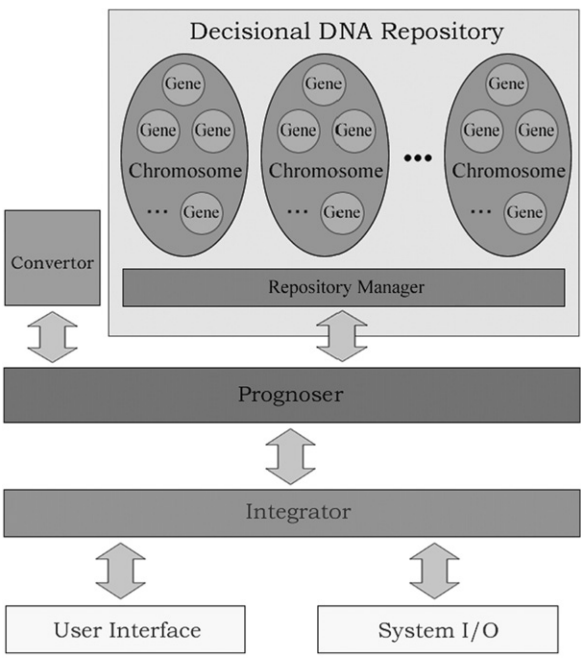

Fig. 5. System Architecture for Decisional DNA iTV.

Convertor: The Convertor translates knowledge statements generated by the Prognoser into the Decisional DNA structure and interprets the retrieved Decisional DNA experiences for future reusing. In this case, we used Decisional DNA XML-based.

Decisional DNA Repository: The Decisional DNA Repository is the core architecture component in the iTV approach. It is the place where experiences are stored and managed. It contains the Repository Manager which is the interface of the Decisional DNA Repository. It answers operation commands sent by the Prognoser and manages the Chromosomes.

3.2.2. *iTV case study*

At this stage, the main purpose of our experiments was to prove that Decisional DNA could be implemented with Java TV providing its domain with the ability of experience capturing and reusing. For testing the concept of Decisional DNA applied to iTV, we used Java TV SDK on a generic setup box (Digitel+HD3000) and considered only five types of movies, namely action, adventure, animation, comedy, and crime. We simulated viewers watching movies on the Decisional DNA iTV, where each movie was represented by its type and an ID number, for example Action1, Comedy2, and with 20 movies/type making a pool of 100 movies.

Fig. 6 shows a screenshot of the viewers' TV. As it can be seen, the viewers' screen is composed of five components: Service Name which shows "Movies", Service Information which displays information about a selected movie, Ranking of the selected movie, Movie Showcase which shows movies recommended by the system, and "Show More …" button where the viewer can access additional movies. Initially, Decisional DNA iTV recommends two movies from each movie type creating an initial selected group of 10 movies. Once the system start collecting experiences, it recommends movies according to those experiences.

We capture viewers' watching experiences by collecting movie and user's knowledge and information, that includes rules relating preferences, times, dates, actors, ranking, director, among others. Such knowledge is gathered and organized by the Integrator to be sent to the Prognoser, which finally, transforms and stores them into a SOEKS XML format. Once the system captures such experiences, it begins to analyze the viewers' watching

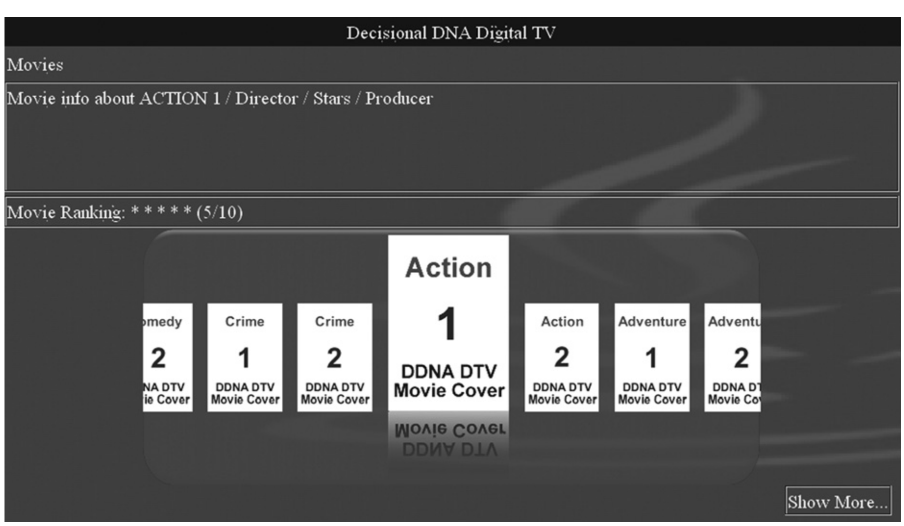

Fig. 6. Screenshot of Decisional DNA iTV.

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experiences and provides viewers with smart recommendations based on his/her past viewing experiences.

During the process in which the Prognoser recommends new movies to the viewer, it retrieves watching experiences stored in the Decisional DNA Repository and analyses those experiences from the perspective of the user's settings. In our experiments, we analyze the movie types, most frequent week day and time, and preferences collected in the Decisional DNA iTV for each viewer. At this stage, simple mathematical model have been implemented; however, more advanced mathematical models are in our future research agenda. For instance, Eq. (1) demonstrates how the system calculates the number of movies that should be considered for the movie recommendation list:

$$N = (T \times 100/D + 5)/10 \tag{1}$$

where N represents number of movies that should be recommended from a specific movie type; T tells us how many movies of a specific movie type have been watched on a given week day; D represents the total number of movies watched on that given week day. For example, suppose that there is a viewer who watched 11 movies in total during a given weekend and 5 of those movies were action movies. Therefore, according to (1) there should be five out of ten action movies in the next recommendation list: $(5 \times 100\ /\ 11 + 5)\ /\ 10 = 5$. During a number of weeks of capturing experience, the system learns and remembers that this viewer watched on average five action movies, two adventure movies, one animation movie, two comedy movies, and one crime movie on weekends so far. As the result, the system would recommend for this viewer similar a movie composition on the next Friday for the following weekend. Fig. 7 shows the screenshot of a newly recommended movie list in this case.

We presented an approach that integrates Decisional DNA with iTV allowing capturing and reusing viewers' TV watching experiences. Further research involves query enhancement, refinement and further development of the Prognoser algorithms, and implementation of more advanced ways to interpret the viewer experience.

3.3. Clinical decision support system Decisional DNA-based

The interest of making Clinical Decision Support Systems (CDSS) for the diagnosis of Alzheimer Disease (AD) is huge, as it is the leading cause of dementia in developed countries. Early diagnosis of AD is commonly carried out analyzing results of different medical tests, which are multidisciplinary by nature, such as neurological, neuropsychological, and neuroimaging tests [30]. During this process, large amounts of parameters are generated and making a proper diagnosis becomes a knowledge handling problem. CDSS help physicians overcome knowledge handling problems that they face in their work. During diagnosis processes, CDSS analyze data from medical tests and present results to physicians such that they can diagnose properly in a easily and efficiently from.

In this section, we present a CDSS that (i) supports physicians during diagnosis of AD and (ii) offers tools needed to fulfill the aforementioned need of discovering relevant parameters for this diagnosis. In fact, this CDSS is based on the experience acquired or learned from the user, and it enables the discovery of new knowledge in the system and the generation of new rules based on experience that drive the reasoning. Among several approaches that can be used to endow the proposed system with the ability of adapting and discovering rules when special conditions are encountered, we have chosen the Set Of Experience Knowledge Structure (SOEKS) and the Decisional DNA (DDNA) [6] [29] in their OWL form [31] as a novel way of attaining this behavior. These elements will allow the system to capture previous experiences and discover new knowledge using bio-inspired techniques and the reasoning capabilities offered by ontologies, for instance, the fast query systems presented by Toro et al. [15].

In our system, the experience of the physician while using our system is stored and, with this experience, the system is able to (i) *make explicit the implicit knowledge contained in the system* and (ii) *generate new criteria to drive reasoning*. Supporting our system are widely used ontologies within the medical domain; they are: the Semantic Web Application in Neuromedicine (SWAN) [32] and the Systematized Nomenclature of Medicine Clinical Terms (SNOMED CT) [33].

The CDSS system is based on Decisional DNA OWL based for the knowledge representation and a semantic reasoning process that inferred diagnoses for patients. The semantic reasoning was driven by a static set of production rules provided by AD experts. Its architecture consists of 5 layers: Data Layer, Translation Layer, Ontology and Reasoning Layer, Experience Layer and Application Layer. Among these layers, the Experience Layer is based on the SOEKS and the Decisional DNA, and it is in charge of storing users' experiences (the methodology and criteria used for the diagnosis process), in forms that represent FDE in an explicit way. This experience is then applied, and new knowledge and new rules that drive the diagnosis are discovered by the system. In this way,

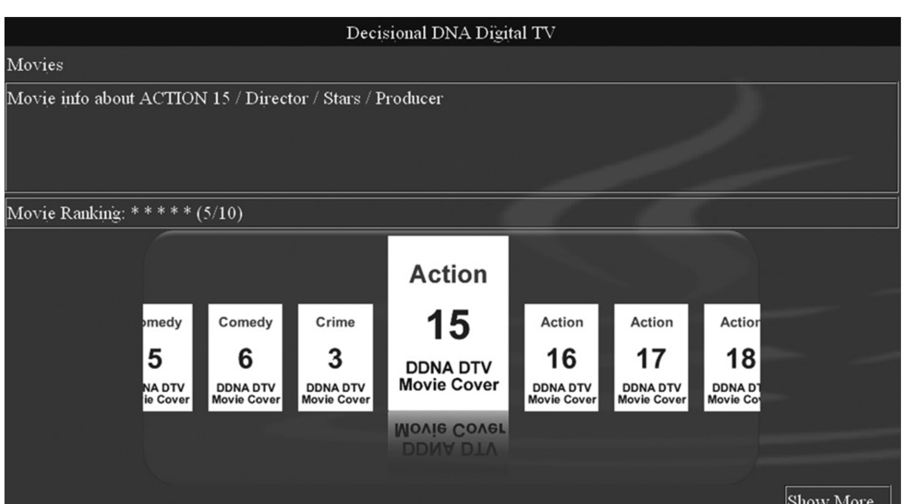

Fig. 7. Newly recommended movie list for the experimental viewer.

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physicians are suggested not only diagnoses but also new or modified rules to achieve those diagnoses.

The implementation of the CDSS Decisional DNA-based is being developed as part of the Spanish MIND project (http://www.portalmind.es), which follows a multidisciplinary approach for the early detection of AD. Clinical trials are being performed on more than 350 patients in three hospitals of Valencia (Spain), with the intention of gathering information about the early diagnosis of AD.

3.3.1. Evolving the set of rules by the means of Decisional DNA

As a type of decision-makers, medical experts also base their current decisions on lessons learnt from previous similar situations, which in the context of Alzheimer diagnosis are represented by studies performed on several groups of patients under different contexts. In spite of the wide range of scenarios considered by medical studies, the rules and conditions that derived from them may prove to be insufficient, too general, or simply not relevant in scenarios with very particular characteristics. This situation clearly illustrates the need for an automated solution capable of determining adaptability in the set of rules of the diagnosis system, with the purpose of increasing the accuracy and effectiveness of the diagnoses made by medical experts. The use of Decisional DNA takes existing decisions made by experts stored in the system and feed them into a SOEKS/DDNA ontology. Additionally, each decision is translated into its corresponding SOEKS equivalent, and then the system will be able to infer new rules in three categories:

- Fine tuned rules: combination of existing rules to generate a new one.
- Deprecated rules: rules are deemed not to be relevant anymore based on previous experiences.
- Original rules: rules discovered by the system which were not apparent to the experts.

In order to successfully accomplish the system's aim, some considerations were taken into account. Firstly, rules in the Ontology and Reasoning layer are defined by experts, in other words, they are heuristics representing the experience of several medical practitioners, which means they are decisions and when translated into SOEKS, they were considered as FDE. Second, for all knowledge stored in the ontologies, several restrictions on variables possible values have been defined, however, not mathematical functions that relate the different variables in an independent/dependent form were defined.

Initially, the system requires data from the different trials performed on the patients. Such data is gathered via a web-based system called ODEI. When new data is loaded, the MIND Ontology is instantiated using the information provided by users through ODEI's user interface. Then, a semantic reasoning process based on the initial set of production rules is executed with the objective of inferring diagnoses. An evaluation of the inferred diagnoses and decisions on the appropriate course of action are made by the physicians; their final decisions are loaded to the Decisional DNA ontology. As described previously, a translation and inference process between the SOEKS/Decisional DNA ontology is required. However, performing such translation process on a 1-on-1 basis is not practical, it is time consuming with a large number of concurrent users, and may lead to inaccurate results when the system is "learning" (i.e., has little or no experiences in its initial state). This last issue is caused because an accurate inference requires the evaluation of similar elements or situations; therefore, numerous experiences are preferred in order to execute the automated inference process. Consequently, a micro-batch approach is proposed, similarly to the ones used in data warehouses that allows processing a reasonable amount of data without the heavy workload of large batch processes, or the inherent infrastructure complexity required for real-time or near real-time processing. Additionally, processing small batches of knowledge allows the system to deliver better inference results even when the system is still "learning". The batch process loading the Decisional DNA ontology has two main steps, translating and inferencing. The translation process uses a parser in charge of reading the knowledge from the MIND ontology, extracting the details of all OWL classes, individuals and attributes and inserting them into the SOEKS-OWL form using the SOEKS API. This API is a Java-based library that provides the means to create manipulate and import/export SOEKS in XML or OWL formats. The parser comprises different sub modules, each module creates an image in memory of the SOEKS that is being processed, which is written to the Decisional DNA ontology once the extraction is finished. To illustrate the functionality of the modules, we use an example production rule. It is assumed that the variables and restrictions in the following example are already stored in the MIND ontology:

```
IF((CLASS NeuropsychologicalInformation WITH THE
PROPERTY  NeuropsychologicalInformation_FAQPfef-
fer GREATER THAN 5)) AND (CLASS Neuropsychologica-
lInformation        WITH        THE        PROPERTY
NeuropsychologicalInformation_GDS SMALLER THAN 6)
THEN (( CLASS Diagnosis WITH THE PROPERTY Diagno-
sis_ReasonedDiagnosis EQUALS TO ProbableAlzheimer
) AND (CLASS Diagnosis WITH THE PROPERTY Diagnosis_-
ReasonedRisk EQUALS TO Low))
```

In the first place, the class module reads every class in the MIND ontology and translates them into individual SOEKS. In the example, we have the classes NeurophsycologicalInformation and Diagnosis; as a result, two SOEKS instances (i.e., two experiences) are created, as follows:

```
SOEKS NeurophsycologicalInformation =new SOEKS();
  Category cat=new Category();
  cat.setArea(''Neuro   Psychological   Informa-
tion'');
  NeurophsycologicalInformation.setCategory(-
cat);
  SOEKS Diagnosis =new SOEKS();
  cat.setArea(''Diagnosis'');
  Diagnosis.setCategory(cat);
```

Each of these experiences has different variables. For the `NeurophsycologicalInformation` class, the variables are `FAQPfeffer` and `GDS`, and for the Diagnosis class, the variables are `ReasonedDiagnosis` and `ReasonedRisk`; therefore, the variable module creates two variables as shown below:

```
Variable   FAQPfeffer   =new   Variable(''FAQPfef-
fer'',Variable.VARIABLE_TYPE_NUMERICAL,causeVa-
lue,effectValue,unitType,true);
  Variable GDS =new
  Variable(''GDS'',Variable.VARIABLE_TYPE_NUMER-
ICAL,causeValue,effectValue,unitType,true);
  Variable ReasonedDiagnosis =new Variable(''Rea-
sonedDiagnosis'',Variable.VARIABLE_TYPE_CATEGOR-
ICAL,causeValue,effectValue,unitType,true);
  Variable ReasonedRisk =new Variable(''Reasone-
dRisk'',Variable.VARIABLE_TYPE_CATEGORICAL,cau-
seValue,effectValue,unitType,true);
```

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Once the SOEKS and its variables are created, the constraints module will read the OWL properties and constraints for every variable and construct the constraints elements in memory. For example, according to the production rule, `FAQPfeffer` is greater than 5; therefore a constraint based on this knowledge should look like this:

```
Constraint FAQ_Constraint=new Constraint();
      FAQ_Constraint.value(5);
      FAQ_Constraint.symbol('' > '');
      FAQ_Constraint.variable(FAQPfeffer);
```

This process is repeated for every constraint and variable in the system. The last step before inserting the experience into the Decisional DNA ontology is to link all the elements of each SOEKS together. To do this, we create the different sets of the SOEKS. The following code fragment illustrates the process with the `NeuropsychologicalInformation` SOEKS.

```
VariableSet varSet=new VariableSet();
  varSet.add(FAQPfeffer);
  varSet.add(GDS);
  NeurophsycologicalInformation.setSetOfVaria-
bles(varSet);
  ConstraintSet consSet=new ConstraintSet();
  consSet.add(FAQ_Constraint);
  NeurophsycologicalInformation.setSetOfCon-
straints(consSet);
```

Finally, the translation process writes the SOEKS in an OWL ontology. This is done by simply calling the `soeksToOWL()` method provided by the SOEKS API. After all the experiences in the batch are translated using the ideas described before, the inference process is executed to discover new rules according to the categories described above. Then, assuming the existence of more knowledge in the system, under specific conditions and after validation against other experiences, the inference process is able to determine that the values obtained from the Folstein test and the probabilities of suffering from AD are related. As a result, the original rule discovered by the system is as follows:

```
IF ((CLASS NeuropsychologicalInformation WITH THE
PROPERTY  NeuropsychologicalInformation_MMSEfol-
stein SMALLER THAN 16 ))
  THEN ( CLASS Diagnosis WITH THE PROPERTY Diagno-
sis_ReasonedDiagnosis EQUALS TO ProbableAlzheimer)
```

As a result of the extension of the system with the Experience Layer, using SOEKS and Decisional DNA, the system is now able to discover new knowledge and rules using bio-inspired techniques, and the reasoning capabilities offered by ontologies. By using these methods, the system acts as an advisor for physicians and supports their decisions.

4. Conclusions

Along this paper, we have focused on the technical elements required to implement Decisional DNA and SOEKS on different technologies and showed that these novel knowledge representations can be shared or interpreted in several ways across different domains. Additionally, we present different conceptual strategies that might be used to exchange knowledge represented as Decisional DNA and SOEKS, with the goal of supporting complex decision-making processes by autonomous and intelligent means, regardless of the underlying technology. Once Decisional DNA is collected, the possibilities are increased if converted into a standard language such as XML or OWL. Thus, Decisional DNA can offers transportability and shareability characteristics, and therefore, collected experience can be reused in different systems that conform to the Decisional DNA specifications. Additionally, once the Decisional DNA is constructed, the experience repository acts as an enhancing tool for different systems by adding predicting capabilities and facilitate knowledge engineering processes inside decision making.

Decisional DNA and SOEKS can indeed improve the current state of the art of Knowledge Engineering Applications. The benefits of using the Decisional DNA are evident; however, we believe that some challenges are still open. Some of such challenges are the testing of Decisional DNA in more technologies as well as on multimedia applications in a way that can collect FDE related to images and sound.

Decisional DNA enables us to distribute experience among different applications, and in that form, and through a decisional community, organizations that are expanding the knowledge management concept externally, can explore new ways to put explicit classifiable knowledge in the hands of employees, customers, suppliers, and partners.

5. Future work

In terms of software agents, our intention is to develop a platform that takes into account the aforesaid ideas and concepts as the driving force that will help us create a knowledge market using *SOEKS* and *Decisional DNA*. There have been some work and experiments as first steps toward the development of such platform, and further refinement, validation and testing is being carried out. Another topic in the future research agenda for the *E-Decisional Community* is *Decisional DNA* appropriation, which means using the elements defined above we plan to determine how new knowledge is merged with the one that an entity already possesses. Determining the quality of knowledge and user satisfaction, among other criteria, will support this process. Desirably, once agents have assimilated knowledge after several interactions, the answer of a query should eventually converge to a common and globally accepted solution.

In regards to embedded systems, we are using robotics as test platforms. We have worked in an approach that allows a robot to capture and reuse its own experiences by applying Decisional DNA. Since the Decisional DNA applied to robotics is at its early development stages, there are further research and refinement remaining to be done, some of them are: Refinement of the requirements of Decisional DNA for robotics, such as inter-process communication strategies, life cycle management and protocols need to be explored in detail; enhancement of the compactness and efficiency of Decisional DNA: optimization of algorithms, evaluation and comparison of the different strategies for Decisional DNA repository storage and query; and, technical review of distributed systems and middleware to determine their viability for a future implementation of the Decisional DNA applied to robotics. Including shareability of gained experience among different robots.

References

[1] E. Feigenbaum, P. McCorduck, The Fifth Generation, Addison-Wesley, London, 1983.
[2] P. Drucker, The Post-Capitalist Executive: Managing in a Time of Great Change, Penguin, New York, 1995.
[3] Oxford University Press, Oxford Dictionary of English, 〈http://www.askoxford.com〉, Accessed Oct 2010.
[4] D. Noble, Distributed situation assessment, in Proc. FUSION '98, P. H. R. Arabnia (Ed.), University of Georgia, Athens, 478–485, 1998.

[5] W. Arnold, J. Bowie, Artificial Intelligence: A Personal Commonsense Journey, Prentice Hall, New Jersey, 1985.
[6] C. Sanin, E. Szczerbicki, Experience-based knowledge representation SOEKS, Cybernet Syst. 40 (2) (2009) 99–122.
[7] R. Davis, H. Shrobe, P. Szolovitz, What is a knowledge representation? AI Mag. 14 (1) (1993) 17–33.
[8] B. Schatz, G. Mohay, A. Clark, Rich Event Representation for computer forensics, in Proc. 5th Asia Pacific Industrial Engineering and Management Systems Conference – APIEMS, QUT, Gold Coast (2004) 12–15.
[9] K.R. Miller, J. Levin, Biology, Prentice Hall, Saddle River, 2002.
[10] W. Ryu. DNA Computing: A Primer, 〈www.arstechnica.com/reviews/2q00/dna/dna-1.html〉, Accessed Nov 10, 2010.
[11] J.W. Lloyd, Logic for Learning: Learning Comprehensible Theories from Structure Data, Springer, Berlin, 2003.
[12] Y. Malhotra, From information management to knowledge management: beyond the 'hi-tech hidebound' systems, in: K. Srikantaiah, M.E.D. Koening (Eds.), Knowledge Management for the Information Professional, Information Today Inc, 2000, pp. 37–61.
[13] E.M. Goldratt, J. Cox, The Goal, Grover, Aldershot-Hants, 1986.
[14] C. Sanin, E. Szczerbicki, Genetic algorithms for Decisional DNA: solving sets of experience knowledge structure, Cybernet Syst. 38 (5) (2007) 475–494.
[15] C. Toro, C. Sanín, E. Szczerbicki, J. Posada, Reflexive Ontologies: enhancing ontologies with self-contained queries, Cybernet Syst. 39 (2) (2008) 1–19.
[16] S. Blakeslee, Lost on earth: Wealth of Data Found in Space, New York Times, March 20, (1990) C1.
[17] L. Corti, G. Backhouse, Acquiring qualitative data for secondary analysis, Forum: Qualitative Social Res. 6 (2005) 2.
[18] C. Humphrey, Preserving research data: a time for action, in Proc. Preservation of Electronic Records: New Knowledge and Decision-making: postprints of a conference – Symposium 2003, Canadian Conservation Institute, Ottawa (2004) 83–89.
[19] P. Johnson, Who you gonna call? Technicalities 10 (4) (1990) 6–8.
[20] C. Sanin, E. Szczerbicki, Using XML for implementing set of experience knowledge structure, in Proc. Int. Conf. on Knowledge-base and Intelligent Information and Engineering Systems – KES, Part I LNCS 3681, Springer (2005) pp. 946–952.
[21] Protégé, Stanford Medical Informatics, 〈http://protege.stanford.edu/index.html〉, (2005).
[22] C. Sanin, E. Szczerbicki, Similarity metrics for set of experience knowledge structure, in Proc. Int. Conf. on Knowledge-base and Intelligent Information and Engineering Systems – KES, Part I LNAI 4251, Springer (2006) 663–670.
[23] C. Sanin, E. Szczerbicki, A Decisional Trust Implementation on a maintenance system by the means of Decisional DNA and Reflexive Ontologies, in Proc. International Conference on Web Intelligence and Intelligent Agent Technology – WI-IAT '08 IEEE/WIC/ACM, Springer, Sydney (2008) 5–8.
[24] N.T. Nguyen, Inconsistency of knowledge and collective intelligence, Cybernet Syst. 39 (6) (2008) 542–562.
[25] S. Heath, Embedded Systems Design, EDN Series for Design Engineers, 2nd edn., Newnes, 2003.
[26] W. Wolf, Computers as Components, Morgan Kaufmann, San Francisco, 2001.
[27] C.E. Pereira, L. Carro, Distributed real-time embedded systems: recent advances, future trends and their impact on manufacturing plant control, Annu. Rev. Control 31 (1) (2007) 81–92.
[28] E. Schwalb, iTV Handbook: Technologies & Standards, Prentice Hall, Upper Saddle River, NJ, 2003.
[29] C. Sanin, C. Decisional DNA and the Smart Knowledge Management System: Knowledge Engineering and Knowledge Management applied to an Intelligent Platform, LAP Lambert Academic Publishing, Berlin, 2010.
[30] B. Monien, L. Apostolova, G. Bitan, Early diagnostics and therapeutics for Alzheimer's disease – how early can we get there? Expert Rev. Neurother 6 (2009) 1293–1306.
[31] C. Sanin, C. Toro, E. Szczerbicki, An OWL ontology of set of experience knowledge structure, J.UCS (J. Universal Comput. Sci.) 13 (2) (2007) 209–223.
[32] P. Ciccarese, E. Wu, G. Wong, M. Ocana, J. Kinoshita, The SWAN biomedical discourse ontology, J Biomed. Inf. 41 (2008) 739–751.
[33] M. Nyström, A. Vikström, G.H. Nilsson, H. Ahlfeldt, H. Orman, Enriching a primary health care version of ICD-10 using SNOMED CT mapping, J Biomed. Semant. 1 (7) (2010).

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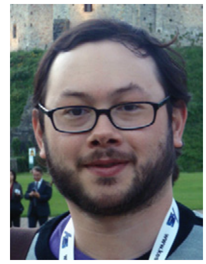

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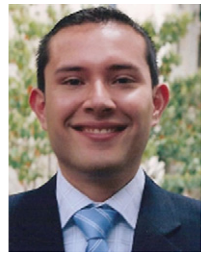

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Bridging challenges of clinical decision support systems with a semantic approach. A case study on breast cancer

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ABSTRACT

The integration of Clinical Decision Support Systems (CDSS) in nowadays clinical environments has not been fully achieved yet. Although numerous approaches and technologies have been proposed since 1960, there are still open gaps that need to be bridged. In this work we present advances from the established state of the art, overcoming some of the most notorious reported difficulties in: (i) automating CDSS, (ii) clinical workflow integration, (iii) maintainability and extensibility of the system, (iv) timely advice, (v) evaluation of the costs and effects of clinical decision support, and (vi) the need of architectures that allow the sharing and reusing of CDSS modules and services. In order to do so, we introduce a new clinical task model oriented to clinical workflow integration, which follows a federated approach. Our work makes use of the reported benefits of semantics in order to fully take advantage of the knowledge present in every stage of clinical tasks and the experience acquired by physicians. In order to introduce a feasible extension of classical CDSS, we present a generic architecture that permits a semantic enhancement, namely Semantic CDSS (S-CDSS). A case study of the proposed architecture in the domain of breast cancer is also presented, pointing some highlights of our methodology.

1. Introduction

During the last 50 years numerous technologies for clinical decision support have been proposed worldwide (Blomqvist, 2012; Wright and Sittig, 2008; Holsapple, 2008; Berner, 2007). The benefits given by clinical decision support systems (CDSS) have also been broadly stated: e.g. they provide medical professionals with knowledge at appropriate times and manner. In general CDSS (i) facilitate an efficient and effective decision making about individual patients, (ii) reduce preventable medical errors and (iii) improve the quality of healthcare provided to patients (Berner, 2007; Peleg and Tu, 2006).

Nevertheless, the integration of such systems in daily clinical environments has not been fully achieved yet (Osheroff et al., 2007). Several authors have reported the factors affecting this lack of success (Peleg and Tu, 2006; Sittig et al., 2008; Kawamoto et al., 2005; Osheroff et al., 2007; Das and Eichner, 2010; Friedlin et al., 2007; Holbrook et al., 2003; Garg et al., 2005; Niès et al., 2006; Greenes, 2006; Liu et al., 2006) and have identified and reported the main challenges that current CDSS need to bridge.

1. The first of these challenges is that decision support should be computerized and not paper-based (Kawamoto et al., 2005). Current trends are oriented towards the development of computer-based medical guidelines, as reported by Isern and Moreno (2008). However, actual knowledge representation models for clinical guidelines do not prioritize reasoning as it could be argued that they are mainly focused on alignment and integration of data. These approaches, although signifying a stepping stone towards the inclusion of semantics in CDSS, still lack of the exploitation of the knowledge embedded in the aligned data, and thus, improvements in knowledge representation and reasoning capabilities are still in need.
2. A second aspect being reportedly identified is the fact that clinical workflow integration is recognized as a key aspect for CDSS (Holbrook et al., 2003; Kawamoto et al., 2005; Das and Eichner,

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2010). The importance of workflow integration is evident in the direct impact in the minimization of time consumption during the introduction of patient data and results. In this sense efforts should be done for the integration of CDSS with clinical systems already present in hospitals and medical centers (Holbrook et al., 2003; Das and Eichner, 2010). Additionally, CDSS should be presented as complete solutions that assist clinicians during all different tasks of their daily duties, and not only during specific activities. This fact would promote and normalize the use of clinical decision support.

3. The third challenge states that the design of the system should be developed to allow maintainability and extensibility (Peleg and Tu, 2006). Hence, cost-save solutions are needed to maintain the underlying knowledge model and the criteria for reasoning of the system. For that purpose, there is a need for creating knowledge representations that are sufficiently transparent to be understood directly by domain experts (Greenes, 2006). At the same manner, easy-to-use, and technology-transparent tools for domain experts need to be developed. Ease of use is not only conveyed towards GUI enhancements, but also in allowing medical practitioners to visualize and edit the knowledge models and criteria for the reasoning in a simple, yet powerful way. Apart from that, and following the same learning paradigm as clinicians, the knowledge and criteria embedded in CDSS should evolve with daily experiences (Berner, 2007). Therefore, experience-based approaches are needed.
4. The fourth challenge states that timely advice should be provided in CDSS (Holbrook et al., 2003; Peleg and Tu, 2006). The aforesaid leads to the need of fast reasoning processes, aimed to provide real time, or quasi-real-time, responses from those semantically enhanced clinical decision support systems.
5. The fifth challenge is related to the evaluation of the costs and effects of the CDSS itself (Sim et al., 2001; Peleg and Tu, 2006). Therefore, mechanisms for the quantitative and qualitative evaluation of the performance of the system, as well as of the quality of the knowledge and the models in it should be provided (Liu et al., 2006).
6. The last challenge states that there is a need of creating an architecture oriented at sharing and reusing CDSS modules and services (Sittig et al., 2008).

Our contribution is aimed at overcoming these reported difficulties. To this end, we firstly propose a new clinical task model oriented at the integration of CDSS to the whole clinical workflow. The presented model is both, cyclic and federated.

In our work we propose a generic architecture for Semantic CDSS (S-CDSS), which follows the clinical task model. We have implemented our proposed architecture within the framework of a research project dealing with breast cancer as case study.

We present also an evaluation methodology for our architecture. Such methodology will be applied in the planned evaluation process of the aforesaid research, which will be taking place during 2013.

Our previous work in CDSS architectures is completely aligned with the ideas proposed in this article. Particularly, in Toro et al. (2012) we proposed the development of an architecture aimed to the early detection of Alzheimer's disease (AD). It was able to learn following the same paradigm as physicians, which consists of fine-tuning criteria with the experience acquired during day-to-day tasks. In that work we proposed a vertical architecture based on five layers (i.e. data, translation, ontology and reasoning, experience, and application) and the use of semantic technologies and experience-based reasoning processes. It was specifically focused on the discovery of new knowledge in the system; which in the case of early detection of AD would be a clear benefit. Nevertheless, it did not approach other current challenges of decision support, such as (i) the integration of CDSS during all different stages of the clinical workflow, (ii) the automation of CDS, or (iii) the evaluation of the quality of the performance and the knowledge on the system. Therefore, we have evolved our previous vertical architecture into a federated approach based on multi agent systems.

This article is arranged as follows: in Section 2 the related work relevant for our approach is presented; in Section 3 our contributions related to the clinical task model and the generic architecture for S-CDSS are proposed; in Section 4 a case study of the architecture for the breast cancer domain is presented; in Section 5 an evaluation methodology for our architecture is presented, and finally, in Section 6 conclusions and future work are summarized.

2. Background concepts

In this section we describe the framework of ideas in which our system is build upon. We first introduce the different tasks of the care process and then we present a short overview of solutions and technologies applied to CDSS covering experience-based, semantic and multi agent-based approaches.

2.1. Clinical tasks and decision support

During daily clinical practice, clinicians perform a series of tasks framed in the care process, which include diagnosis, prognosis, treatment, evolution and prevention.

Diagnosis is the process that identifies the syndrome or the disease of the patient (Bickley and Szilagyi, 2003). As every symptom can refer to multiple causes, physicians need to narrow the possibilities. In order to do so, physicians first gather the clinical history, which consists of asking the patient about (i) relevant details of the symptoms of the disease, (ii) past medical history, (iii) family history, and also (iv) about habits related to work and leisure. Physical explorations (i.e. auscultation, palpation, inspection and olfaction) are then performed by physicians to detect the signs of the disease that patients cannot sense. Finally, complementary explorations such as functional tests, image-based diagnostic tests, endoscopies, biopsies, laboratory tests, and electrocardiography tests, increase or decrease the likelihood of the diagnosis.

Prognosis is the process of generation of a set of forecasts about the pathologic process that affects the patient, such as life expectancy, total or partial functional recovery to treatment and future complications (Banerjee and Watson, 2011; De Castro, 2006; Rozman, 2006).

Treatment implies the understanding the global effects of a diagnosed disease on a patient, which can be physical, psychical, economical and social, for the prescription of the appropriate therapeutic resources, i.e. hygienic, dietetic, pharmacologic, physical, surgical, psychological (Rozman, 2006; De Castro, 2006). An effective communication with patients and their social environment (e.g. family and caregivers), is also an essential part of the treatment.

The evolution of the patients during their disease is controlled by following up the effects of the treatment and the recovery process (De Castro, 2006; Rozman, 2006). Chronic disease management is particularly focused on this stage.

Prevention is the process aimed at avoiding a disease (Gérvas et al., 2008), which can be oriented at immunizations and vaccinations and health education, amongst others (Rozman, 2006).

Decision making plays an essential role during these stages and it is hypothesized that decision support resources aid physicians to carry out them in a more effective and efficient manner (Osheroff et al., 2007).

2.2. Experience-based clinical decision support

Different technologies have been proposed for CDSS since 1960. Power (Power, 2008) summarizes the different approaches of decision support systems (DSS) in general, in five groups: (i) model driven systems, based on simple quantitative models which are defined by limited data and parameters that decision makers need when analyzing a situation (Mathe et al., 2009); (ii) data-driven systems, based on the access and manipulation of huge amounts of data (Rinott et al., 2011); (iii) communications-driven systems, which use network and communications technologies to facilitate decision-relevant collaboration and communication (Fortney et al., 2010); (iv) document-driven systems, which use computer storage and processing technologies to provide document retrieval and analysis (Power, 2008), and finally (v) knowledge-based systems, that contain knowledge about a particular domain, the understanding of problems within that domain, and skill at solving some of these problems (Kalogeropoulos et al., 2003).

Since physicians are already using knowledge and their experience to make decisions, in our work we implicitly show that experience-based systems are yet to be considered as a new category in (Power, 2008), when applied to the clinical domain.

With that challenge in mind, previous works using case-based reasoning have been proposed (Frize and Walker, 2000; Aamodt et al., 2010), but they do not consider the possible evolution of the underlying knowledge model, which occurs indeed in real clinical domains. Machine learning approaches are also present in the literature (Eom et al., 2008), although they require arguably a high cost during system training.

Therefore, for building CDSS we propose in our work the use of experience modeling and reasoning techniques, such as SOEKS and DDNA (Sanin et al., 2007; Sanin and Szczerbicki, 2008). With the use of these technologies CDSS not only integrate in the decision making process of physicians during clinical workflow, but they are also able to learn from the everyday experiences as well as physicians do.

2.3. Semantic and multi-agent based CDSS

Semantic technologies have reportedly been described in the literature as a promising approach to solve knowledge handling and decision support in the medical domain (Gnanambal and Thangaraj, 2010; Lindgren, 2012; Blomqvist, 2012; Hussain et al., 2007; Yu and Jonnalagadda, 2006). In particular, ontologies are very promising, as presented by Mahmud et al. (2011), Farion et al. (2009), Abidi et al. (2007), Subirats and Ceccaroni (2011) and Houshiaryan et al. (2005). They are defined by Gruber (1995) in the computer science domain as the explicit specification of a conceptualization.

For clinical decision support, ontologies can efficiently fulfill the needs for (i) organized and standardized terminologies, (ii) reusability at a structural level and (iii) knowledge representation models for reasoning and inferring of new knowledge (Houshiaryan et al., 2005; Yu and Jonnalagadda, 2006).

In our work we hypothesize that a yet unreportedly need of CDSS is the reutilization of the knowledge gathered among the different clinical stages, as is done by physicians during their different decisions. Nevertheless, we have not found in the literature reported approaches covering this aspect. For instance, Colantonio et al. (2009) present an interoperable and standardized CDSS based on ontologies and a rule-based reasoner tool, intended to integrate the system in the whole clinical workflow. However, the different clinical stages are proposed as separate tasks, and therefore no direct reutilization of knowledge between the stages is supported.

We intend to bridge this aspect with the combination of semantic technologies and Multi -Agent Systems (MAS). The latter are applications in which many autonomous software agents are combined to solve large problems that are beyond the individual capabilities or knowledge of each agent (Isern et al., 2010; Flores-Mendez, 1999). MAS are defined by four main characteristics: (i) each agent has incomplete capabilities to solve a problem; (ii) there is no global system control; (iii) data is decentralized; and, (iv) computation is asynchronous (Sycara, 1998).

Different MAS have been already proposed for medical applications in general, and for clinical decision support in particular (Isern et al., 2010; Paranjape and Sadanand, 2010; Laleci et al., 2008; Shirabad et al., 2012). They are mainly oriented at the reutilization of medical resources distributed in different health centers. The work presented in Shirabad et al. (2012) shares some ideas with our approach. They focus on supporting the entire clinical decision making process with the use of MAS, although no knowledge reutilization is supported between the different stages, as separate decision systems are proposed for each stage. Additionally, no learning mechanisms based on user experience are provided.

3. Proposed model and architecture for a Semantic CDSS

In this section we propose our Semantic CDSS (S-CDSS) that intends to bridge some of the challenges described in Section 1. In our approach we focus on clinical workflow integration, by formalizing clinical tasks as cyclic and federated processes. This model imposes some technological and architectural requirements to the S-CDSS, which allows us to effectively address also the rest of the identified challenges.

3.1. Proposed clinical task model

Decisions made by physicians largely depend on the knowledge available at the moment of decision making. However, conclusions could change by new gathered evidence or even posterior medical results (Rozman, 2006). In other words, decisions made during each stage of clinical tasks, are not final by any means, as exemplified in the cycle in Fig. 1. The cyclic inspiration is found in the work of Ortiz-Fournier and Ramaswamy (2010).

In our work, we partially share the aforesaid view with the ulterior evidence that the different stages do not necessarily need to form part of the cycle and could also act independently. Furthermore, we believe that such models do not take into account the role of the decision maker missing theoretically important inputs.

A decision maker in this context, would potentially handle the knowledge involved in the whole clinical workflow and also learn from every situation, in order to apply the experience acquired in future decisions (Rozman, 2006).

It is this fact that makes an urgent necessity of clinical task models supporting reutilization of knowledge among different stages.

All these characteristics can be achieved only if each stage in the model is both (i) independent, but (ii) at the same time is related to a central entity that controls the generated knowledge for its reutilization.

The aforesaid characteristics are similar to the concept of federation in politics, where a type of sovereign state is characterized by a union of partially self-governing states united by a central government (Xing and Shengjun, 2010).

For the aforementioned reasons, we propose the combination of a cyclic and federated Clinical Task Model (CTM) (Fig. 2). In our model, diagnosis, prognosis, treatment, monitoring and prevention are partially independent stages, which (i) follow a cyclic paradigm and (ii) are united to a central decision maker. The central decision maker consists generally of a multidisciplinary team of clinical

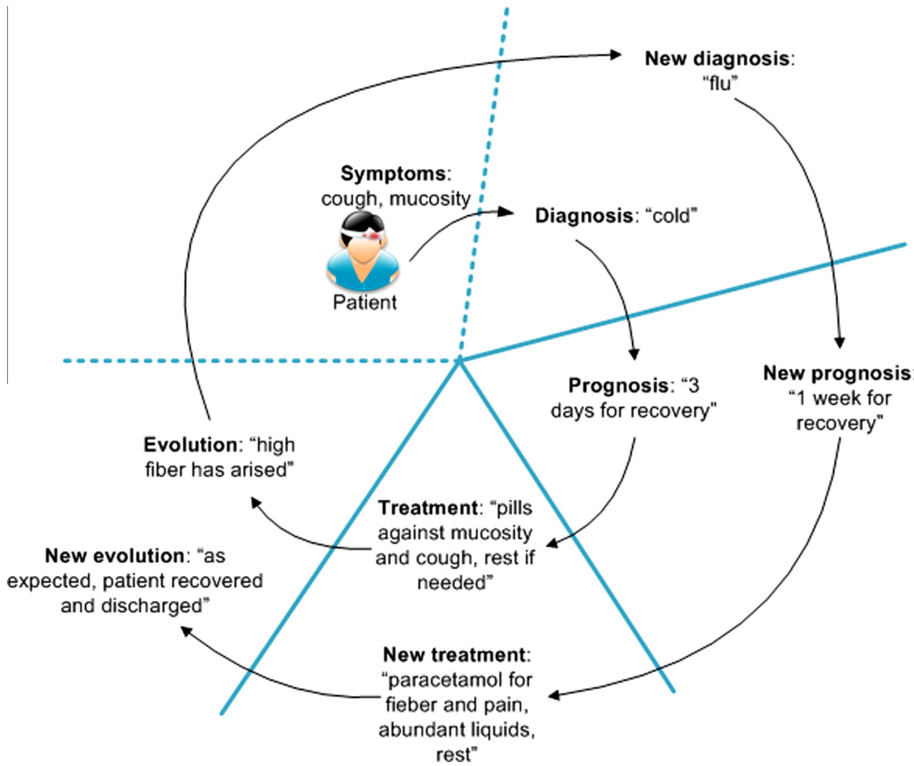

Fig. 1. Example showing clinical decision making process for a patient apparently suffering from cold.

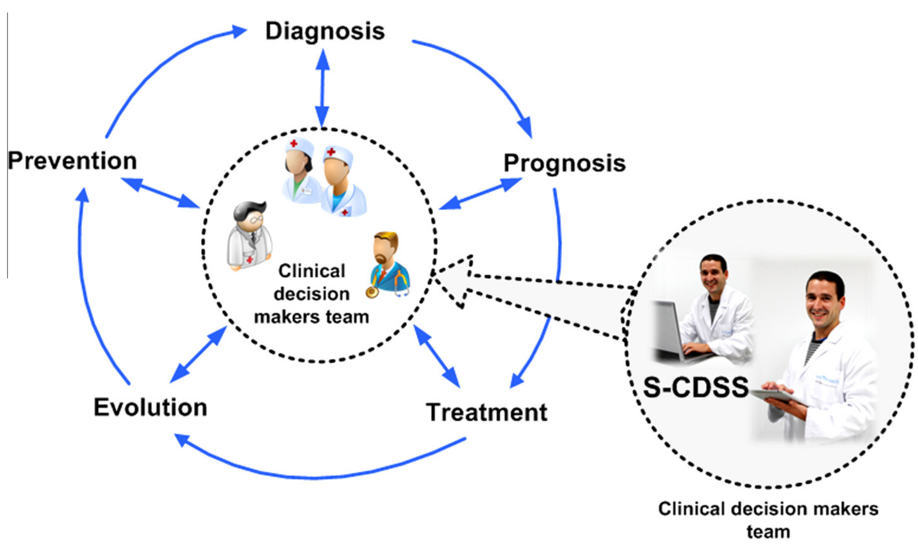

Fig. 2. Proposed clinical task model and its connection to S-CDSS.

professionals that collaborate together to make the different decisions involved during clinical tasks. CDSS will also be located in the center of our CTM together with the decision maker team.

In order to fit in the CTM, the proposed CDSS must provide (a) specialization, to cover the different tasks performed during the stages, (b) control, to handle the knowledge and the performance of the system, and also (c) knowledge reutilization. Both specialization and control capabilities are adequately approached by multi-agent systems (MAS), where each agent can be oriented at specific tasks, also covering inter-agent communication and synchronization. On the other side, knowledge reutilization is supported by the application of semantic technologies. With the combination of those, we propose the concept of Semantic CDSS (S-CDSS).

3.2. Proposed architecture

Fig. 3 depicts an overview of our architecture. At the top, the users of the systems are shown, which could be (i) clinicians or domain expert users, (ii) patients, (iii) patient relatives or caregivers, and (iv) medical institutions, associations or hospitals. They interact with a multi-agent based system, explained in detail in Section 3.3.

Some of the tasks performed by the latter require the access to patient clinical data or the storage of the obtained results. Data are located in the data repository, which consists of (i) a set of databases (DB), such as clinical systems, electronic health record (EHR) repositories, medical image repositories, picture archiving

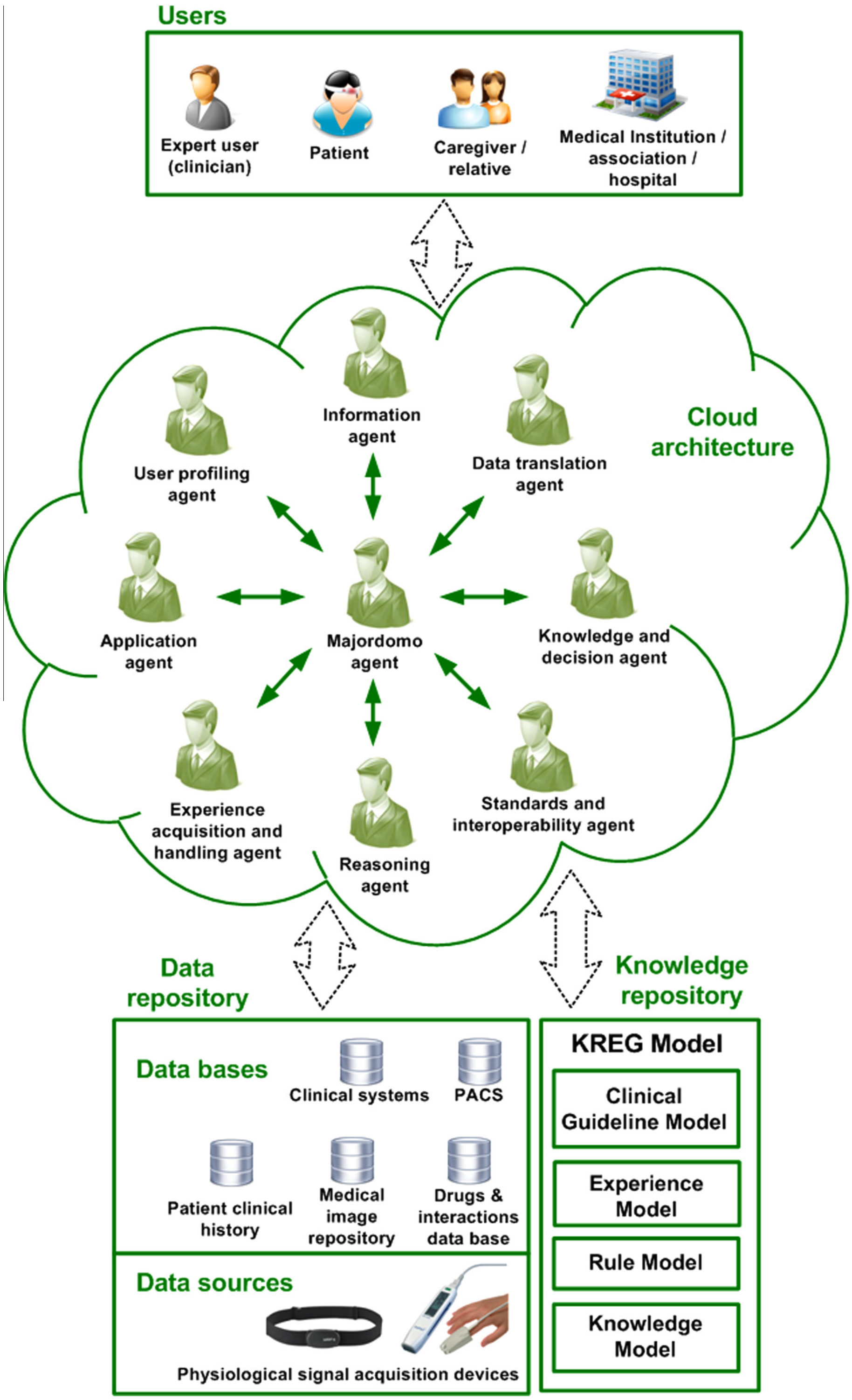

Fig. 3. Proposed architecture for clinical decision support.

and communications systems (PACS), and drugs & interactions DB, and (ii) a set of data sources, like physiological signal acquisition devices (ECG, EEG, respiration rate and effort, spirometry, oximetry, temperature) or other patient monitoring devices. In particular, the different data bases and sources in the repository may be heterogeneous in terms of serialization formats, communication protocols, size, implemented security levels, and location.

The Multiagent system will also perform reasoning tasks, which are based on a knowledge and decision model, stored in the knowledge repository. We call this model the KREG model, as we have divided it into four layers: (i) Knowledge, (ii) Rule, (iii) Experience, and (iv) Clinical Guidelines.

The Knowledge layer contains a set of domain ontologies describing the classes and properties covered by the CDSS. The set of domain ontologies comes from user experience gathering and some other domain ontologies used in the medical domain, such as ontologies in Bioportal (Whetzel et al., 2011).

The criteria for the reasoning is expressed in terms of rules provided by domain experts and is contained in the Rule layer. Adequate tools will be given to allow expert users edit both ontologies and rules.

Additionally, clinical process models and recommendation criteria coming from clinical guidelines and protocols will be included in the Clinical Guideline layer. Recommendation criteria will be mapped to the rule layer.

Finally, during execution time, for every action performed by a user, the variables, rules, functions and constraints involved in the decisional event are stored in the Experience layer.

3.3. Multiagent architecture

The use of an agents-based paradigm provides the system with the required modularity (Sycara, 1998), and in this way scalability is also intrinsically accomplished by the system. In order to achieve the latter, our system supports the inclusion of new agents, which could be implemented in the future and then incorporated. These new agents could fulfill for instance specific functions belonging to other medical sub-domains, so that their inclusion could broaden the decision support services offered by the architecture and the domains for which it is applied.

Fig. 3 depicts an overview of our architecture. There are nine distinct agents: (i) information agent, (ii) data translation agent, (iii) knowledge and decision agent, (iv) standards and interoperability agent, (v) reasoning agent, (vi) experience acquisition agent, (vii) application agent, (viii) user profiling agent and (ix) majordomo agent.

3.3.1. Information agent

This agent accesses the information stored in the data repository of the architecture. It is in charge of handling (saving, retrieving and editing) data and deals with the corresponding web services and data accessing language and protocols.

3.3.2. Data translation agent

The approach for clinical workflow integration presented in the previous section requires that plain information of the system is semantically enhanced to support richer reasoning processes. In order to do so, the data translation agent performs the mapping of the data structure in the data repository to the KREG Model.

3.3.3. Knowledge and decision agent

The knowledge and decision agent deals with the creation, edition and visualization of the KREG Model, and it is aimed at guaranteeing the maintainability and extensibility of the knowledge in the system. Tools adapted to each of the four layers of the KREG Model are proposed: (i) graphical ontology editors and tools for knowledge extraction from evidence-based medicine (Straus et al., 2011) sources; (ii) tools for rule edition and visualization, as well as for the extraction of the decision criteria embedded in the clinical guideline semantic models; (iii) tools for the visualization and navigation of decisional events in the experience model of the system; and finally (iv) tools for extracting the knowledge from clinical guidelines.

3.3.4. Standards and interoperability agent

The standards and interoperability agent is in charge of aligning the KREG model with standards that will provide the system with interoperability for the communication with other clinical systems and possible CDSS. It will also allow the creation of shareable and understandable clinical decision support services, which open new business models for clinical decision support, e.g. Clinical Decision Support As A Service (CDSaaS). Standards covered by this agent include (i) EHR related standards, such as HL7 (Berson, 2012) and ISO 13606 (Santos et al., 2010), (ii) standardized ontologies, as for instance SNOMED CT (Nyström et al., 2010), ICD-10 (Merabti et al., 2010), UMLS (Merabti et al., 2010), as well as (iii) standards for clinical guideline representation (GLIF) (Patel et al., 1998).

3.3.5. Reasoning agent

The reasoning agent interacts with the KREG Model, a classical semantic reasoning tool and the query engine, in order to obtain inferred responses that will aid clinicians during decision making. In our previous work, we have studied fast querying and reasoning techniques used to provide time efficient performance. We use Reflexive Ontologies (Toro et al., 2008; Artetxe et al., 2013) to provide quasi-real time responses from those knowledge sources. Reflexive Ontologies store the queries that have already been made in a query structure which is a new class added to the original ontology, where individuals are the queries and the corresponding pointers to answers. Thus, every time a new query is made the answer is searched first within this class, and is only computed if it is not present there.

3.3.6. Experience acquisition and handling agent

The experience acquisition and handling agent gathers and stores the experience of clinicians or other users in the system, providing automatic maintenance and updating of the KREG Model. For this purpose, variables, functions, constraints and rules involved in every decisional event are handled.

3.3.7. Application agent

The application agent is in charge of the interaction between the user and the system, that will be held by graphical user interfaces (GUI) oriented at different purposes: (i) decision support, (ii) authoring tools for the edition or visualization of the underlying models, and (iii) patient interface for accessing clinical results, non-clinical results and physiological signals coming from user medical devices. Visual analytic techniques will be presented to facilitate the visualization of patient data, criteria for decision, next steps on the process, and most probable diagnosis or suitable treatments for a specific patient, among others. The main objective of the application agent is to be easy, in order to facilitate the work to clinicians and increase the acceptability of CDSS for their inclusion in the clinical workflow.

3.3.8. User-profiling agent

When a user is logged in, the user-profiling agent characterizes it, using the minimum number of parameters that could characterize user behavior and user attributes. There exist some user characterization modules such as GOMS (Gray et al., 1993) and CommonKADS (Hasan and Isaac, 2011), that present implementation and logic modules for user characterization.

3.3.9. Majordomo agent

The majordomo agent is in charge of the synchronization and control of the agents in the platform. We follow a blackboard approach (Craig, 1995) where agents are explicitly not allowed to talk to each other. For that purpose they must interact through the majordomo. Thereby, security issues are reduced and inconsistencies due to simultaneous communications between different agents are avoided (asynchronism). Whereas the rest of the agents are specialized in different task, the majordomo agent specialization is the control and performance of the rest of the system.

4. Case study: breast cancer

We have implemented this architecture within the research framework of the Spanish project LIFE (Life Consortium, 2012) as case study for the Breast Unit (BU) of the Valencia University General Hospital.

BU are multidisciplinary teams of physicians that work complementarily to treat breast cancer patients. The main characteristic of the BU is that decisions about the healthcare process of patients are made both, individually and collectively. Weekly the most critical cases are analyzed together during a plenary meeting and relevant aspects of their treatment are agreed. Therefore, risky decisions depend on the combination of the knowledge and experiences of different professionals.

In particular, the medical team in the LIFE project is formed by the following services: (i) radiodiagnosis, (ii) nuclear medicine, (iii) radiotherapy, (iv) rehabilitation, (v) anatomical pathology, (vi) general surgery, (vii) medical oncology, and (viii) psychology.

In order to support both, individual- and team-work of the BU, our system must provide integration at the levels of (a) clinical data and results from the different services, (b) domain knowledge and criteria for the decisions involved in each of the services, and (c) the experience acquired during the individual and collective decision making process.

To do so, we have implemented the nine-agent based architecture presented in Section 3. For each agent the following four characteristics have been defined: (i) an id, (ii) the description of the corresponding roles or tasks carried out, (iii) a status, which can be whether idle, running, or stopped, and (iv) an in/out inter-agent communication channel, called the talker.

The talker is used by the majordomo agent for communicating the rest of the agents when to start running and, if needed, which agent to connect. The strategy to decide which agent to launch is given by the functional dependencies established by each task. For instance, for the task of providing recommendations about a treatment to a clinician: (1) the Reasoning agent is launched first in order to obtain the recommended treatments; (2) during the reasoning process, the access to some patient clinical data may be needed (Information agent); (3) then the User profiling agent characterizes the clinician, and (4) the Application agent provides this user a personalized interface with decision support on treatments.

At data level, a mySQL database has been proposed for the unification of the former eight different databases of the hospital (a database per medical service). We call it LifeDB and it contains all information needed by the team of physicians to make decisions. Our industrial partner has been leading this unification, (i) analyzing the current databases, (ii) gathering the requirements and needs of each of the services that should be covered by the new design, and (iii) then aligning such databases.

The data structure of LifeDB is aligned with the KREG model in the knowledge repository. To do so, we have implemented the translation agent, which creates two xml documents in real time every time data is created or modified in LifeDB: (i) one xml document containing the structure of the data and (ii) another containing the query calls to those data in LifeDB. These two xml documents are programmatically loaded to the Knowledge Layer of the KREG model.

In particular, we have implemented the Knowledge Layer with three ontologies, as we argued in our previous work (Sanchez et al., 2011) that SNOMED CT (Nyström et al., 2010), SWAN (Ciccarese et al., 2008) and a domain ontology are sufficient for the modeling of the underlying knowledge of a CDSS. The three ontologies are: (i) SNOMED CT, for clinical description of the patient, the breast cancer and the procedures involved during its diagnosis and treatment; (ii) SWAN, for bibliographic endorsement of criteria for decision making, and (iii) a new domain ontology of breast cancer, containing the results of the specific clinical tests carried out to patients that we name the Life Ontology. A partial view of the Life Ontology is depicted in Fig. 4.

The Rule Layer of the KREG Model consists of an initial set of production rules generated by the medical professionals of the BU. These rules model the different decisions attached to each service. In our implementation, rules follow an IF-THEN-ELSE structure and are both, (i) weighted within an importance hierarchy of rules, and (ii) endorsed by the corresponding bibliographic source. This implementation follows the syntax presented in our previous work (Sanchez et al., 2011), where a rule syntax similar to Rule ML is proposed and serialized following an xml-based paradigm.

The knowledge and decision agent implements tools and techniques oriented to medical domain experts, for the edition and visualization of these production rules and domain ontologies. Graph-based visualization engines have been developed for this purpose.

The application agent is the one in charge of the interaction between the system and the user, which is in our case a medical professional. Therefore, it shows different web-based graphical user interfaces (GUI) for each of the different tools provided to the users: (i) an interface to enable remote access to the gathered patient data and to facilitate the introduction of the clinical results of each service; (ii) an interface for the graph-based visualization,

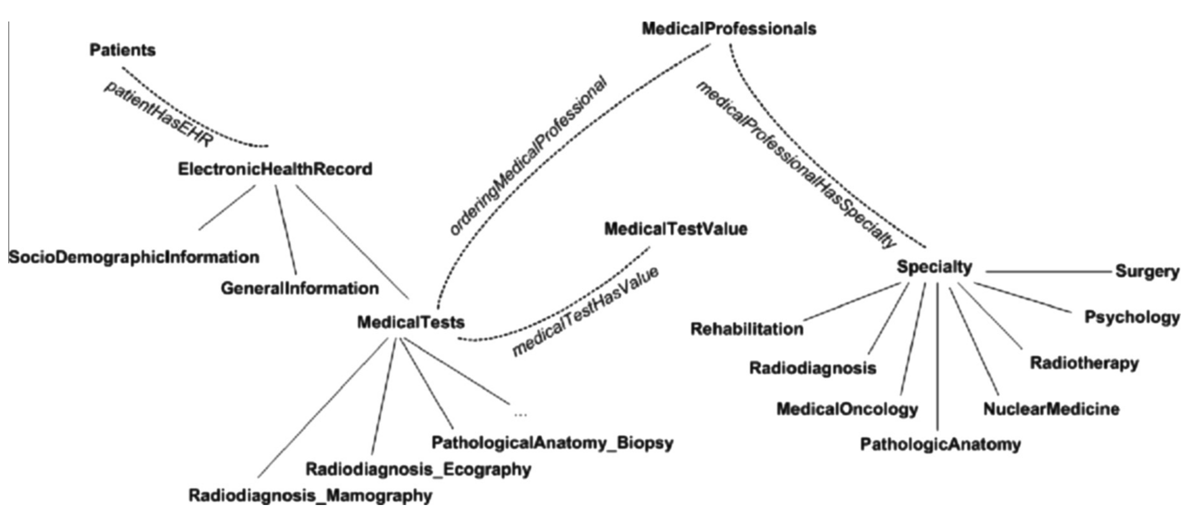

Fig. 4. Overview of the LIFE Ontology.

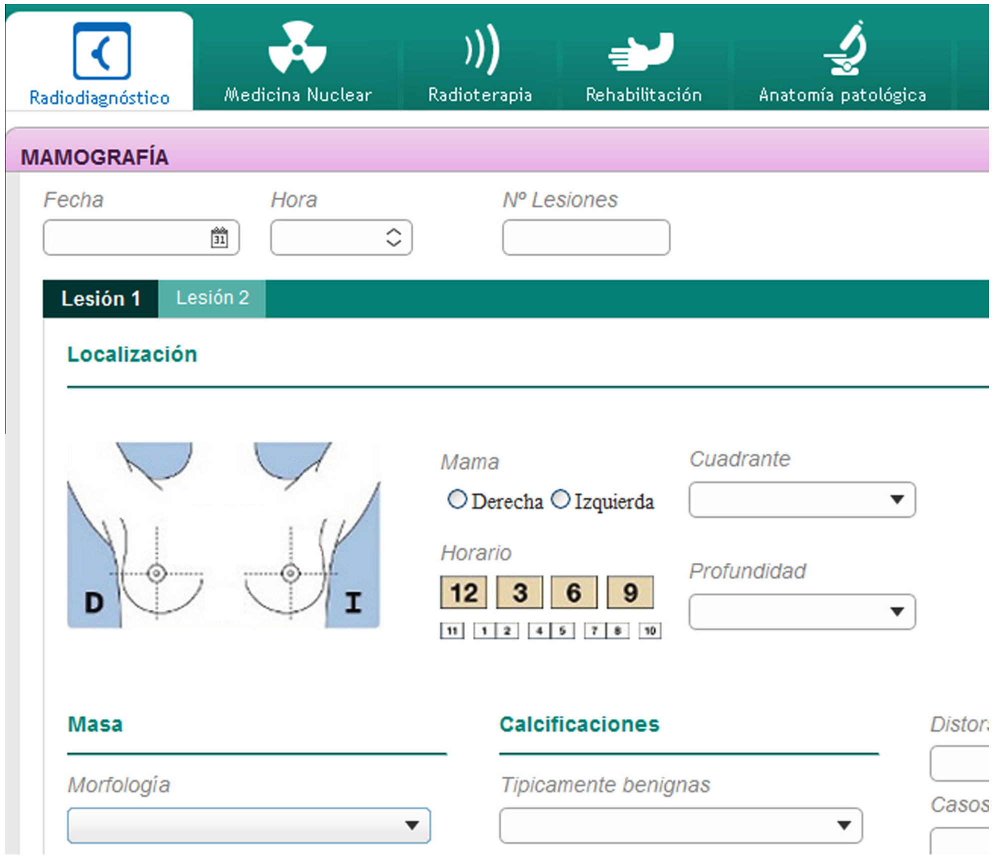

Fig. 5. Example screenshot of the data gathering interface.

edition and mapping of ontologies; (iii) a visual rule editor to ease the generation and the maintainability of rules and decision criteria, and (iv) an interface which reports recommendations supporting the decision as a pie chart, with their attached bibliographic proof. Fig. 5 shows an example screenshot of the data gathering interface.

The reasoning process to infer the corresponding diagnoses, prognoses, treatment plans, monitoring plans and prevention actions is handled by the reasoning agent. In order to provide such mechanisms, we have developed a series of methods programmed using the Protégé OWL API. The semantic reasoning process is based on the Pellet reasoner tool and we have implanted the fast querying technique of Reflexive Ontologies (RO) (Toro et al., 2008; Artetxe et al., 2013) in order to speed up the reasoning time.

In the Experience layer of the KREG model, DDNA and SOEKS technologies have been implemented using their ontology form (Sanin et al., 2007). The experience acquisition agent implements a reasoning process that enables the evolution of the initial set of rules with experience, as was presented in our previous work (Toro et al., 2012). More specifically, for each decisional event, the system stores both, the output of the reasoner and the final decision made by the corresponding physician. Decisions that do not follow the output of the reasoner drive an evolution of the set of rules in the KREG Model.

5. Evaluation methodology

The implementation of our system has been carried out in a real clinical environment and a deep and methodological evaluation of the system will be performed during 15 months starting in June 2013.

Following the work presented by Bürkle et al. (2001), our intended evaluation methodology, consists of four parts: (i) verification, (ii) validation, (iii) evaluation of the human factors, and (iv) evaluation of the clinical effects of the system.

5.1. Verification

Verification is the process of checking whether the development of the system complies with specifications (Bürkle et al., 2001) in terms of provided support for the recommendations. In our case it is trivially done by manual verification.

5.2. Validation

Validation is the process of checking whether the developed design carries out tasks adequately during a real clinical environment (Bürkle et al., 2001). Let $R_t = \{r_1, r_2, \ldots, r_{Kt}\}$ be the set rules of the KREG Model at time t, which contain the criteria for decision making embedded in the S-CDSS. We assume that the knowledge embedded in the system is time-varying, and therefore the set of rules may change in time. More specifically, in (Toro et al., 2012) we described the possible changes as fine-tuning of rules, deprecation or creation of new rules. Each rule is a tuple $r_k = \langle a_k, q_k, w_k, b_k \rangle$, where a_k denote the antecedents of the rule, q_k denote the rule consequent, w_k, is a rule weight, and b_k is the bibliographic endorsement. Let $D = \{d_1, d_2, \ldots, d_D\}$ be the set of different decision domains considered in the S-CDSS. Examples of such decision domains are the diagnosis of a patient, the type of treatment prescribed, and the quantity of drug doses, amongst others. For each decision domain d_i the system outputs a collection of decision tuples $o_i = \{\mathbf{dp}_{i,1}, \mathbf{dp}_{i,2}, \ldots, \mathbf{dp}_{i,C1}\}$. A decision tuple is given by $\mathbf{dp}_{ij} = \langle c_{ij}, p_{ij}, R_{ij} \rangle$, where c_{ij}, is a selected decision value, p_{ij}, is the probability attached to that decision value, and R_{ij} is a set of rules that provide the supporting evidence for the aforementioned value. R_{ij} is formed by the rules $\boldsymbol{r}_k$ whose consequent q_k are equal to the selected decision value c_{ij}, being $R_{ij} = \{\boldsymbol{r}_k | q_k = c_{ij}\}$.

In our validation two different aspects will be checked: (i) similarity between the output of the system and the final decision made by physicians, and (ii) reduction of the error as the experience is acquired by the system.

5.2.1. Similarity between the output of the system and the final decision of physicians

Both, quantitative and qualitative analysis will be carried out in order to validate whether our system infers appropriate results or not.

We define, for the quantitative analysis a **similarity measure** $S(f_i, o_i)$ between (i) the system output decision o_i (collection of decision tuples) inferred for each decisional event d_i and (ii) the final decision f_i made by physicians. At this point, the similarity measure compares the decision value selected by the physician versus the output given by the reasoning tool.

Experimental design: We will collect data corresponding to o_i and f_i of 1000 decisional events, of 10 different decision domains applied to 100 patients. $S(f_i, o_i)$ will be calculated for each decisional event and cases where the normalized similarity value is higher than the 90% will be counted as true positives. As a result of our validation we will report sensitivity of the system, as well as similarity measure distributions by patient and by decision.

The qualitative evaluation will be performed from a short questionnaire filled by the physicians stating their own supporting evidences. This trace of the physician reasoning will be compared with the recommendations of the S-CDSS.

5.2.2. Reduction of the error with the experience

The experience-based evolution process of rules needs to be also validated. For this purpose after 12 months the same patient data will be introduced again in the system. At this time, the system will contain an evolved version of the ruleset, R_{t1}, and thus, inferred outputs could differ from previous ones.

Analyzing the new output for every decisional event allows to measure the **increasing of similarity** with the physician response relative to the initial rule set R_{t0}. From this analysis we will conclude the effectiveness of this agent.

5.3. Human factor evaluation

The human factor evaluation process consists of checking the usefulness of the system, its usability and the satisfaction of the user with the different aspects of the system (Bürkle et al., 2001). Both quantitative and qualitative measures will be obtained.

The qualitative analysis will be focused on a questionnaire where physicians can provide their opinion about usability and utility of the system. The results obtained will be studied for improving the system in a future work.

The quantitative analysis, on the other side, will be based on a log, storing the number of times physicians have voluntarily accessed the decision support module. These statistics will be compared with the answers in the questionnaires in order to conclude which of the reported factors are in fact the most influential ones.

5.4. Evaluation of the clinical effects

Finally, the evaluation of the clinical effects of the system will be carried out comparing statistical outcome quality indicators (i.e. number of diagnosed patients, number of treated patients, number of recovered patients) for (i) the last 12 months before the LIFE system was integrated in the hospital and (ii) the first 12 months of use of it. Possible external changes in between, such as new medical infrastructure acquired by the hospital or changes in available personnel will be taken into account.

6. Conclusions and future work

In this article we have presented a generic software architecture of S-CDSS, oriented to bridging some of the reported challenges of clinical decision support.

Our main contribution consists of a new clinical task model where the different clinical information processing stages (i.e. diagnosis, prognosis, treatment, evolution and prevention) are assumed as a cyclic chain of federated information processing agents. On the basis of this clinical task model, our architecture permits the integration and reutilization of decision support systems along the whole clinical workflow.

Our previous work on CDSS focused on the discovery of new knowledge (implicit). In this article we contribute advances in order to bridge remaining CDSS challenges. We have presented details about the implementation carried out in the breast cancer domain, and about the evaluation methodology that will be used to test the system. Evaluation at the clinical level requires lengthy data gathering processes; in that matter validation results will be available and published in a future work.

In our approach it is not possible to perform a classical validation, where a training data set is used to build the system and a validation data set is used to evaluate it. This is related to the nature of our system of being based on a knowledge model provided by a team of domain experts. Due to the aforesaid reasons the correctness cannot be guaranteed with a classical metric. Our system assumes that the model is correct, and we validate this model comparing decisions recommended by the system with decisions made by end-users (physicians), in order to evaluate discrepancies from a real world decision maker solution.

As future work we will study the full computerized automation of the decision support. We will focus on the acquisition of decision criteria and rules directly from current available knowledge sources, such as clinical guideline repositories and Evidence Based Medicine databases. In particular, we will work on the extraction of the recommendations contained in clinical guidelines. We will model these recommendations as rules, which will feed the Rule Layer of the KREG Model. For this purpose, we will explore natural language processing techniques.

Additionally, we will also work on the application of decision support standards for the modeling of the knowledge and criteria in the system, in order to provide a universal clinical decision support service.

Finally, we aim to explore methodologies and tools for the qualitative and quantitative evaluation of knowledge and experience stored in the system.

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References

Aamodt, A., Gundersen, O.E., Loge, J.H., Wasteson, E., Szczepanski, T., 2010. Case-based reasoning for assessment and diagnosis of depression in palliative care. In: Proceedings of the IEEE 23rd International Symposium on Computer-Based Medical Systems (CBMS), pp 480–485.

Abidi, S.R., Abidi, S.S., Hussain, S., Shepherd, M., 2007. Ontology-based modeling of clinical practice guidelines: a clinical decision support system for breast cancer follow-up interventions at primary care settings. Stud. Health Technol. Inform. 129 (2), 845–849.

Artetxe, A., Sanchez, E., Toro, C., Sanin, C., Szczerbicki, E., Graña, M., Posada, J., 2013. Impact of reflexive ontologies in semantic clinical decision support systems. Cybern. Syst. 44 (2–3), 187–203.

Banerjee, A., Watson, T.F., 2011. Pickard's manual of operative dentistry. Diagnosis, Prognosis, Care Planning: Information Processing. Oxford University Press, Chapter 3.

Berner, E.S., 2007. Clinical Decision Support Systems, Theory and Practice, second ed. Springer, New York.

Berson, T., 2012. Principles of Health Interoperability HL7 and SNOMED. Health Information Technology Standards, second ed. Springer London, United Kingdom.

Bickley, L.S., Szilagyi, P.G., 2003. Bates' Guide to Physical Examination and History Taking, 8th ed. Lippincott Williams & Wilkins, Philadelphia.

Blomqvist, B., 2012. The Use of Semantic Web Technologies for Decision Support – A Survey. Semantic Web journal, IOS Press, pp. 1–24.

Bürkle, T., Ammenwerth, E., Prokosch, H.U., Dudeck, J., 2001. Evaluation of clinical information systems. What can be evaluates and what cannot? J. Eval. Clin. Pract 7 (4), 373–385.

Ciccarese, P., Wu, E., Wong, G., Ocana, M., Kinoshita, J., 2008. The SWAN biomedical discourse ontology. J. Biomed. Inform. 41, 739–751.

Colantonio, S., Martinelli, M., Moroni, D., Salvetti, O., Chiarugi, F., Emmanouilidou, D., 2009. A decision support system for aiding heart failure management. In: Proceedings of the Ninth International Conference on Intelligent Systems Design and Applications, Pisa, Italy, pp. 351–356.

Craig, I., 1995. Blackboard Systems. Ablex Publishing, Norwood, US.

Das, M., Eichner, J., 2010. Challenges and Barriers to Clinical Decision Support (CDS) Design and Implementation Experienced in the Agency for Healthcare Research and Quality CDS Demonstrations. AHRQ Publication, Rockville, MD, No. 10–0064-EF.

De Castro, S., 2006. Manual de Patología General. In: Perez, J.L. (Ed.), 6th ed. 6th ed. Elsevier-Masson, Barcelona, Spain.

Eom, J.H., Kim, S.C., Zhang, B.T., 2008. AptaCDSS-E: a classifier ensemble-based clinical decision support system for cardiovascular disease level prediction. Expert Syst. Appl. 34 (4), 2465–2479.

Farion, K., Michalowski, W., Wilk, S., O'Sullivan, D., Rubin, S., Weiss, D., 2009. Clinical decision support system for point of care use – ontology-driven design and software implementation. Methods Inf. Med. 48 (4), 381–390.

Flores-Mendez, R.A., 1999. Towards the standardization of multi-agent system frameworks: an overview. ACM Crossroads, Special Issue on Intelligent Agents, Association for Computer Machinery, Issue 5.4, pp. 18–24.

Fortney, J.C., Pyne, J.M., Steven, C.A., Williams, J.S., Hedrick, R.G., Lunsford, A.K., Raney, W.N., Ackerman, B.A., Ducker, L.O., Bonner, L.M., Smith, J.L., 2010. A web-based clinical decision support system for depression care management. Am. J. Manage. Care 16 (11), 849–854.

Friedlin, J., Dexter, P.R., Overhage, J.M., 2007. Details of a successful clinical decision support system. AMIA Annu. Symp. Proc., 254–258.

Frize, M., Walker, R., 2000. Clinical decision-support systems for intensive care units using case-based reasoning. Med. Eng. Phys. 22 (9), 671–677.

Garg, A.X., Adhikari, N.K., McDonald, H., Rosas-Arellano, M.P., Devereaux, P.J., Beyene, J., Sam, J., Haynes, R.B., 2005. Effects of computerized clinical decision support systems on practitioner performance and patient outcomes: a systematic review. JAMA 293 (10), 1223–1238.

Gérvas, J., Starfield, B., Heath, I., 2008. Is clinical prevention better than cure? The Lancet 372, 1997–1999.

Gnanambal, S., Thangaraj, M., 2010. Research directions in semantic web on healthcare. J. Comput. Sci. 1, 449–453.

Gray, W.D., John, B.E., Atwood, M.E., 1993. Project ernestine: validating a GOMS analysis for predicting and explaining real-world performance. Hum. Comput. Interact. 8 (3), 237–309.

Greenes, R.A., 2006. Why clinical decision support is hard to do. AMIA Annu. Symp. Proc. 2o06, 1169.

Gruber, T.R., 1995. Toward principles for the design of ontologies used for knowledge sharing. Int. J. Hum. Comput. Stud. 43 (5–6), 907–928.

Hasan, S.S., Isaac, R.K., 2011. An integrated approach of MAS-CommonKADS, model-view-controller and web application optimization strategies for web-based expert system development. Expert Syst. Appl. Int. J. 38 (1), 417–428.

Holbrook, A., Xu, S., Banting, J., 2003. What factors determine the success of clinical decision support systems? AMIA Annu. Symp. Proc. 2003, 862.

Holsapple, C.W., 2008. DSS architecture and types. In: Burstein, F., Holsapple, C.W. (Eds.), Handbook on Decision Support Systems 1, Part II - Decision Support System Fundamentals. Springer, Berlin Heidelberg, pp. 163–189.

Houshiaryan, K., Kim, H.S., Kim, H.H., Tung, T., Kim, I.K., Kwak, Y.S., Cho, H. 2005. Customized ontology-based intelligent medical terminology tool. In: Proceedings of 7th International Workshop on Enterprise networking and Computing in Healthcare Industry, pp. 320–324.

Hussain, S., Abidi, S.R., Abidi, S.S.R., 2007. Semantic web framework for knowledge-centric clinical decision support systems. Artif. Intell. Med. 4594, 451–455.

Isern, D., Moreno, A., 2008. Computer-based execution of clinical guidelines: a review. Int. J. Med. Inf. 77, 787–808.

Isern, D., Sanchez, D., Moreno, A., 2010. Agents applied in health care: a review. Int. J. Med. Inf. 79, 145–166.

Kalogeropoulos, D.A., Carson, E.R., Collison, P.O., 2003. Towards knowledge-based systems in clinical practice. Development of an integrated clinical information and knowledge management support system. Comput. Methods Programs Biomed. 72, 65–80.

Kawamoto, K., Houlihan, C.A., Balas, E.A., Lobach, D.F., 2005. Improving clinical practice using clinical decision support systems: a systematic review of trials to identify features critical to success. BMJ 330 (7494), 765.

Laleci, G.B., Dogac, A., Olduz, M., Tasyurt, I., Yuksel, M., Okcan, A., 2008. SAPHIRE: a multi-agent system for remote healthcare monitoring through computerized clinical guidelines. In: Annicchiarico, R., Cortés, U., Urdiales, C. (Eds.), Agent Technology and e-Health. Whitestein Series in Software Agent Technologies and Autonomic Computing. Birkhäuser, Basel, pp. 25–44.

Life Consortium, 2012. Life Project Home Page (only in Spanish), URL: www.proyectolife.com (Last accessed 11.20.2012).

Lindgren, H., 2012. Towards personalized decision support in the dementia domain based on clinical practice guidelines. User Model. User-Adap. Inter. 21 (4), 377–406.

Liu, J., Wyatt, J.C., Altman, D.G., 2006. Decision tools in health care: focus on the problem, not the solution. BMC Med. Inf. Decis. Making 6 (4).

Mahmud, F.B., Yusof, M.M., Shahrul, A.N., 2011. Ontological based clinical decision support system (CDSS) for weaning ventilator in Intensive Care Unit (ICU). In: Proceeding of 2011 International Conference on Electrical Engineering and Informatics (ICEEI), pp. 1–5.

Mathe, J.L., Ledeczi, A., Nadas, A., Sztipanovits, J., Martin, J.B., Weavind, L.M., Miller, A., Miller, P., Maron, D.J., 2009. A model-integrated, guideline-driven, clinical decision-support system. Softw. IEEE 26 (4), 54–61.

Merabti, T., Joubert, M., Lecroq, T., Rath, A., Darmoni, S.J., 2010. Mapping biomedical terminologies using natural language processing tools and UMLS: Mapping the Orphanet thesaurus to the MeSH. IRBM 31, 221–225.

Niès, J., Colombet, I., Degoulet, P., Durieux, P., 2006. Determinants of success for computerized clinical decision support systems integrated into CPOE systems: a systematic review. AMIA Annu. Symp. Proc. 2006, 594–598.

Nyström, M., Vikström, A., Nilsson, G.H., Ahlfeldt, H., Orman, H., 2010. Enriching a primary health care version of ICD-10 using SNOMED CT mapping. J. Biomed. Semant. 1 (7).

Ortiz-Fournier, L., Ramaswamy, M., 2010. Healthcare knowledge collection for clinical decision support systems. Issues Inf. Syst. 11 (1), 538–546.

Osheroff, J.A., Teich, J.M., Middleton, B.F., Steen, E.B., Wright, A., Detmer, D.E., 2007. A roadmap for national action on clinical decision support. JAMIA 14 (2), 141–145.

Paranjape, R., Sadanand, A., 2010. Multi-agent systems for healthcare simulation and modeling: applications for system improvement. IGI Global, Hershey, PA, USA.

Patel, V.L., Allen, V.G., Arocha, J.F., Shortliffe, E.H., 1998. Representing clinical guidelines in GLIF. Individual and collaborative expertise. J. Am. Med. Inf. Assoc. 5, 467–483.

Peleg, M., Tu, S.W., 2006. Decision support, knowledge representation and management in medicine. In: Haux, R., Kulikowski, C. (Eds.), 2006 IMIA Yearbook of Medical Informatics: Assessing Information – Technologies for Health. Schattauer Verlagsgesellschaft GmbH, Stuttgart, pp. 72–80.

Power, D.J., 2008. Decision support systems: a historical overview. In: Burstein, F., Holsapple, C.W. (Eds.), Handbook on Decision Support Systems, Part I – Foundation of Decision Support Systems. Springer, Berlin Heidelberg, pp. 121–140.

Rinott, R., Carmeli, B., Kent, C., Landau, D., Maman, Y., Rubin, Y., Slonim, N., 2011. Prognostic data-driven clinical decision support – formulation and implications. In: Moen, A., Andersen, S.K., Aarts, J., Hurlen, P. (Eds.), Studies in Health Technology and Informatics 169, User Centred Networked Health Care – Proceedings of MIE 2011, pp. 140–144.

Rozman, C., 2006. Compendio de Medicina Interna, 3rd ed. Elsevier, Madrid, Spain.

Sanchez, E., Toro, C., Carrasco, E., Bueno, G., Parra, C., Bonachela, P., Graña, M., Guijarro, F., 2011. An architecture for the semantic enhancement of clinical decision support systems. In: König, A., Dengel, A., Hinkelmann, K., Kise, K., Howlett, R., Jain, L. (Eds.), Knowledge-Based and Intelligent Information and Engineering Systems, LNCS 6882. Springer, Berlin Heidelberg, pp. 611–620.

Sanin, C., Szczerbicki, E., 2008. Decisional DNA and the smart knowledge management system: a process of transforming information into knowledge. In: Gunasekaran, A. (Ed.), Techniques and Tools for the Design and Implementation of Enterprise Information Systems. IGI, New York, pp. 149–175.

Sanin, C., Szczerbicki, E., Toro, C., 2007. An OWL ontology of set of experience knowledge structure. J. Univ. Comput. Sci. 13 (2), 209–223.

Santos, M.R., Bax, M.P., Kalra, D., 2010. Building a logical EHR architecture based on ISO 13606 standard and semantic web technologies. Stud. Health Technol. Inf. 60, 161–165, MEDINFO 2010.

Shirabad, J.S., Wilk, S., Michalowski, W., Farion, K., 2012. Implementing an integrative multi-agent clinical decision support system with open source software. J. Med. Syst. 36 (1), 123–137.

Sim, I., Gorman, P., Greenes, R.A., Haynes, R.B., Kaplan, B., Lehmann, H., Tang, P.C., 2001. Clinical decision support systems for the practice of evidence-based medicine. J. Am. Med. Inf. Assoc. 8 (6), 527–534.

Sittig, D.F., Wright, A., Osheroff, J.A., Middleton, B., Teich, J.M., Ash, J.S., Campbell, E., Bates, D.W., 2008. Grand challenges in clinical decision support. J. Biomed. Inf. 41 (2), 387–392.

Straus, S.E., Glasziou, P., Richardson, W.S., Haynes, R.B., 2011. Evidence-based medicine. How to practice and teach it, fourth ed. Elsevier.

Subirats, L., Ceccaroni, L., 2011. An ontology for computer-based decision support in rehabilitation. In: Proceedings of the 10th Mexican international conference on Advances in Artificial Intelligence (MICAI) Part I. Springer-Verlag, Berlin, pp. 549–559.

Sycara, K.P., 1998. Multiagent systems. AI Mag. 19 (2), 79–92.

Toro, C., Sanín, C., Szczerbicki, E., Posada, J., 2008. Reflexive ontologies: enhancing ontologies with self-contained queries. Cybern. Syst. Int. J. 39, 171–189.

Toro, C., Sanchez, E., Carrasco, E., Mancilla-Amaya, L., Sanín, C., Szczerbicki, E., Graña, M., Bonachela, P., Parra, C., Bueno, G., Guijarro, F., 2012. Using set of experience knowledge structure to extend a rule set of clinical decision support system for alzheimer's disease diagnosis. Cybern. Syst. 43 (2), 81–95.

Whetzel, P.L., Noy, N.F., Shah, N.H., Alexander, P.R., Nyulas, C., Tudorache, T., Musen, M.A., 2011. BioPortal: enhanced functionality via new Web services from the National Center for Biomedical Ontology to access and use ontologies in software applications. Nucleic Acids Res. (39(Web Server issue)), W541–W545.

Wright, A., Sittig, D.F., 2008. A four-phase model of the evolution of clinical decision support architectures. Int. J. Med. Inf. 77 (10), 641–649.

Xing, L., Shengjun, Z., 2010. One mountain with two tigers – China and the United States in East Asian Regionalism. Perspect. Fed. 2 (3), 110–129.

Yu, W.D., Jonnalagadda, S.R. 2006. Semantic Web and Mining in Healthcare. e-Health Networking, Applications and Services, pp. 198–201.

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Decisional DNA for modeling and reuse of experiential clinical assessments in breast cancer diagnosis and treatment

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ABSTRACT

Clinical Decision Support Systems (CDSS) are active knowledge resources that use patient data to generate case specific advice. The fast pace of change of clinical knowledge imposes to CDSS the continuous update of the domain knowledge and decision criteria. Traditional approaches require costly tedious manual maintenance of the CDSS knowledge bases and repositories. Often, such an effort cannot be assumed by medical teams, hence maintenance is often faulty. In this paper, we propose a (semi-) automatic update process of the underlying knowledge bases and decision criteria of CDSS, following a learning paradigm based on previous experiences, such as the continuous learning that clinicians carry out in real life. In this process clinical decisional events are acquired and formalized inside the system by the use of the SOEKS and Decisional DNA experiential knowledge representation techniques. We propose three algorithms processing clinical experience to: (a) provide a weighting of the different decision criteria, (b) obtain their fine-tuning, and (c) achieve the formalization of new decision criteria. Finally, we present an implementation instance of a CDSS for the domain of breast cancer diagnosis and treatment.

1. Introduction

The human factor is decisive in the success of clinical decisions, as the reasoning capabilities and prior knowledge on the problem are important at the time where decisions are made [60]. Recently, several studies have discussed human errors in medicine and their impact to the health system [19,20,36,10,33]. According to [36] it is estimated that between 44.000 and 98.000 patients died every year in the 1990s in US due to medical errors, with costs exceeding the 17 and 29 billion American dollars. Brennan et al. [10] argued that about 50% of those errors were preventable. At the beginning of the 2000s,a patient safety movement became stronger, influenced by other sectors such as aviation or nuclear power, where the tolerated failure rates were in comparison extremely lower [33], while, at the same time, human error in the health system was becoming to be accepted as inevitable. Since then, efforts have been made towards the development and the implementation of solutions aimed at the reduction of the incidence and impact of preventable medical errors [33]. In this context the development of Clinical Decision Support Systems (CDSS) has been encouraged, due to their expected ability of highlight errors, thus increasing error prevention [32,7].

By definition, CDSS are active knowledge resources that use patient data to generate case specific advice at the space-time point where decisions are made [7,40]. They provide several modes of decision support, including alerts, reminders, advice, critiques, and suggestions for improved care [32]. CDSS have been successfully proven at the academic level [8], without reaching transference to real clinical environments yet. Factors affecting this lack of success have been analyzed recently [40,47,62,35]. In particular, difficulties in knowledge base maintenance and updating have been identified as a key factor [62,4].

In order to provide recommendations, CDSS need to incorporate knowledge about the different domains, disease mechanisms,

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considered intervention details and/or decision criteria. This knowledge is generated from various sources, such as Clinical Practice Guidelines (CPG), medical journals, conferences, books and hospital internal reports.

In general, specification of a knowledge domain is usually made by a group of domain experts, who share their knowledge and reach an agreement [71]. The process steps are as follows [45]: (i) literature review, (ii) evidence evaluation, (iii) drafting of the domain knowledge and decision criteria, (iv) consultation and peer review between different domain experts, and (v) approval of contents. Two main issues arise at this point:

- New findings and discoveries take place each and every day in the clinical domain. Therefore content updating should be redone periodically. Medical teams cannot assume the effort because they lack the resources needed for such tasks, and thus the CDSS supporting knowledge may easily become out-dated, and even obsolete.
- The manual updating of domain rules has a great risk of introducing inconsistencies and semantic noise. On the other hand, we need that the relevant-to-the-domain rulesets are as extensible as possible. Therefore, tools for rule handling are required to facilitate the addition of new rules ensuring the correctness of the updated system. Additionally, each rule has a different weight or importance in a decision (i.e. in diagnosing flu, having fever is more decisive than having cough and mucosity). When the process of rule generation is performed by hand, rule weighting becomes subjective. Objective metrics that could lead in the future to rule comparison are hence required for standardization.

In this paper, we propose a technological solution that allows a (semi-)automatic updating of the underlying knowledge bases and decision criteria of CDSS. We hypothesize that they can be updated by following the same continuous learning paradigm followed by clinicians in real life, which is based on the knowledge acquired along with real life experience. In order to achieve that, in our system clinical Decisional Events are acquired and formalized by the use of experiential knowledge representation techniques, such as Set Of Experience Knowledge Structure (SOEKS) [13] and Decisional DNA (DDNA) [53].

We present specifications of the experience model, as well as of the experience acquisition and consolidation process. Based on those techniques, we propose three different algorithms processing experience in order to evolve the initial ruleset of a CDSS: rule weight evolution, rule fine-tuning, and rule generation. We also present an implementation of our approach within a Semantically steered CDSS (S-CDSS) for the domain of breast cancer diagnosis and treatment.

The structure of the paper is as follows: in Section 2 we present relevant concepts about the state of the art in clinical decision making, experience acquisition and experience modeling techniques; in Section 3 we give the specification of the experience modeling structure and describe the experience acquisition and consolidation process; in Section 4 we present three different rule evolution algorithms: rule weight evolution, rule fine-tuning, and new rule generation; in Section 5 we present a case study of the system for the breast cancer domain, and finally, in Section 6, conclusions and future work are summarized.

2. Background concepts

In this section we describe relevant concepts regarding clinical decision-making. First, we introduce clinical reasoning. Prior experiences of medical professionals play an important role in this context, thus our CDSS should consider the management of clinical experience. Then, a brief introduction to experience acquisition and experience modeling techniques is presented. Following our applied Decisional DNA and Set of Experience Knowledge Structure technologies are introduced. Finally, a brief state of the art is presented, including a critical discussion of other approaches for knowledge adaptation and learning, which could be competing or complementary to our work.

2.1. Clinical decision making and decision support

The process of clinical decision-making was not studied in deep until the late 1990s, when concerns on avoiding medical errors arose. Before, clinical decision-making was widely accepted as an esoteric matter that only concerned physicians, and no systematic effort was done to analyze possible errors and their causes [19]. Recently, the underlying processes have been studied and a consensus has been reached acknowledging the Dual Process Theory [19,44,23,24,48] as a valid model which differentiates two types of clinical reasoning: analytical and intuitive [19]. The former consists of testing hypotheses and concluding the most likely one [23]. It is focused on scientific rigor following a rule-based approach (deductive reasoning).

Nevertheless, the analytical approach requires a high effort from the doctors [24,44,48,66], therefore most of them follow an intuitive clinical reasoning based on their previous experiences on similar situations [49,17]. Intuitive reasoning requires much less effort to decision makers, but is subject to a higher error rate [19]. In fact, if the clinical case is not correctly identified and the similarity based reasoning process with prior experiences does not take into account all relevant parameters, the final decision may not be adequate. In general, everyday clinical practice is heavily influenced by previous experiences. This fact is reflected in medical learning and training programs, which emphasize the continuous acquisition of new experiences to enrich the knowledge of trainees [66,70,34].

Increasingly, the reasoning processes of CDSS are becoming similar to those followed by physicians in real life. In fact, recent approaches on CDSS follow both reasoning types. The intuitive approach is followed by Case-Based Reasoning systems [11,21,27,74,2,1]. Their major limitation is that the quality of the output depends on the previous cases included in the knowledge base. Examples of CDSS following the analytic approach [39,38] generate recommendations based on knowledge that is extracted from medical literature and evidence. Their major weakness is the difficulty for continuously updating the knowledge and decision criteria applied for the reasoning.

We hypothesize that, in the same manner as with physicians, a combined approach of analytic and intuitive modes for the CDSS reasoning processes could support both the production of recommendations and the update of the knowledge in the system. Thus, in our proposed mixed approach (i) recommendations are generated based on a set of production rules given by medical experts and (ii) those rules are updated by the system with the acquired experience. Next we review the state of the art techniques for CDSS acquisition and modeling of decisional experience.

2.2. Experience acquisition and experience modeling

Experience, as a general concept, comprises previous knowledge or a skill obtained through daily life [68,67]. Experience is understood as a kind of knowledge gained from real world practice rather than books, research, and studies [61]. In this way, experiential knowledge can be regarded as a specialization of knowledge that includes information and strategies obtained from performing previous tasks. When these tasks involve making decisions, we talk about gaining *decisional experience*.

The importance of decisional experience in knowledge engineering, and especially in knowledge sharing, has been recognized at least since the last ten years. European and Australian studies reported in [9] have established that the primary research aim of knowledge management (KM) should be to use the vast experience accumulating each day within organizations and systems, as far as true knowledge is developed through learning from current and past experiences [25,6]. Experience management (EM), its formalization, representation, and experience based systems development are capturing increasingly growing attention of researchers and practitioners. However, formulating the underlying problems and their solutions has not shown much progress yet. The fundamental limitation of current research in this area is that none of the proposed approaches uses experience as ongoing, real time knowledge source along the decisional process as happens naturally when humans make decisions to answer a new situation.

In summary, we require experience based modeling systems to store and reuse experience in an ongoing, real-time representation system endowed with the following critical features:

- Adaptability and cross-platform portability.
- Compactness and efficiency.
- Configurability and shareability.
- Security and trust.
- Being exclusively experience oriented.

2.3. Decisional DNA

We follow an approach to experience acquisition inspired in the way DNA stores and transmits information and knowledge. In nature, DNA contains "…the genetic instructions used in the development and functioning of all known living organisms. The main role of DNA molecules is the long-term storage of information. DNA is often compared to a set of blueprints and the DNA segments that carry this genetic information are called genes" [22]. The contribution of this approach is an architecture to support discovering, adding, storing, improving and sharing information and knowledge among agents, machines, and organizations through experience. We introduce a novel Knowledge Representation (KR) approach in which experiential knowledge is represented by Set of Experience (SOE), and is carried into the future by Decisional DNA (DDNA) [13,53] (see Fig. 1). The expressions "Set of Experience – SOE" and "Decisional DNA – DDNA" were coined during works in the period 2006–2007 [12,56,55,54]. Since then, our research efforts resulted in multi-technology shareable knowledge structure for decisional experience with proven portability, adaptability, shareability, security, and trust [57] and clinical decision-making environments [3,52,72].

2.4. State of the art approaches

Most current Computational Intelligence techniques for decisional system require quantified data that can be processed by analytically sound methods. When dealing with imprecise knowledge, as in CDSS, the basic requirement of quantified noise-free data may be an overwhelming condition. Following we present some relevant state of the art approaches, discussing their limitations for experience based knowledge modeling in the context of CDSS.

Support Vector Machines (SVM) [73,26,69] are supervised learning models for classification and regression analysis. In essence, they find a discriminating surface as a (non-)linear

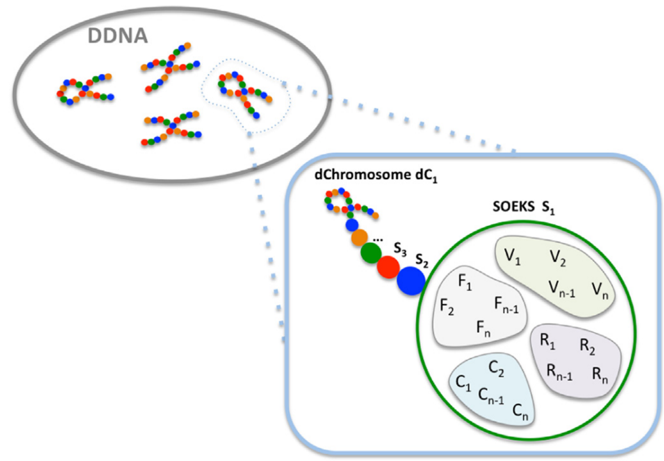

Fig. 1. SOE is combination of four components that characterize decision making actions (variables, functions, constraints, and rules) and it comprises a series of mathematical concepts (a logical component), together with a set of rules (a ruled based component), and it is built upon a specific event of decision-making (a frame component); Sets of Experience (Decisional Genes) are grouped according to their phenotype creating Decisional Chromosomes and groups of chromosomes create the Decisional DNA.

combination of support vectors providing the maximal separation (margin) between the classes, providing the greatest generalization of the classifier to unseen new data samples. The learning process consists of a dual minimization of a cost function, in which the classification error and some ad hoc regularization parameters are involved. In order to obtain good performance, hyperparameter optimization is needed, and therefore each learning experiment in SVM needs to be wrapped with a grid search procedure [42]. Though SVM have become a kind of de-facto standard for classification problems in many application domains, it is well known that they are very sensitive to data normalization, imbalanced distributions, and variations of the distributions which imply dramatic variations of the SVM hyperparameters when the data sample is changed. In summary, SVM would be rather inadequate as the basis for a CDSS which tries to follow the changes in clinical experience, where data may be unstable and imprecise, some problem instances have scarce samples, and decisions have some risk of noise.

Artificial Neural Networks (ANN) [51,29,28] are a collection of simple computational units interlinked by a system of connections [16] whose computation and training follow an early biological inspiration. Perceptrons are the basic ANN. Examples of more complex ANN approaches are Radial Basis Function networks (RBF) [15,29] whose neuron activation function is a radial basis function, and Probabilistic Neural Networks (PNN) [65], which in the context of classification use a kernel-based approximation to build an estimation of the probability density function of each class. Learning vector quantization (LVQ) [37,64] provides a method for supervised training competitive networks [58]. The input space is partitioned by an unsupervisedly trained competitive layer, and according to crisp clustering (input region) and/or soft clustering (degree of membership) input data is labelled by a supervisedly trained output layer. Extreme learning machine (ELM) [31,30] is a fast training approach for the single layer feed-forward neural networks (SFLN), providing on average good quality classification and regression results whose computation burden is orders of magnitude lower than conventional backpropagation training. However, ELM major criticism is the uncertainty of its performance due to the random generation of the hidden layer weights. Ensemble methods [5,14] may overcome such criticism with increasing computational cost. In general, ANN have sound and robust, though some of them are very time consuming, training algorithms. In some problem instances they retain their appeal because of their resilience. However, in the context of CDSS, one important criticism to ANN is their lack of explanation capacity, because there is no explicit representation of knowledge, as it is implicitly represented in the patterns of interactions between network components [43].

In a broad characterization, Computational Intelligence approaches as discussed above require the specification of a dataset which is assumed as a sample of the real process. Training algorithms may or not be sensitive to some numerical conditions, such as missing data and data scarcity, but they are definitively dependent of this dataset, and they often lack adaptability to new data or non-stationary environments. In general, they cope with this problem by retraining the system from scratch. Moreover, the bare data representation of the decisional event may not be enough in CDSS which require also to take into account the decision context. In fact, the context of a decisional event provides relevant information on how and why such decision was made, rather than only focusing on the final decision value. In order to represent the context of a decision, relations between data should be included in the experience representation model (such as restrictions, rules and functions in general). Such needs are not easily satisfied by SVM or ANN approaches.

The Case-Based Reasoning (CBR) approach [59,50] represents each decisional event independently as a case, and stores them into a previous case database. For each new case inputed to the system, (i) first, the relevant previous cases are retrieved; (ii) following, the knowledge in the cases retrieved is reused to propose a solution (classification) for the new one; (iii) the proposed solution is then revised by external means; and (iv) finally, the system learns by retaining the new case in the previous case base. The CBR allows some incremental learning, however the main limitation of current works on CBR [11,21,27,74,2,1] is their need to rely on static quantitative case characterizations in order to compute some kind of distance among cases to perform the search in the case database. The development of CDSS deals with imprecise and evolving characterizations of the decisional events that may not easily be dealt with by CBR.

3. Specification and reutilization of the experience model

Decisional experience is gathered by means of acquiring a historic file of Decisional Events that take place. Elements that conform a Decisional Event are captured into a SOEKS object every time a decision is made. We assume the clinical environment in the following.

Let a SOEKS be specified as a tuple $\mathbb{S}_t = \langle \{\mathcal{V}_n\}, \{C_m\}, \{\mathcal{R}_k\}, \{\mathcal{F}_p\} \rangle$, where

(i) $\{\mathcal{V}_n\}$ is a set of variables involved during the Decisional Event happening to a patient instance $I_i \in I$ to which the decision is oriented. Variables formally describe experience-based knowledge structure using an attribute-value language [12,46]. Let $\{\mathcal{V}_n\}$ be the set of variables of a domain, where a variable $\mathcal{V}_n = \langle V_n, v_n \rangle$ is composed by a variable specification V_n and a value v_n. Let a variable specification be the tuple $V_n = \langle t_V, \{\mathcal{C}_m\} \rangle$, where t_V is the type of variable (i.e. Integer, Float, Double, String) and $\{\mathcal{C}_m\}$ is a set of constraints, as defined below.

(ii) $\{\mathcal{C}_m\}$ is a set of constraints selecting a subspace ϕ_m of the value range of variables $\mathcal{V}_n$. Constraints describe relationships among variables, restricting the possibilities of feasible values. Each constraint is specified as a predicate, which can be expressed as follows: $\phi_m = \{v | C_m(v).\}$.

(iii) $\{\mathcal{R}_k\}$ is a set of rules that apply for the decision. Rules are used to express logical relationships among variables. They are specific evaluations of variables under a given fact. They are suitable for representing inferences, or for associating actions with conditions under which actions should be performed [46]. Each single rule describes a relationship between a condition and a consequence linked by the statements IF-THEN-ELSE. Let us specify a rule as a tuple $\mathcal{R}_k = \langle A_k, S_k, L_k, W_k, B_k \rangle$, where A_k denotes the antecedent clauses (IF-part), Q_k and L_k the consequent actions of the rule (THEN- and ELSE-parts, respectively), W_k the weight of the rule such that $W_k \in [0,1]$, and B_k is an auxiliary parameter. A_k sets value intervals for a subset of variables $\{\mathcal{V}^c_{n_k}\}$, that we call the conditional variables. Let us denote $M(A_k, \mathbb{S}_t)$ the matching predicate, which is true when values of a SOEKS $\mathbb{S}_t$ are within the value intervals set by the antecedent A_k. Q_k and L_k set action values to a different subset of variables $\{\mathcal{V}^s_{n_k}\}$, that we call consequent variables. Each consequent variable establishes a decision category d_i to which a rule $\mathcal{R}_k$ can provide recommendations.

(iv) $\{\mathcal{F}_p\}$ is a set of functions that evaluate variables. Functions describe associations between a dependent variable and a set of input variables. Abusing the notation, we can say that $\mathcal{F}_p : \times_{n \in N} \mathbb{V}_n \rightarrow \mathbb{V}_p$, that is, $v_p = \mathcal{F}_p(v_{n_1}, \ldots, v_{n_N})$, where $\mathbb{V}_n$ denotes the range of values of variable $\mathcal{V}_n$. Functions can be applied to reduce ambiguity between the different possible states of the variable set and to reason optimal states.

A sequence of SOEKS on the same decision category d, indexed by their time of occurrence, are stored, together with the corresponding final decision f_t carried out by the decision maker, in a Decisional Chromosome (DChromosome) $\mathbb{C}_d = \{(\mathbb{S}^t, f_t)\}$. A Decisional DDNA (DDNA) is a collection of DChromosomes $\mathbb{D}_m = \{\mathbb{C}_d\}$, which is specific for each decision maker m.

3.1. Experience acquisition and consolidation process

In our approach, a Decisional Event represents a decision made on an individual I_i, and a decision category d_i, for which a set of recommendations have been generated based on a given set of rules. The action of making the decision implies the selection of a final decision $f \in \mathbb{F}$ by the decision maker m_i. Such final decision can be made according to the provided recommendations or not. In a very general setting, a Decisional Event is stored into a SOEKS as follows:

1. Data associated with I_i is mapped into variables $\{\mathcal{V}_n\}$. Variable values v_n and constraints $\{\mathcal{C}_n\}$ are also mapped into $\{\mathcal{V}_n\}$.
2. Rules applying to decision domain d_i are stored in $\{\mathcal{R}_k\}$.
3. Applying functions are stored in $\{\mathcal{F}_p\}$.

The set of SOEKS stored into DChromosomes and DDNA will follow a temporal succession. Once Decisional Events are acquired into a SOEKS structure, the information they contain can be used by ruleset evolution algorithms. In the next sections, some of those algorithms will be presented, allowing to (i) gradually and repeatedly correct rules as well as deprecate them relying on the existing experience, and (ii) generate new rules. In particular, three different algorithms will be presented, two for rule edition/deprecation (i.e. rule weight evolution and fine-tuning of rules), and a case based reasoning algorithm for new rule generation.

Suggested changes on rules resulting from those methods will be provided at a secondary rule set. Such secondary ruleset will then be analyzed by a committee of domain experts, that will agree which of those changes to include in the primary ruleset.

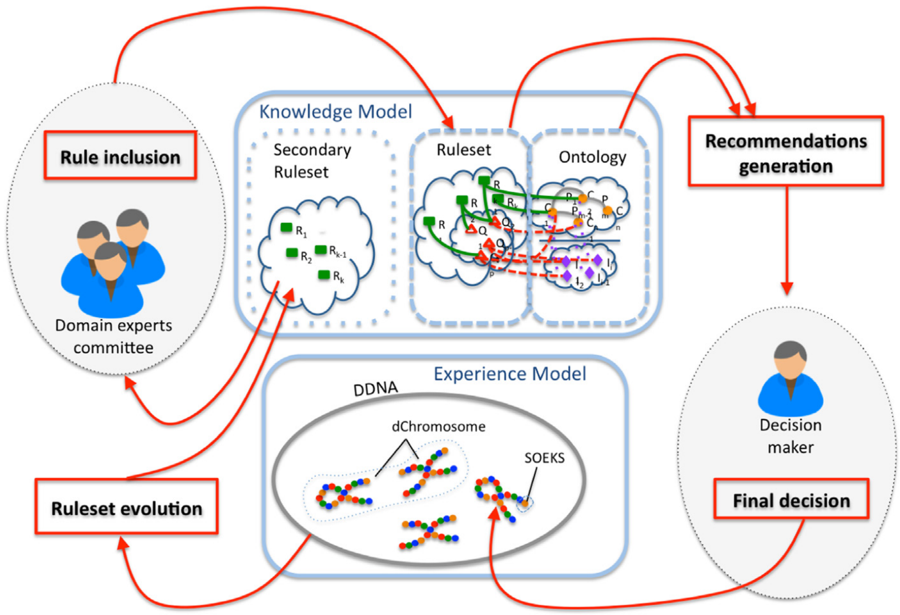

Fig. 2. Experience acquisition process.

Fig. 2 illustrates the complete experience acquisition process, including the generation of SOEKS and the evolution of the ruleset.

4. Rule evolution algorithms

In this section three different rule evolution algorithms will be presented: first, a rule weight evolution algorithm based on quantitative and qualitative criteria; additionally, an algorithm for the fine-tuning of rule conditional query clauses based on a qualitative measure, and finally, a case based reasoning algorithm for new rule generation.

4.1. Rule-weight evolution

Rule weight is a core feature of each rule in the SOEKS, used to indicate its importance with regard to other rules that provide recommendations for the same decision. The weight of a rule, W_k, objectively measured, is influenced by three distinct aspects:

1. *Quantitative measure*: The number of times a rule matches conditions of individuals, and, thus, its consequent value is recommended by the Decision Support System (DSS).
2. *Qualitative measure*: The number of times that, when a rule matches conditions of individuals, its consequent value coincides with the final value chosen by the decision maker.
3. *Trust/reputation of decision.*

Let $\mathbf{X} = \{X_1, X_2, \ldots, X_t, \ldots, X_T\}$ be a condition matching vector and $\mathbf{E} = \{E_1, E_2, \ldots, E_t, \ldots, E_T\}$ an error vector, such that

$$X_t = \{x_{t1}, x_{t2}, \ldots, x_{tk}, \ldots, x_{tK_t}\},$$
$$E_t = \{e_{t1}, e_{t2}, \ldots, e_{tk}, \ldots, e_{tK_t}\},$$

where T is the number of SOEKS in a dChromosome $\mathbb{C}_d$, and K_T is the number of rules in a SOEKS $\mathbb{S}_t$. Entries x_{tk} and e_{tk} in these matrices have two possible values, 1 or 0, defined as

$$x_{tk} = \begin{cases} 1 & \text{if } M(A_k, \mathbb{S}_t) \\ 0 & \text{otherwise} \end{cases},$$

$$e_{tk} = \begin{cases} 1 & \text{if } (x_{tk} = 1) \text{ and } (S_k = f_t) \\ 0 & \text{else} \end{cases}.$$

Let us define a collection of trust parameters associated to each decision made by decision maker $m : \boldsymbol{\alpha}_m = \{\alpha_{mt}\}$ where each $\alpha_{mt} \in [0, 1]$ is associated to a different decision maker. Let α_{m_t} be the trust of the final decision associated to a $\mathbb{S}_t$. We define the weight W_k of a rule r_k in the following expression:

$$W_k(\alpha) = \frac{\sum_m \sum_t (x_{mtk} - \alpha_{mt} e_{mtk})}{\sum_m \sum_t \sum_k (x_{mtk} - \alpha_{mt} e_{mtk})}.$$

4.1.1. Trust

In the expressions above, $\boldsymbol{\alpha}_m$ are subjective parameters which measure the perceived trustworthiness of a set of decisions. Trust indicates the level of supervised learning of the process of rule evolution, where a higher α_i implies higher supervision:

(i) When $\alpha_{mt} = 0$: no trust is put on decision maker m, and thus an unsupervised learning is used (quantitative-driven evolution only).
(ii) When $\alpha_{mt} > 0$: the trust level on decision maker m influences the level of supervised learning applied (quantitative- and qualitative-driven evolution).

Each α_{mt} can either be agreed by the team of decision makers, or be set up by every decision maker independently. In the latter case, different weights will be assigned to the same rule, depending on which decision maker sets α_m. The assignment of α_{mt} is done previous to rule weight evolution, and new values can be assigned in the future, if trust on the different decision makers changes.

4.1.2. Recalculation of W_k and convergence of the algorithm

Recalculation of rule weights can be performed either (i) automatically, after a decision occurs or following a certain pre-established frequency such as daily or weekly, or (ii) manually, on demand. When W_k is calculated all SOEKS $\mathbb{S}_t$ for the complete time interval that contain rule r_k are taken into account. Rule-weight evolution algorithm converges towards weights that provide recommendations that correspond either

(i) to the more frequently chosen decisions, in the case of quantitative-driven evolution only, or

(ii) to the ones that are more similar to the final choices of the decision maker, in the case of quantitative- and qualitative-driven evolution.

4.1.3. Weight zero meaning

Weight zero $W_k=0$ has two different meanings:

(i) Rule r_k has not matched yet any individuals data.
(ii) Rule r_k has matched some individuals, and at the 100% of the matches the final decision of the decision maker has been different to the recommended.

At the second case, rules r_k such that $W_k=0$ and $\exists x_{tk}|x_{tk}=1$ are recommended to deprecation.

4.2. Fine-tuning of rules

Fine-tuning of rules consists of adapting rule condition intervals to reduce the difference between recommendations and the final decisions. Let the antecedent of a rule, A_k, be specified by a set of simple query clauses $q^s_{kl}=\langle V,o,v\rangle$, where V is a variable, o is the comparison operator (i.e. $>$, $<$, $=$), and v a value of the range of V. Let us recall the matching predicate $M(A_k,\mathbb{S}_t)$ and extend it as $M(q_{kl},\mathbb{S}_t)$, which is true (active) when the simple query clause q^s_l matches the values of a SOEKS $\mathbb{S}_t$. Without loss of generality, we consider only categorical variables V_n. Let us define two parameters (i) μ_{kl}, counting the total amount of times that a query clause is active in a rule whose antecedent matches some SOEKS, and (ii) ρ_{kl}, counting the total amount of times that the query clause is active in a rule that matches a SOEKS and the final decision of the decision maker is the same as the recommendation of the rule consequent S_k. Formally,

$$\mu_{kl}=\sharp\{\mathbb{S}_t|M(A_k,\mathbb{S}_t) \text{ and } M(q^s_{kl},\mathbb{S}_t),\ q^s_{kl}\in A_k\},$$
$$\rho_{kl}=\sharp\{\mathbb{S}_t|M(A_k,\mathbb{S}_t) \text{ and } M(q^s_{kl},\mathbb{S}_t) \text{ and } (S_k=f_t),\ q^s_l\in A_k\},$$

where $\sharp$ denotes the cardinality of the set.

We define error prone query clauses as those having an error rate $e_{kl}=\rho_{kl}/\mu_{kl}$ greater than a threshold θ. Error prone query clauses are recommended for revision, by a domain experts committee that will decide whether to keep them, change them or remove them. Particularly, query clauses with error rates equal to 100% are recommended for deprecation. Algorithm 1 contains the pseudo code of the rule fine tuning algorithm.

4.2.1. Evolution activation and convergence of the algorithm

The process of fine tuning of rules is activated (i) automatically, after a decision occurs or following a certain pre-established frequency such as daily or weekly, or (ii) manually, on demand.

When fine tuning is calculated all SOEKS $\mathbb{S}_t$ since last change of rules are taken into account.

Algorithm 1 converges towards rules that provide recommendations more similar to the final choices of the decision maker.

Algorithm 1. Pseudocode for rule clause evolution.

```
Set θ
for 𝕊t = 1 to Number of SOEKS
{
  for k = 1 to Number of rules
  {
    if M(Ak, 𝕊t) then
    {
      for l = 1 to Number of query clauses in rule k
      {
        if M(qkl, 𝕊t) then
        {
          μkl = μkl + 1
          if Sk ≠ f then
          {
            ρkl = ρkl + 1
          }
        }
      }
    }
  }
}
for 𝕊t = 1 to Number of SOEKS
{
  for k = 1 to Number of rules
  {
    for l = 1 to Number of query clauses in rule k
    {
      ekl = ρkl / μkl
      if ekl > θ then
      {
        if ekl = 1 then
        {
          Recommend deprecation of query clause qkl in rule rk
        }
        else
        {
          Recommend revision of query clause qkl in rule rk
        }
      }
      else
      {
        Recommend no revision of qkl
      }
    }
  }
}
```

4.3. Rule generation

To generate new rules we propose to follow a case based reasoning approach. Let us assume that a final decision has been made after analyzing a set of recommendation provided by a CDSS. Let $\{V_s\}$ be the set of variables that are relevant for such final decision stored in SOEKS $\mathbb{S}_t$, such that V_s is a variable included in query clauses of A_k and $M(A_k,\mathbb{S}_t)$. Every time a final decision is made decision makers are then asked to validate the set of $\{V_s\}$. They are asked to include the variables V_s that they considered during decision making and to remove the non-relevant ones, generating a new set of relevant variables $\{V'_s\}$.

Changes in $\{V_s\}$ mean that the recommendations that generated the CDSS are not complete. Thus, we generate a new rule where the antecedent equals to the values contained in the new set of relevant variables $\{V'_s\}$ and the consequent equals the final decision f (generated rules are of type IF/THEN).

4.3.1. Ruleset post-processing

The generation of new rules is performed on a secondary ruleset. They are introduced on the ruleset of the Decision Support System (DSS) when analyzed by a committee of domain experts, that will agree which of those rules to include. Thus a post processing of the generated secondary ruleset is needed, in order to detect

(i) spurious rules,
(ii) rules already included in others and
(iii) rules that generate inconsistencies

Such post-processing is done before the analysis of the domain experts committee.

5. Case study: breast cancer diagnosis and treatment

We have implemented a S-CDSS for the domain of diagnosis and treatment of breast cancer, presented in Sanchez et Al [52], under the framework of the Spanish research project LIFE [18]. It is aimed at supporting the Breast Unit of the Valencia University General Hospital (BUV), formed by eight different services of the hospital: (i) radiodiagnosis, (ii) nuclear medicine, (iii) radiation oncology, (iv) rehabilitation, (v) anatomical pathology, (vi) surgery, (vii) medical oncology, and (viii) psychology.

Let us recall the ontology and the ruleset we developed for the LIFE S-CDSS:

- *The LIFE Ontology, depicted in* Fig. 3:
  It is formed by three main classes: *Patient*, *Doctor* and *EHR*. *EHR* stands for Electronic Health Record and contains all patient-related general, sociological and clinical information. These three types of information are reflected in the three subclasses of *EHR*: *General_Information*, *Socio_Demographic_Information*, and *Medical_Tests*.
  Two main object type properties relate the three main classes: *correspondingPatient*, linking an *EHR* instance with a *Patient*, and *orderingDoctor*, linking an *EHR* instance with a *Doctor*.
  Subclass *Medical_Tests* contains eight different subclasses, one for each medical service of the BUV: *Radiodiagnosis*, *Nuclear_Medicine*, *Radiation_Oncology*, *Rehabilitation*, *Anatomical_Pathology*, *Surgery*, *Medical_Oncology*, and *Psychology*.
  The variables contained in the LIFE Data Model are reflected in the LIFE Ontology, by means of data type properties whose domains are these eight classes. An example is depicted in Fig. 3, where two data type properties related to the Radioagnosis service are shown: the BIRADS value for the mammography ("*RD_Mammography_BIRADS*") and the BIRADS value for the ultrasonography ("*RD_Ultrasonography_BIRADS*").
- *The LIFE ruleset, containing decision criteria for diagnosis and treatment of breast cancer*:
  In order to facilitate the creation of the ruleset, the medical team has proposed a new rule generation methodology:
  1. First, for each variable included in the LIFE Data Model (e.g. radiotherapic protocol type, from the radiotherapic oncology service), physicians identify whether it depends on other variables (e.g. the type of radiotherapic protocol applied to each patient depends on the type of surgery applied, the size of the surgical piece of pathologic anatomy, the number of lymph nodes found in the patient during radiodiagnosis and the existence of hypersensibility).
  2. Then, the dependence conditions for every different possible value of the former variable are established (e.g. radiotherapic protocol MAMA-50 is recommended when the type of surgery applied is conservative, there are no lymph nodes, there exists hypersensibility, and the size of the surgical piece of pathologic anatomy is T0, T1mic, T1a or T1b). The different rules will be formed by these conditions.
  3. Finally, each rule is introduced to a web based rule generator tool, integrated within the CDSS application and designed to easily create rules, without dealing with rule syntax. Fig. 4 depicts an example rule generated by the system after it is introduced in the rule generator tool, rule RT0001.

The LIFE S-CDSS allows physicians to request decision recommendations for a certain decision domain. As decision aids for doctors, three different features are provided by the system: (a) patient relevant data summary, (b) recommendation options with their corresponding percentages and a graphical pie chart plot, and (c) bibliography attached to each recommendation option. Finally, physicians select a final decision value, included or not in the set of recommended options. Such Decisional Event is formalized to a SOEKS serializing variables and rules into such structure, and the SOEKS is added to the DDNA of the system.

We evaluated the aforementioned rule evolution algorithms. We selected 62 rules, covering decision criteria for radiation

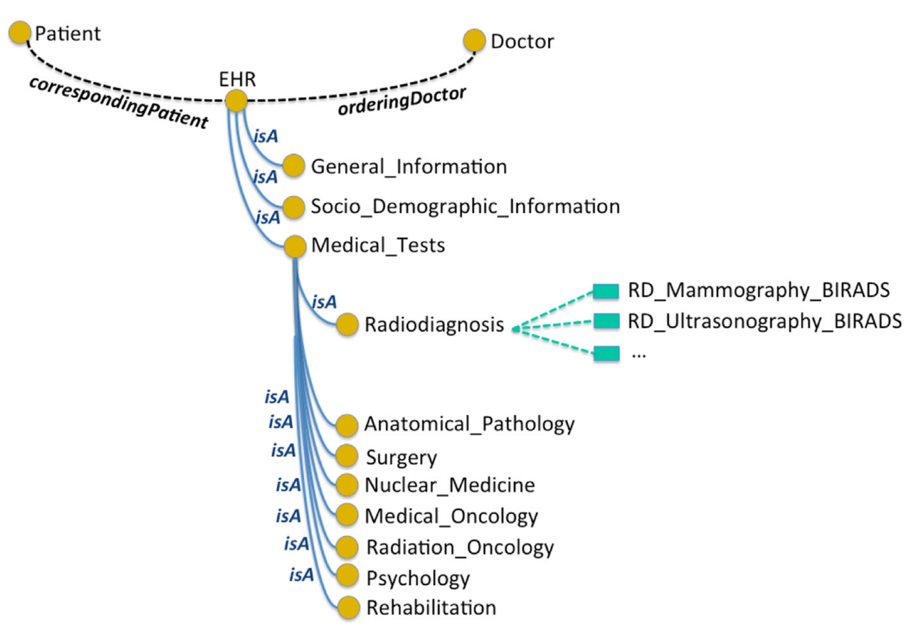

Fig. 3. The LIFE ontology.

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<RuleSet>
        <LoadRule>
                <RuleID>RT0001</RuleID>
                <Rule>If (( CLASS Anatomical_Pathology with the PROPERTY AP_SurgicalPiece_Size EQUALS TO T0 )
OR ( CLASS Anatomical_Pathology with the PROPERTY AP_SurgicalPiece_Size EQUALS TO T1mic )
OR ( CLASS Anatomical_Pathology with the PROPERTY AP_SurgicalPiece_Size EQUALS TO T1a )
OR ( CLASS Anatomical_Pathology with the PROPERTY AP_SurgicalPiece_Size EQUALS TO T1b )
AND ( CLASS Surgery with the PROPERTY S_InterventionType EQUALS TO Conservative )
AND ( CLASS Radiation_Oncology with the PROPERTY RO_hypersensitivity EQUALS TO Yes )
AND ( CLASS Anatomical_Pathology with the PROPERTY AP_SurgicalPiece_LymphNodes EQUALS TO 0 ))
then ( CLASS Radiation_Oncology with the PROPERTY RO_ProtocolName EQUALS TO MAMA-50 ) </Rule>
                <weight>100</weight>
                <AccordingTo>
                        <classes>
                                <class>GivenBySpecialist</class>
                        </classes>
                        <specialist>
                                <specialistType>Radiotherapist</specialistType>
                                <specialistPlace>Hospital General Universitario de Valencia</specialistPlace>
                                <reportTitle>NE</reportTitle>
                        </specialist>
                </AccordingTo>
        </LoadRule>
</RuleSet>
```

Fig. 4. Generated rule example.

oncology, and we introduced in the system 71 example patients. Particularly, the patients introduced in the system only match conditions of a subset of 7 of the rules included in the complete set: rules RT0001, RT0002, RT0011, RT0017, RT0045, RT0061, and RT0062. For each patient a final decision was introduced into the system about the assigned type of radiotherapic protocol. The corresponding SOEKS object was stored into the DDNA of the system.

During the introduction of each final decision the proposed case-based approach for new rule generation was followed. New rules were generated when according to the decision maker the set of variables relevant for such final decision were different from those proposed by the system. The new rules were introduced into a secondary ruleset of the system for a future revision by a domain experts committee.

After the 71 patients were introduced, both the rule weight evolution algorithm and the fine tuning of rules have been executed. Table 1 contains the weights of the 7 rules that match conditions, the percentage of error prone rules, as well as the number of query clauses per rule (NQC) and the number of error prone query clauses (Error NQC) that have an associated change recommendation.

The highest rule weight values when α is set to 0 (i.e. quantitative evolution) are taken by rules RT0001, RT0002 and RT0061 (weight value: 19.14%). They are the most frequent matching rules for our set of 71 patients. However, when we consider $\alpha=1$ (i.e. qualitative and quantitative evolution) the highest rule weight values are taken by rules RT0001 and RT0062 (value: 33.02%). Rules RT0002 and RT0061 are highly error-prone rules (respectively, 87.5% and 100% of the times when a rule matches patient conditions, the final decision of the physician has been a different one), and thus their associated weights decrease with the qualitative mode. In particular, rule RT0061 loses completely its weight, due to a 100% associated error rate.

The fine-tuning of rules algorithm provides the change recommendation for 5 of the 7 rules: RT0001, RT0002, RT0017, RT0061 and RT0062. Particularly, the last column in Table 1 shows the number of query clauses that have an associated change recommendation. Fig. 5 shows an example screenshot of fine-tuning of of rule RT001, where the value T1mic for the surgical piece size is recommended to be removed from the rule (it has an associated error rate of 100%).

Table 1
Rule weights and error prone clauses.

Rule	Weight $\alpha=0$ (%)	Weight $\alpha=1$ (%)	Error prone rules (%)	NQC	Error NQC
RT0001	19.14	33.02	12.5	7	1
RT0002	19.14	4.72	87.5	7	3
RT0011	3.83	7.55	0	3	0
RT0017	11.00	0	100	7	4
RT0045	11.00	21.70	0	6	0
RT0061	19.14	0	100	7	3
RT0062	16.75	33.02	0	1	0

6. Conclusions and future work

In this paper we have presented an experience-based approach that allows the (semi-)automatic maintenance and update of Semantically Steered Clinical Decision Support Systems (S-CDSSS). In our work we have proposed an experience-driven learning process that evolves the ruleset of a S-CDSS based on the previous Decisional Events experienced by physicians (their day-to-day expertise). Particularly, we have proposed three rule evolution algorithms:

(i) A rule weight evolution algorithm that allows the production of rule weights based on a non-subjective metric.
(ii) A rule fine-tuning algorithm that facilitates to the clinical experts committee the rule-maintenance by suggesting error prone rules and query clauses to be reviewed.
(ii) A new rule generation algorithm that extends the ruleset in an easy way, by considering the new cases that appear on the daily routine.

Such evolution process allows the discovery of new knowledge in the system (intrinsic knowledge) (a) facilitating the evaluation of the decisions made previously and the analysis of the actions followed, in order to improve the performance at clinical, ethical or economical levels, (b) allowing the training of new team members or facilitating current members to keep up-to-date, and (c) suggesting new knowledge that could be validated, driving clinical research activities or trials. In this sense, our approach could foster research activities of the medical team.

Our work is based on the experiential knowledge representation techniques SOEKS and Decisional DNA. These techniques have been applied to different domains, but in this work we have shown a successful case study for diagnosis and treatment of breast cancer.

As a future work, we will work on decision traceability, in order to allow analysis of the contribution of each link in the decision chain to the final results.

Also, we will work on the semantization of the Electronic Health Record (EHR), to allow direct integration of S-CDSS in the

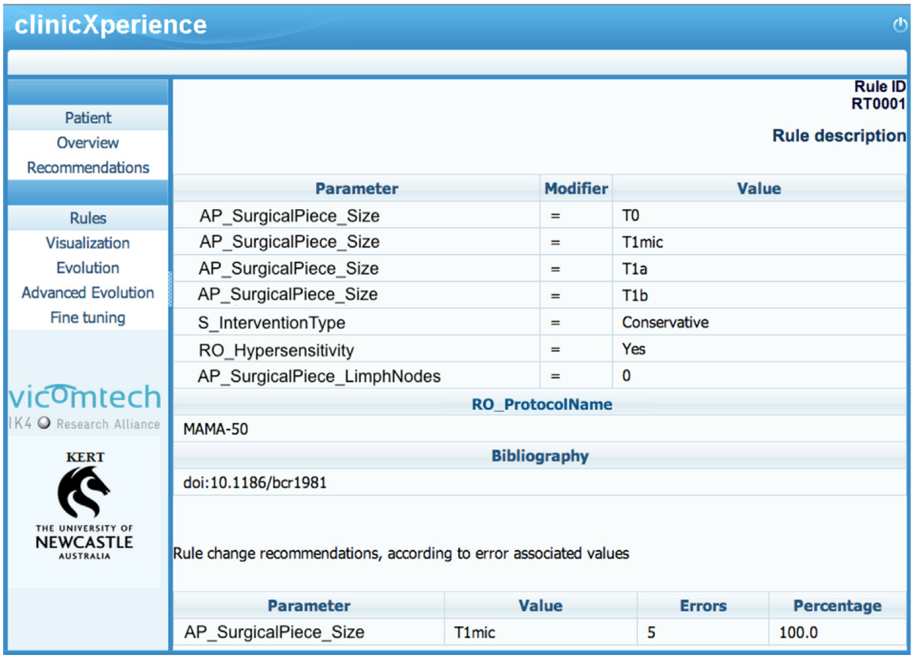

Fig. 5. Screenshot example of fine-tuning of rules.

clinical workflow. Some previous works [63,41] have stated current problems of EHR standards and we will continue our research line in semantic technologies to provide integration with our platform.

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References

[1] Agnar Aamodt, Enric Plaza, Case-based reasoning; foundational issues, methodological variations, and system approaches, AI Commun. 7 (1) (1994) 39–59.
[2] Mobyen Uddin Ahmed, Shahina Begum, Peter Funk, Case studies on the clinical applications using case-based reasoning, in: Maria Ganzha, Leszek A. Maciaszek, Marcin Paprzycki (Eds.), FedCSIS2012, pp. 3–10.
[3] Arkaitz Artetxe, Eider Sanchez, Carlos Toro, Cesar Sanin, Edward Szczerbicki, Manuel Graña, Jorge Posada, Impact of reflexive ontologies in semantic clinical decision support systems, Cybern. Syst. 44 (2–3) (2013) 187–203.
[4] Joan S. Ash, Dean F. Sittig, Emily M. Campbell, Kenneth P. Guappone, Richard H. Dykstra, Some unintended consequences of clinical decision support systems, in: Proceedings of the AMIA Annual Symposium, 2007, pp. 26–30.
[5] Borja Ayerdi, Manuel Graña, Hybrid extreme rotation forest, Neural Netw. 52 (0) (2014) 33–42.
[6] R. Bergmann, Experience Management, Springer, New York, 2004.
[7] Eta S. Berner, Tonya J. La Lande, Clinical decision support systems theory and practice, in: Overview of Clinical Decision Support Systems, second ed., vol. 1, Springer, New York, 2007.
[8] B. Blomqvist, The use of semantic web technologies for decision support – a survey, in: Semantic Web journal Undefined, 2012, pp. 1–24.
[9] Michael Boahene, George Ditsa, Knowledge management, in: Conceptual Confusions in Knowledge Management and Knowledge Management Systems: Clarifications for Better KMS Development, IGI Global, Hershey, PA, USA, 2003, pp. 12–24.
[10] T.A. Brennan, L.L. Leape, N.M. Laird, L. Hebert, A.R. Localio, A.G. Lawthers, J. P. Newhouse, P.C. Weiler, H.H. Hiatt, Incidence of adverse events and negligence in hospitalized patients, results of the harvard medical practice study I, N. Engl. J. Med. 324 (February (6)) (1991) 370–376.
[11] E.C. Maurente, S. Ocampo Edye, D. Herrera Delgado, Rodriguez García, Innovations and advances in computer sciences and engineering, in: Evaluation of Case Based Reasoning for Clinical Decision Support Systems applied to Acute, Springer Netherlands, 2010, pp. 259–264.
[12] E. Szczerbicki, C. Sanin, Towards the construction of decisional DNA: a set of experience knowledge structure java class within an ontology system, Cybern. Syst.: Int. J. 38 (2007) 859–878.
[13] E.SzczerbickiC. Sanin, Experience-based knowledge representation soeks, Cybern. Syst.: Int. J. 40 (2) (2009) 99–122.
[14] Jiuwen Cao, Zhiping Lin, Guang-Bin Huang, Nan Liu, Voting based extreme learning machine, Inf. Sci. 185 (1) (2012) 66–77.
[15] S. Chen, C.F.N. Cowan, P.M. Grant, Orthogonal least squares learning algorithm for radial basis function networks, IEEE Trans. Neural Netw. 2 (2) (1991) 302–309.
[16] Bing Cheng, D.M. Titterington, Neural networks: a review from a statistical perspective, Stat. Sci. 9 (February (1)) (1994) 2–30.
[17] J. Cioffi, A study of the use of past experiences in clinical decision making in emergency situations, Int. J. Nurs. Stud. 38 (5) (2001) 591–599.
[18] Life Consortium, Life proyect, 2014, ⟨www.proyectolife.com⟩.
[19] P. Croskerry, G.R. Nimmo, Better clinical decision making and reducing diagnostic error, J. R. Coll. Physicians Edinb. 42 (2011) 155–162.
[20] E.N. de Vries, M.A. Ramrattan, S.M. Smorenburg, D.J. Gouma, M. A. Boermeester, The incidence and nature of in-hospital adverse events: a systematic review, Qual. Saf. Health Care 17 (3) (2008) 216–223.
[21] Klaus Dieter Althoff, Ralph Bergmann, Stefan Wess, Michel Manago, Eric Auriol, Oleg I. Larichev, Er Bolotov, Yurii I. Zhuravlev, Serge I. Gurov, Case-based reasoning for medical decision support tasks: the inreca approach, in: Artificial Intelligence in Medicine, vol. 12, 1998, pp. 25–41.
[22] P. Drucker, The Post-Capitalist Executive: Managing in a Time of Great Change, Penguin, New York, 1995.
[23] Arthur S. Elstein, Alan Schwarz, Clinical problem solving and diagnostic decision making: selective review of the cognitive literature, Br. Med. J. 324 (March (7339)) (2002) 729–732.
[24] Arthur S. Elstein, Thinking about diagnostic thinking: a 30-year perspective, Adv. Health Sci. Educ. 14 (1) (2009) 7–18.
[25] H.M. Ghaziri, E.M. Awad, Knowledge Management, Prentice Hall, New Jersey, 2004.
[26] G. Fung, J. Stoeckel, SVM feature selection for classification of SPECT images of Alzheimer's disease using spatial information, Knowl. Inf. Syst. 11 (2) (2007) 243–258.
[27] Jairo Robledo Jr., H. Kashfi, Towards a case-based reasoning method for openehr-based clinical decision support, in: Proceedings of the 3rd International Workshop on Knowledge Representation for Health Care (KR4HC'11) Bled, Slovenia, July 2011.
[28] M.T. Hagan, H.B. Demuth, M.H. Beale, Neural Network Design, Har/Dsk edition, PWS Pub. Co., Boston, MA, USA, December 1995.
[29] S. Haykin, Neural Networks: A Comprehensive Foundation, 2 edition, Prentice Hall, Upper Saddle River, NJ, USA, 1998.
[30] Guang-Bin Huang, DianHui Wang, Yuan Lan, Extreme learning machines: a survey, Int. J. Mach. Learn. Cybern. 2 (2) (2011) 107–122.

[31] Guang-Bin Huang, Qin-Yu Zhu, Chee-Kheong Siew, Extreme learning machine: theory and applications, Neurocomputing 70 (1–3) (2006) 489–501.
[32] Chiang S. Jao, Daniel B. Hier, Clinical decision support systems: an effective pathway to reduce medical errors and improve patient safety, in: Decision Support Systems, Number 8, INTECH, 2010.
[33] M. Johnstone, Patient safety ethics and human error management in ed contexts part i: development of the global patient safety movement, Australas. Emerg. Nurs. J. 10 (1) (2007) 13–20.
[34] JeromeP. Kassirer, Teaching clinical reasoning: case-based and coached, Acad. Med.: J. Assoc. Am. Med. Coll. 85 (July (7)) (2010) 1118–1124.
[35] K. Kawamoto, C.A. Houlihan, E.A. Balas, D.F. Lobach, Improving clinical practice using clinical decision support systems: a systematic review of trials to identify features critical to success, Br. Med. J. 330 (7494) (2005) 765.
[36] L.T. Kohn, J. Corrigan, M.S. Donaldson, To Err is Human: Building a Safer Health System, National Academy Press, Washington, 2000.
[37] T. Kohonen, Self-Organization and Associative Memory, 3rd edition, Springer-Verlag, New York, Inc., 1989.
[38] Guilan Kong, Dong-Ling Xu, Jian-Bo Yang, Clinical decision support systems: a review on knowledge representation and inference under uncertainties, Int. J. Comput. Intell. Syst. 1 (2) (2008) 159–167.
[39] Kuan-Liang Kuo, Chiou-Shann Fuh, A rule-based clinical decision model to support interpretation of multiple data in health examinations, J. Med. Syst. 35 (6) (2011) 1359–1373.
[40] Joseph Liu, Jeremy C. Wyatt, Douglas G. Altman, Decision tools in health care: focus on the problem, not the solution, BMC Med. Inf. Decis. Mak. 6 (January (4)) (2006).
[41] Raimundo Lozano-Rubi, Xavier Pastor, Building a clinical repository based on iso-13606, in: Proceeding of the third Symposium on Healthcare Systems Interoperability, 2011.
[42] O. Luaces, F. Taboada, et al., Predicting the probability of survival in intensive care unit patients from a small number of variables and training examples, Artif. Intell. Med. 45 (January (1)) (2009) 63–76 (PMID: 19185475).
[43] George F. Luger, William A. Stubblefield, Artificial Intelligence – Structures and Strategies for Complex Problem Solving, second ed., Benjamin/Cummings, Redwood City, CA, USA, 1993.
[44] Joy Higgs Megan Smith, Elizabeth Ellis, Clinical reasoning in the health professions, in: Factors Influencing Clinical Decision Making, third ed., Butterworth Heinemann, Amsterdam, 2008, pp. 89–100.
[45] Scottish Intercollegiate Guidelines Network. Sign 50: A Guideline Developer's Handbook, Revised Edition, Technical Report, Scottish Intercollegiate Guidelines Network, Edinburgh, November 2011.
[46] E. Szczerbicki, P. Wang, C. Sanin, Introducing the concept of decisional DNA based web content mining, Cybern. Syst.: Int. J. 37 (2012) 97–117.
[47] M. Peleg, S.W. Tu, Decision support, knowledge representation and management in medicine, in: 2006 IMIA Yearbook of Medical Informatics: Assessing Information – Technologies for Health, Schattauer Verlagsgesellschaft GmbH, Stuttgart, 2006, pp. 72–80.
[48] Jean.E. Pretz, Intuition versus analysis: strategy and experience in complex everyday problem solving, Mem. Cognit. 36 (April (3)) (2008) 554–566.
[49] S. Rasmequan, C. Roe, S.B. Russ, Strategic decision support systems: an experience-based approach, in: 18th IASTED Conference on Applied Informatics, Innsbruck, Austria, February 2000, pp. 14–17.
[50] Juan A. Recio-García, Pedro A. González-Calero, Belén Díaz-Agudo, jcolibri2: a framework for building case-based reasoning systems, Sci. Comput. Program. 79 (0) (2014) 126–145 (Experimental Software and Toolkits (EST 4): A special issue of the Workshop on Academic Software Development Tools and Techniques (WASDeTT-3 2010)).
[51] D.E. Rumelhart, G.E. Hinton, R.J. Williams, Learning Internal Representations by Error Propagation, MIT Press, Cambridge, MA, USA (1986) 318–362.
[52] Eider Sanchez, Carlos Toro, Arkaitz Artetxe, Manuel Graña, Cesar Sanin, Edward Szczerbicki, Eduardo Carrasco, Frank Guijarro, Bridging challenges of clinical decision support systems with a semantic approach, a case study on breast cancer, Pattern Recognit. Lett. 34 (October (14)) (2013) 1758–1768.
[53] Cesar Sanín, Leonardo Mancilla-Amaya, Edward Szczerbicki, Paul CayfordHowell, Application of a multi-domain knowledge structure: the decisional DNA, in: Raymond Chiong, Sandeep Dhakal (Eds.), Intelligent Systems for Knowledge Management, Studies in Computational Intelligence, vol. 250, Springer, Berlin Heidelberg, 2009, pp. 65–86.
[54] Cesar Sanin, Edward Szczerbicki, Dissimilar sets of experience knowledge structure: a negotiation process for decisional DNA, Cybern. Syst. 38 (5–6) (2007) 455–473.
[55] Cesar Sanin, Edward Szczerbicki, Genetic algorithms for decisional DNA: solving sets of experience knowledge structure, Cybern. Syst. 38 (5–6) (2007) 475–494.
[56] Cesar Sanín, Edward Szczerbicki, Carlos Toro, An owl ontology of set of experience knowledge, J. Univers. Comput. Sci. February (2007) 209–223.
[57] Cesar Sanín, Carlos Toro, Haoxi Zhang, Eider Sanchez, Edward Szczerbicki, Eduardo Carrasco, Peng Wang, Leonardo Mancilla-Amaya, Decisional DNA: a multi-technology shareable knowledge structure for decisional experience, Neurocomputing 88 (2012) 42–53.
[58] Alexandre Savio, Maite García-Sebastián, Carmen Hernández, Manuel Grana, Jorge Villanúa, Classification results of artificial neural networks for alzheimer's disease detection, in: Emilio Corchado, Hujun Yin (Eds.), IDEAL, Vol. 5788 of Lecture Notes in Computer Science, Springer, Berlin Heidelberg, 2009, pp. 641–648.
[59] Roger C. Schank, Robert P. Abelson, Scripts, Plans, Goals and Understanding: An Inquiry into Human Knowledge Structures, L. Erlbaum, Hillsdale, NJ, 1977.
[60] Alan Schwartz, George Bergus, Medical Decision Making: A Physician's Guide, Cambridge University Press, New York, 2008.
[61] Neeraj Sharma, Kawaljeet Singh, D.P. Goyal, Is technology universal panacea for knowledge and experience management? answers from indian it sector, in: Sumeet Dua, Aryya Gangopadhyay, Parimala Thulasiraman, Umberto Straccia, Michael A. Shepherd, Benno Stein (Eds.), ICISTM, Communications in Computer and Information Science, vol. 285, Springer, Berlin Heidelberg, 2012, pp. 187–198.
[62] D.F. Sittig, A. Wright, J.A. Osheroff, B. Middleton, J.M. Teich, J.S. Ash, E. Campbell, D. W Bates, Grand challenges in clinical decision support, J. Biomed. Inf. 41 (2) (2008) 387–392.
[63] Barry Smith, Werner Ceusters, Hl7 rim: an incoherent standard, in: Arie Hasman, Reinhold Haux, Johan van der Lei, Etienne De Clercq, Francis H. Roger France (Eds.), MIE Studies in Health Technology and Informatics, vol. 124, IOS Press, Amsterdam, Netherlands, 2006, pp. 133–138.
[64] P. Somervuo, T. Kohonen, Self-organizing maps and learning vector quantization for feature sequences, Neural Process. Lett. 10 (2) (1999) 151–159.
[65] Donald F. Specht, Probabilistic neural networks, Neural Netw. 3 (1) (1990) 109–118.
[66] William W. Stead, John R. Searle, Henry E. Fessler, Jack W. Smith, Edward H. Shortliffe, Biomedical informatics: changing what physicians need to know and how they learn, Acad. Med.: J. Assoc. Am. Med. Coll. 86 (April (4)) (2011) 429–434.
[67] Z. Sun, G.R. Finnie, Intelligent Techniques in E-Commerce: A Case Based Reasoning Perspective, Studies in Fuzziness and Soft Computing, Springer, Berlin Heidelberg, 2004.
[68] Zhaohao Sun, Finnie G. Brain-like architecture and experience-based reasoning. In Proceedings of the 7th Joint Conference on Information Sciences (JCIS), Cary, North Carolina, USA, September 2003, pp. 1735–1738.
[69] D. Tao, X. Tang, X. Li, X. Wu, Asymmetric bagging and random subspace for support vector machines-based relevance feedback in image retrieval, IEEE Trans. Pattern Anal. Mach. Intell. 28 (7) (2006) 1088–1099.
[70] Jill Elizabeth Thistlethwaite, David Davies, Samilia Ekeocha, Jane M. Kidd, Colin MacDougall, Paul Matthews, Judith Purkis, Diane Clay, The effectiveness of case-based learning in health professional education, a beme systematic review: Beme guide no. 23, Med. Teach. 34 (6) (2012) e421–e444.
[71] Carlos Toro, Manuel Gra na, Jorge Posada, Javier Vaquero, Edward Szczerbicki, Domain Modeling Based on Engineering Standards, September 2009, pp. 95–102.
[72] Carlos Toro, Eider Sanchez, Eduardo Carrasco, Leonardo Mancilla-Amaya, Cesar Sanín, Edward Szczerbicki, Manuel Graña, Patricia Bonachela, Carlos Parra, Gloria Bueno, Frank Guijarro, Using set of experience knowledge structure to extend a rule set of clinical decision support system for Alzheimer's disease diagnosis, Cybern. Syst. 43 (2) (2012) 81–95.
[73] V.N. Vapnik, Statistical Learning Theory, Wiley-Interscience, New York, NY, USA, September 1998.
[74] Anna Wills, Ian Watson, Building a case-based reasoner for clinical decision support, in: Chengqi Zhang, Hans W. Guesgen, Wai-Kiang Yeap (Eds.), PRICAI, Vol. 3157 of Lecture Notes in Computer Science, Springer, Berlin Heidelberg, 2004, pp. 554–562.

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ERRATUM

Erratum to: Role of cognitive and functional performance in the interactions between elderly people with cognitive decline and an avatar on TV

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This erratum is published following a request signed by Javier Yanguas, Cristina Buiza, Mari Feli Gonzalez, Aitziber Etxaniz, Eduardo Carrasco and Gorka Epelde (as co-authors), as well as Javier Yanguas (as Scientific Director of INGEMA) and Jorge Posada (as Scientific Director of Vicomtech). Ingema and Vicomtech as Institutions, as well as the signing researchers who confirm that Vicomtech researchers Eduardo Carrasco and Gorka Epelde should appear as co-authors of the original published article. The article describes and analyzes results from collaborative research work of the two centers.

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LONG PAPER

Role of cognitive and functional performance in the interactions between elderly people with cognitive decline and an avatar on TV

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Abstract The complexity of new information technologies (IT) may limit the access of elderly people to the information society, exacerbating what is known as "the digital divide," as they appear to be too challenging for elderly citizens regardless of the integrity of their cognitive status. This study is an attempt to clarify how some cognitive functions (such as attention or verbal memory) may determine the interaction of cognitively impaired elderly people with technology. Twenty participants ranging from mild cognitive impairment to moderate Alzheimer's disease were assessed by means of a neuropsychological and functional battery and were asked to follow simple commands from an avatar appearing on a TV by means of a remote control, such as asking the participant to confirm their presence or to respond Yes/No to a proposal to see a TV program. The number of correct answers and command repetitions required for the user to respond were registered. The results show that participants with a better cognitive and functional state in specific tests show a significantly better performance in the TV task. The derived conclusion is that neuropsychological assessment may be used as a useful complementary tool for assistive technology developers in the adaptation of IT to the elderly with different cognitive and functional profiles. Further studies with larger samples are required to determine to what extent cognitive functions can actually predict older users' interaction with technology.

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1 Introduction

Patients suffering from a mild to moderate stage of progression of Alzheimer's disease typically present cognitive and functional impairments affecting memory, concentration, and learning [1]. This decline of functions, together with the lack of information technology (IT) skills in the generation of people of 60 and over, poses a barrier to exploiting the opportunities offered by technology. Hence, new technologies may exacerbate the digital divide problem if certain properties of technologies are too challenging for elderly citizens, regardless of the integrity of their cognitive status [2]. Indeed, some studies [3, 4] show how, when learning to use a computer, older adults take longer to master the system, make more errors, and require more help than younger people. Since software applications tend to increase in complexity over time, they may overload the processing capacity of elderly people. However, technology has been identified as a tool that can be used to promote independent living, improve the safety and autonomy of people with dementia, and support their quality of life [5].

People with dementia are not used to learning how to operate new devices. Limitations in knowledge and understanding of the technology merge with the limitations in communication between the user and the technology [6, 7]. However, the ACTION participatory design model [8] (which comprises the identification of user needs, early program development, testing and refining) defends the possibility that people with dementia are able to enjoy computer training sessions and gain considerable

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satisfaction from learning a new skill that they previously thought was not feasible.

Also, family caregivers of patients suffering from Alzheimer's disease spend almost all their time caring about their relatives [8–13]. There are many technological solutions that could assist in the care of patients with Alzheimer's at home [5, 7, 14, 15]. However, caregivers usually fall into the same age range (i.e., elder spouses or daughters, taking care of demented husbands or parents), so the barriers put in front of them are the same as for the rest of elderly people.

In this context, the i2home project funded by the European Commission 6th Framework Program aims to build devices for the usage of domestic electronic and communication devices for elderly and disabled people, based on industry standards. This means that devices developed in the project will be based on the same standards for technologies used in the industry of electric and electronic devices, for example, standards for ovens, washers, dishwashers, air conditioners, etc., in order to facilitate the future integration of technologies and devices in the homes of these people. In other words, if an older person or a person with a disability wants to integrate new electric and electronic devices in the future for their living environment, they can do it easily without needing to make new physical or technological adaptations in their homes, without needing to buy a whole set of new devices, or without needing to learn new and complex ways to use the electronic devices they will have at their homes. The scope of i2home is to make devices and appliances more accessible and to provide intuitive interaction (understood here as the "interaction based on the use of knowledge that people have gained from other products and/or experiences of their past" [16]) for people suffering from different degrees of cognitive decline from mild cognitive impairment (MCI) to moderate Alzheimer's disease.

Taking into account the lack of IT skills and cognitive and functional impairments, the TV and the remote control were selected as user interfaces in the i2home project, because the former is previously learned interfaces. A total of 98.3 % of the elderly from 60 to over 80 years old posses and regularly use a TV set [17], which is the reason why TV sets are a very well-suited technological platform to improve the quality of life of elderly people through tailored information and communication technology (ICT)-based applications.

The particularity of the i2home interface for elderly patients suffering from cognitive decline is the inclusion of an avatar with the ultimate aim of giving specific commands that help in the supervision of the end user with dementia. An avatar is a life-like simulation of a virtual assistant generated through computer graphics, and previous studies performed by the authors' research group [18–20] have indicated that interaction between avatars and patients with Alzheimer's disease is possible. Though existing recent literature points to a greater differentiation between avatars and human faces relying on particular features of the face [21, 22], differential responses to human faces versus virtual avatar faces will not be presented here; facial emotional expressions of the avatar used (if compared to a real human face) were minimal, as can be seen in Fig. 1, with just a brief and precise movement of the lips when talking.

In terms of technical parameters of the avatar, as described in [17], an external application renders the avatar using OpenSceneGraph for graphical, and Loquendo 7 for speech output. The raw avatar video is supplied to FFmpeg for real-time encoding to MPEG-TS. A HTTP-streaming server conveys the video to the STB, which is sufficiently reliable for cable home networks. The 2D GUI is also created on the IS using a VNC X-server. Widgets are created dynamically within the IS module using Gtk#. A VNC client in the STB plugin receives the GUI from the IS and renders it to the frame buffer of the Dreambox. It also transfers user input back to the IS. A Weemote® dV programmable remote control was initially thought for user input, though it was substituted by a simplified remote control, with basic commands (YES, NO, +, −, arrow up, arrow down). The switch between the avatar, recorded game, and on-going TV shows was quite abrupt in order to catch users' attention.

This study aims to evaluate what cognitive functions may be involved in the correct interaction with the avatar; more specifically, to assess whether these measures are related to the interactions shown by the users with different

Fig. 1 i2home interface for cognitively impaired users. Avatar on TV and Remote Control

degrees of cognitive decline, including mild to moderate Alzheimer's disease.

2 Methods

2.1 Participants

The sample was composed of 20 participants, 5 male, and 15 female, from MCI to moderate Alzheimer's disease (diagnosed according to NINCDS-ADRDA criteria), ranking from 3 to 5 in the Global Deterioration Scale (GDS) [23]. More specifically, ten subjects scored a GDS = 3, eight scored GDS = 4, and two scored GDS = 5. The average age of the group was 82.43 (SD = 7.65). In terms of education levels, 66.7 % had completed primary studies (i.e., 8 years of education, or schooling until being 14 years old), 14.3 % had completed professional training, and the rest had not fulfilled primary studies; among these, 9.5 % read and wrote normally, 4.8 % read and wrote with difficulty, and 4.8 % were illiterate. All of them were, at the time of the evaluation, attending a day care centre, and all had agreed to participate by means of a signed consent form.

2.2 Procedures

Prior to presenting the avatar to the subjects, they were assessed by means of a neuropsychological screening battery including the following:

- MiniExamen Cognoscitivo (MEC): Adaptation of the MMSE—Mini-Mental State Examination [24] to the Spanish population [25].
- GDS: Global Deterioration Scale [23]. It is a scale for the assessment of primary degenerative dementia and delineation of its stages.
- RAVLT: Rey Auditory Verbal Learning Test validated to the Spanish population [26]. This is a brief, easily administered measure that assesses immediate memory span, new learning, susceptibility to interference, and recognition memory [27], by means of a list of words read aloud for five consecutive trials; after free recall of each trial, a free recall of an interference list occurs; afterward, a delayed recall task and a subsequent recognition task of the first list take place.
- Barthel ADL Index Scale, Spanish version [28]. It is a scale used to measure performance in basic activities of daily living (ADL).
- Digit span (DS) subtest of the Wechsler Adult Intelligence Scale—Third Edition adapted to the Spanish population [29]. It consists of two parts and requires the subject to repeat digits forward and in reverse order.
- Boston Diagnostic Aphasia Examination (BDAE) is a test for the assessment and diagnosis of aphasia [30, 31]. It is composed of 10 subtests, each of them constituted by different items that are complemented by 16 images for its application. For the assessment of the sample the "Commands" category of the auditory comprehension subtest was used, in which the ability for the comprehension of auditory presented simple, semi-complex, and complex commands was assessed.
- In addition to the previous evaluation protocol, simple tests such as a name writing task and a color identification test were created ad hoc and administered in order to measure whether the identification of colors and symbols that appear in the remote control could affect the interaction with the avatar. The same colors and symbols included in the remote control were printed on a separate paper, and the participants had to point with their finger to each one of them when asked. That is, the symbols evaluated were those appearing on the simplified remote control: +, −, YES, NO, arrow up, arrow down. These would later show up as labels on the remote control, not on the TV screen. Moreover, a color identification test was administered as to determine whether the person had any kind of visual, attentional, or cognitive impairment to follow basic commands and differentiate basic stimuli, if an avatar was intended to be presented on a TV set. No personalization of the avatar was considered at this stage of the project in terms of changing hair/eyes/ clothes, but this suggestion will be considered for future developments.

Afterward, in a different session, each subject was positioned in front of the TV set. On a table next to the subject, a piece of paper, a pen, and a remote control (RC) with 2 buttons (labeled YES and NO) were placed.In the application, the assistant explained the following instructions prior to the avatar's presentation on the TV: "We are going to watch a TV program. At any moment, while we are watching TV, a girl will appear on the screen and will ask you some questions which you will have to answer using the remote control. Are you ready? Let's turn the TV on. Is the TV loud enough for you?" After the volume adjustment, a TV program was presented.The procedure started with the subject watching a TV program, and the following sequence of interactions with the avatar was required from the user:

- The presence confirmation of the avatar's 1st presentation. After the subject had been watching the TV for some time, the screen turned black, and an avatar appeared on the screen saying "Mr./Mrs. [name]… Are you there? If you are there, press YES on the remote control." If the subject did not produce any response with the RC (neither YES nor NO), the avatar's previous speech was repeated for a second time "Mr./Mrs. [name]… Are you there? If you are there, press YES on the remote control."

- See-a-program-proposal. Either if the person confirmed its presence to the avatar or if they did not answer anything with the remote control, the avatar continued as follows: "Mr./Mrs. [name], a Basque "pelota" match is going to start. If you want to watch it, press YES on the remote control." If the subject answered YES, the avatar disappeared and a Basque "pelota" match started. If the subject answered NO, the avatar disappeared and the previous TV program continued. Again, if the subject did not produce any response with the RC (neither YES nor NO), the avatar's speech was repeated. "Mr./Mrs. [name], a Basque "pelota" match is going to start. If you want to watch it, press YES on the remote control." If no answer was given at this point, the previous program appeared on the TV screen again as if the answered were "NO" (but the answer was registered as "no response").
- Presence confirmation of the avatar's 2nd presentation. After the subject had been watching the TV for some time, the screen turned black and the avatar reappeared again asking the subject for a presence confirmation.
- Write-your-name proposal. "Mr./Mrs. [name], write-your-name on the piece of paper that you have in front of you." After a while, the avatar would ask "Mr./Mrs. [name] have you already finished? If you have already finished, press YES on the remote control." After the subject's answer with the RC, the avatar said "Thank you very much for your cooperation. See you later!" and the application finished.

3 Results

3.1 Neuropsychological evaluation

Subjects showed a mild to moderate cognitive impairment as measured by the MEC and GDS. In addition, their memory processes, as illustrated by their performance in the RAVLT, were mildly impaired when faced with novel situations (trial 1), when it came to encoding and free retrieval (trial 5), as well as in recognition processes (false positives). Attentional processes also show low scores when measured with direct DS and inverse digit span. The group also showed a mild functional dependency as measured with the Barthel Scale. All these results are summarized in Table 1.

Table 1 Results for neuropsychological and functional tests

Test name	Mean (x)	Standard deviation (SD)
MMSE (MEC)	25.43	4.69
RAVLT: Trial 1	2.15	1.56
Trial 2	3.65	1.90
Trial 3	4.35	2.25
Trial 4	4.40	2.21
Trial 5	4.70	2.96
Trial 6 (delayed)	2.05	3.00
Recognition	8.55	5.35
False positives	6.35	10.19
False negatives	5.10	4.80
Barthel ADL index scale	69.29	22.38
Direct digit span	4.05	1.28
Inverse digit span	2.65	1.14

3.2 Interactions with the avatar

For the purpose of describing the interactions between subjects and the avatar, frequencies of correct answers and repetitions required for a user to respond ("immediate"—i.e., the user respond at the first attempt- vs. "delayed"—i.e., the avatar had to repeat the question for the user to respond) were registered, and verbal responses were analyzed.

3.2.1 First i2home trial

On the first trial with the participants presented with the i2home avatar, 100 % of the users confirmed their presence to the avatar using the remote control, but only 86.7 % accepted to see the "pelota" match, and only 80 % confirmed having written their names on the paper. Hence, a decrease in the RC use was perceived with each subsequent task. Table 2 shows the moment of response (immediate vs. delayed).

It must be highlighted that, even if no directive was given with respect to giving a verbal response to the avatar, 80 % of the sample responded verbally to the avatar, which could reflect to some extent that verbal response is a more natural way of interaction than the use of a remote control for people with mild to moderate cognitive impairment. The relevance of these answers was taken into account, but they were not included in the analyses, since no speech recognition interface was being evaluated. Only answers using the remote control were analyzed.

3.2.2 Second i2home trial

When faced with the i2home task in the second administration, after a mean of 3 week time from the first exposition to the avatar, the sample of participants was reduced to 13, due to severe health problems of 6 and further hospitalization of 2 participants who took part in the first application. After discarding a normal distribution of a

Table 2 Moment of response to the avatar's questions (First trial)

Interaction name	Immediate response (%)	Delayed response (%)
Confirm presence to the avatar's 1st presentation	86.7	13.3
Confirm presence to the avatar's 2nd presentation	80	20
Answer to "see-a-program-proposal"	80	20
Start writing name	80	20
Confirm "write-your-name" task completion	73.3	26.7

great part of the variables, a Wilcoxon test was used to confirm whether they were differences among the first and second application results.

For this second application, for which the instructions were reduced to the sentence "we are going to watch a TV program," most of the users stated that they remembered having done a task like this before. In this context, the use of a remote control was performed by 84.6 % of the sample ($n = 11$) to confirm their presence to the avatar's firs presentation, 92.3 % ($n = 12$) for the second presentation and to confirm having written their names on the paper, and 76.9 % ($n = 10$) to accept watching a "pelota" match. Differences between the first and second application results regarding the use of remote control are not statistically significant (i.e., the use of remote control was similar in both i2home trials).

However, there is a need to highlight a decrease in verbal response to the avatar. On this second trial with the i2home avatar, 69.2 % ($n = 9$) gave a verbal response to the avatar the first time it appeared, and 76.9 % ($n = 10$) when it appeared for the second time. Moreover, the verbal response to the proposal to watch the "pelota" match was only 30.8 % ($n = 4$). A Wilcoxon test performed to clear up differences between the first and second application results showed that these differences were close to be statistically significant ($Z = -1.89$, $p = .059$).

There is a fairly feasible explanation to these results. First, regarding general performance, it was possible that the familiarity with the task stated by most of the participants oriented their answers to the use of the remote control rather than to a verbal response which had no effect in practical terms (i.e., the i2home application responded to the RC answers, not to verbal answers). Moreover, a verbal response to the avatar's question "Are you there?" seems quite more natural than a verbal response to "A 'pelota' match is going to start. If you want to watch it, please press YES on your remote control," where the avatar asks no direct questions to the user. It is very likely that an instruction given in interrogation terms would have elicited verbal responses at a rate similar to the one of the first i2home avatar trials. It remains to be solved in the future whether attention/executive disruptions in mild to moderate Alzheimer patients make them more likely not to inhibit verbal answers when asked direct questions, regardless these questions are asked by a human being (i.e., caregiver) or by a virtual avatar on the screen of a TV set.

3.3 Correlations between neuropsychological testing and human–avatar interactions

On the basis of the current results, statistical analyses were developed to find out whether cognitive and functional measures could relate in any way to the performance shown by the subjects in their interactions with the avatar, both in the first i2home trial (i.e., the one with more elaborated instructions given to the user) and in the second trial (i.e., the one with the simple instruction "we are going to watch a TV program").

3.3.1 Correlations for the first i2home trial

After a normal distribution of a great part of the variables by means of a Kolmogorov–Smirnoff test was discarded, Spearman's rho correlations were calculated, as shown in Table 3.

These results show that the higher the Barthel score (that is, the higher the functional independence), the less repetitions are needed to answer the avatar. Also, the better the performance in an attentional task such as the inverse digit span, the shorter the time needed to answer to a command from the avatar, such as the "see-a-program" proposal. Moreover, relationship between the production of false negative responses in the RAVLT recognition trial and the time needed to confirm the presence of the avatar's 1st presentation may be a signal of a distractibility component that prevents the subject from answering immediately such a simple question as the confirmation of his presence. Finally, the greater the ability to discriminate between relevant and irrelevant stimuli (RAVLT recognition trial), the faster the response to questions asked by the avatar, showing a higher level of sustained attention and concentration.

3.3.2 Correlations for the second i2home trial

As for the results from the first trial, after discarding a normal distribution for a great part of the variables, Spearman's rho correlations were calculated.

As it can be seen in Table 4, in this particular trial, the higher the general cognitive performance (measured by the MEC test -Spanish adaptation of the MMSE), the less the time needed to react to the avatar.

Table 3 Significant correlations between neuropsychological testing and interactions with the avatar (first i2home trial)

	Trials to confirm presence to the avatar	Time needed to answer to see-a-Program proposal	Time to confirm presence (avatar's presentation #1)	Time to confirm presence (avatar's presentation #2)	Time to confirm name writing
Barthel index	−.613*	n.s.	n.s.	n.s.	n.s.
Inverse (backwards) digit span	n.s.	−.600*	n.s.	n.s.	n.s.
RAVLT–false negatives	n.s.	n.s.	.598*	n.s.	n.s.
RAVLT–recognition trial	n.s.	n.s.	−.525*	−.699**	−.515*

n.s. non-significant

* $p < .05$, ** $p < .01$

With regard to the Barthel index for functional independence, a very strong negative correlation was found between Barthel index and the emission of a verbal response both to the avatar's first presentation (ρ (11) = −.716, $p < .01$) and second presentation (ρ (11) = −.735, $p < .01$), showing that a higher functional independence was related to a higher probability for the participant to focus on the specific instructions of the avatar (i.e., use of the remote control). Moreover, as shown in Table 4, functional independence was associated with fewer repetitions and less time needed to give appropriate responses to the avatar's proposal to watch a "pelota" match.

One interesting result was the correlation between false negative answers to the RAVLT and the presence of verbal responses to confirm presence to the avatar's second presentation (ρ (11) = .670, $p < .05$). It is difficult to find an adequate interpretation for this result, since in the second i2home trial, some learning effect from the first trial was expected. One possibility is that verbal response may constitute a sign of a deficit of attention or executive processes, since there are no instructions to give a verbal response. Thus, emission of false negatives in RAVLT, which may be described as a response to relevant or familiar information incorrectly interpreted as irrelevant or unknown, may relate to further attention and memory problems. Maybe, after two applications of the i2home system and the users' familiarity with the remote control, still giving a verbal response is less related to the users' spontaneity and more related to cognitive problems. However, this is an issue that requires further research.

Table 4 Significant correlations between neuropsychological testing and interactions with the avatar (second i2home trial)

	Trials to confirm presence to the avatar	Time needed to answer to see-a-Program proposal	Repetitions needed to answer to see-a-program proposal	Time to confirm presence (avatar's presentation #1)	Repetitions needed to confirm presence (avatar's presentation #1)	Time to confirm presence (avatar's presentation #2)	Repetitions needed to confirm presence (avatar's presentation #2)	Time to confirm name writing
MEC (MMSE)	n.s.	n.s.	n.s.	−.560*	n.s.	n.s.	n.s.	n.s.
Barthel index	−.563*	−.563*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Inverse (backwards) digit span	n.s.	−.600*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
RAVLT–false negatives	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
RAVLT–recognition trial	n.s.	−.665**	−.665**	−.630**	n.s.	−.739**	n.s.	n.s.
Name writing test	n.s.	−.778**	−.778**	n.s.	n.s.	−.734**	−.677*	−.778**
Color identification test	n.s.	n.s.	n.s.	n.s.	n.s.	−1.000**	−1.000**	−1.000**

n.s. non-significant

* $p < .05$, ** $p < .01$

In line with this possibility that verbal response was more a sign of cognitive problems than a sign of spontaneity, RAVLT recognition trial showed that the better the recognition abilities, the shorter the time and the fewer the repetitions needed to give an appropriate response to requirements from the avatar.

However, the clearest differences for this second application derived from the initial screening tests administered, such as name writing test and color identification test, both administered in order to examine users' abilities to follow simple commands, as it has been stated in the procedures' section. A good performance in name writing tasks meant a better focus on the use of the remote control, faster responses, and fewer repetitions (to confirm avatar's second presentation). Finally, the color identification test became the best correlating measure with the participants' interactions with the avatar.

On the contrary, the BDAE showed no statistically significant correlations with the interactions between the users and the avatar. It is likely that the simplicity of the required interactions with the avatar, which did not demand verbal expression and do not seem to affect verbal comprehension, may explain the fact that this test is not a reliable predictor of user interaction in these specific trials. However, for reaching more reliable conclusions, further studies with larger samples including aphasic patients would be required.

4 Conclusions

Conclusions derived from this research show, firstly, that functional measures (such as the Barthel ADL index) can relate to the expected number of trials needed by a person to interact with an avatar. Secondly, cognitive measures (especially those related to attentional and processing speed domains (i.e., digit span) and discrimination between relevant and irrelevant information (i.e., RAVLT) can relate to the latency of response that the subjects show when they respond to the avatar. A similar result was reported by Czaja et al. [32], who found that the successful performance on computer-based information search and retrieval tasks was related with attentional and processing speed cognitive functions. However, to the authors' knowledge, the study presented in this paper is one of the very few studies which address the usefulness of neuropsychological measures as complementary tools for personalizing interfaces for users with mild to moderate cognitive decline.

It is likely that even the simplest brief cognitive screening tools (i.e., name writing task, color identification) may be a shortcut to acknowledge the expected interaction of a person with mild to moderate cognitive impairment with technological devices, such as the one proposed in the i2home project. In other words, it is very likely that cognitive and functional measures may help to predict users' expected response to the avatar if further trials with larger samples are performed, as correlation results with the small sample presented here point to this trend. Also, their cognitive status may explain how much time that interaction will take. It is clear that further research should be required to establish whether these cognitive and functional measures could become by themselves predictors of performance of the elderly with avatars. The size of the sample limits the extrapolation of the results, but still leaves the door open to use cognitive and functional measures for guidance in a better adaptation of ICTs to elderly people. As Slegers et al. [3] explain, knowing which cognitive abilities lead to problems with technology will make it possible to modify devices to accommodate older users' capacities and, as a consequence, improve their efficiency. In this sense, it can be very useful for technology developers to get a quick idea of whether their end users will be able to interact with the technology they are developing, even before any prototype testing is carried out. Even for elderly people with no cognitive impairment, cognitive skills such as speed of information processing, psychomotor processes, working memory, and mental flexibility seem to be critical when using complex technological systems [3].

Also, cognitive and functional statuses observed in the users by means of neuropsychological testing may accurately orient technology developers in the adaptation of their interfaces in a more efficient way. A recent review [5] shows that research on the role of technology in dementia care is still in its infancy, but the aim to integrate technology in elderly people's lives with different cognitive status (from normal to cognitive impairment) in order to maintain their quality of life and their autonomy is worthy of intensive efforts in this area.

One clear limitation of this study is the sample size. This must be seen as a preliminary study in which it was intended to validate the concept of presenting an innovate feature (i.e., the avatar) in a classical user interface (TV set) with a classical way to interact with it (i.e., remote control), that is, familiar to all the users involved regardless of their cognitive status. Once confirmed that the users' interaction with the avatar is as natural as if they were answering to a real person, it is of course necessary to perform further studies with larger samples and contrast control groups to validate this concept and allow generalizability of results to different populations and using commands of increasing complexity. Also, these larger studies are required to determine to what extent cognitive functions can actually predict older users' interaction with technology.

In this regards, could the results of the study do not confirm Blackler et al's [33] findings, measuring the effect of familiarity with technology, since it was an assumed principle that a TV set with a remote control was familiar to all the users involved in the study. Not having considered the effect of familiarity may have confounded the results, and the possibility remains that some of the observed effects attributed to cognitive abilities (mainly, attention and memory) may in part be due to the effects of familiarity.

The effects of previous experience and openness to technology have been clearly documented [34, 35] and should be taken into account in future research that overcome the limitations affecting the current study. Accordingly, an in-depth study like this will of course benefit of the work done so far with regard to utilization of cognitive and functional measures, which will help in the adaptation and simplification of user interfaces to users' abilities. As stated by Gudur et al. [36, 37], keeping the interfaces clean and simple with minimal distractions to reduce use of limited attention resources may be most helpful for older users, especially for those with mild to moderate decline as the ones in this study. It is expected that the work presented here stimulates further research in this area.

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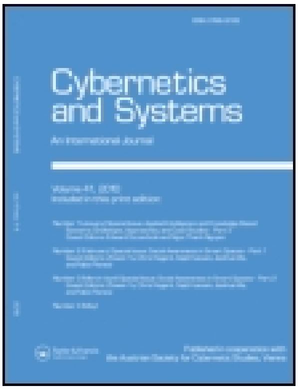
References

1. Salmon, D.P., Bondi, M.W.: Neuropsychological assessment of dementia. Ann. Rev. Psychol. **60**, 1–26 (2009)
2. Wu Y., Van Slyke C.: Interface complexity and elderly users: revisited. In: Proceedings of the Eighth Annual Conference of The Southern Association For Information Systems (SAIS 2005), Savannah, Georgia (2005)
3. Slegers, K., Van Boxtel, M.P., Jolles, J.: The efficiency of using everyday technological devices by older adults: the role of cognitive functions. Ageing Soc. **29**, 309–325 (2009)
4. Hanson, V.L.: Influencing technology adoption by older adults. Interact. Comput. **22**, 502–509 (2010)
5. Topo, P.: Technology studies to meet the needs of people with dementia and their caregivers a literature review. J. Appl. Gerontol. **28**, 5–37 (2009)
6. Nygård, L.: The meaning of everyday technology as experienced by people with dementia who live alone. Dementia **7**, 481–502 (2008)
7. Hanson, E., Magnusson, L., Arvidsson, H., Claesson, A., Keady, J., Nolan, M.: Working together with persons with early stage dementia and their family members to design a user-friendly technology-based support service. Dementia **6**, 411–434 (2007)
8. Bertrand, R.M., Fredman, L., Saczynski, J.: Are all caregivers created equal? Stress in caregivers to adults with and without dementia. J. Aging Health **18**, 534–551 (2006)
9. Etxeberria, I., Yanguas, J.J., Buiza, C., Yanguas, E., Palacios, V., Rodríguez, S.: Effectivity of an early psychosocial intervention program with relative of patients with Alzheimer's disease on first stages [Article in Spanish]. Rev. Esp. Geriatr. Gerontol. **39**, 5–6 (2004)
10. IMSERSO (Spanish Institute for Elderly and Social Services). 93% of informal caregivers of dependent people show a low quality of life [Report in Spanish]. http://www.imsersodependencia.csic.es/documentacion/dossier-prensa/2008/not-13-06-2008.html (2008). Accessed 12 May 2009
11. Losada, A., Izal, M., Montorio, I., Marquez, M., Perez, G.: Differential efficacy of two psycho educational interventions for dementia family caregivers [Article in Spanish]. Rev. Neurol. **38**, 701–708 (2004)
12. Lu, Y.Y., Wykle, M.: Relationships between caregiver stress and self-care behaviours in response to symptoms. Clin. Nurs. Res. **16**, 29–43 (2007)
13. Son, J., Erno, A., Shea, D.G., Femia, E.E., Zarit, S.H., Parris, M.A.: The caregiver stress process and health outcomes. J Aging Health **19**, 871–887 (2007)
14. Elliot, R.: Assistive technology for the frail elderly: an introduction and overview. Department of Health and Human Services, Pennsylvannia (1991)
15. Pilotto, A., D'Onofrio, G., Benelli, E., Zanesco, A., Cabello, A., Margelí, M.C., Wanche-Politis, S., Seferis, K., Sancarlo, D., Kilias, D.: Information and communication technology systems to improve quality of life and safety of Alzheimer's disease patients: a multicenter international survey. J. Alzheimers Dis. **23**, 131–141 (2011)
16. Blackler, A., Popovic, V., Mahar, D.: Investigating users' intuitive interaction with complex artefacts. App. Ergon. **41**, 72–92 (2010)
17. Carrasco, E., Göllner, C.M., Ortiz, A., García, I., Buiza, C., Urdaneta, E., Etxaniz, A., Gonzalez, M.F., Laskibar, I.: Enhanced TV for the promotion of active ageing. In: Eizmendi, G., Azkoitia, J.M., Craddock, G.M. (eds.) Challenges for assistive technology, pp. 159–163. IOS Press, Amsterdam (2007)
18. Buiza C., Urdaneta E., Yanguas J.J., Carrasco E., Göllner C.M., Paloc C: i2home-intuitive interaction for everyone with home appliances based on industry standards. Poster session presented at the 9th European Conference for the Advancement of Assistive Technology, AAATE 2007. San Sebastian, Spain (2007)
19. Carrasco, E., Epelde, G., Moreno, A., Ortiz, A., Garcia, I., Buiza, C., Urdaneta, E., Etxaniz, A., Gonzalez, M.F., Arruti, A.: Natural interaction between virtual characters and persons with Alzheimer's disease. In: Miesenberger, K., et al. (eds.) Computers helping people with special needs, pp. 38–45. Springer-Verlag, Berlin-Heildelberg (2008)
20. Ortiz, A., Carretero, M.P., Oyarzun, D., Yanguas, J.J., Buiza, C., Gonzalez, M.F., Etxeberria, I.: Elderly users in ambient intelligence: does an Avatar improve the interaction? In: Stephanidis, C. (ed.) Universal access in ambient intelligence environments, pp. 99–114. Springer-Verlag, Berlin-Heildelberg (2006)
21. Dyck, M., Winbeck, M., Leiberg, S., Chen, Y., Gur, R.C., Mathiak, K.: Recognition profile of emotions in natural and virtual faces. PLoS ONE **3**, e3628 (2008)
22. Moser, E., Derntl, B., Robinson, S., Fink, B., Gur, R.C., Grammer, K.: Amygdala activation at 3T in response to human and Avatar facial expressions of emotions. J. Neurosci. Methods **161**, 126–133 (2007)
23. Reisberg, B., Ferris, S.H., de Leon, M.J., Crook, T.: The global deterioration scale for assessment of primary degenerative dementia. Am. J. Psychiatr. **139**, 1136–1139 (1982)
24. Folstein, M.F., Folstein, S.E., McHugh, P.R.: "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. J. Psychiatr. Res. **12**, 189–198 (1975)
25. Lobo, A., Ezquerra, J., Gómez-Burgada, F., et al.: The cognoscitive mini exam (a simple, practical 'test' to detect

intellectual disorders in medical patients [Article in Spanish] Actas Luso Españolas de Neurología. Psiquiatría y Ciencias Afines **7**, 189–202 (1979)
26. Ortiz-Marqués N., Amayra-Caro I., Uterga-Valiente J.M., Martínez-Rodríguez S. (2008) Standardization of a Spanish version of Rey Auditory Verbal Learning Test (RAVLT) [Article in Spanish] V Congress of Neuropsychology in Andalucia Huelva, Spain
27. Spreen, O., Strauss, E.: A compendium of neuropsychological tests. Administration norms and commentary. Oxford University Press, New York (1998)
28. Baztán, J.J., Pérez del Molino, J., Alarcón, T., San Cristóbal, E., Izquierdo, G., Manzarbeitia, I.: Barthel index: valid instrument for the functional assessment of patients with cerebrovascular disease [Article in Spanish]. Rev. Esp. Geriatr. Gerontol. **28**, 32–40 (1993)
29. Seisdedos, N., Wechsler, D.: WAIS-III: wechsler adult intelligence scale –third edition technical manual [Book in Spanish]. TEA Ediciones, Madrid (1999)
30. Goodglass, H., Kaplan, E.: The assessment of aphasia and related disorders. Lea & Febiger, Philadelphia (1983)
31. García-Albea, J.E., Sánchez, M., del Viso, S.: Test de Boston para el diagnóstico de la afasia. Adaptación española. In: Goodglass, H., Kaplan, E. (eds.) La evaluación de la afasia y trastornos relacionados. Panamericana, Madrid (1986)
32. Czaja, S.J., Sharit, J., Ownby, D., Roth, D., Nair, S.N.: Examining age differences in performance of a complex information search and retrieval task. Psychol. Aging **16**, 564–579 (2001)
33. Blackler, A., Mahar, D., Popovic, V.: Older adults, interface experience and cognitive decline, pp. 22–26. Paper presented at the OZCHI, Brisbane (2010)
34. Langdon, P., Lewis, T., Clarkson, J.: The effects of prior experience on the use of consumer products. Univers. Access. Inf. Soc. **6**, 179–191 (2007)
35. Lewis, T., Langdon, P.M., Clarkson, P.J.: Prior experience of domestic microwave cooker interfaces: a user study. Des. Incl. Futur. **2**, 3–14 (2008)
36. Gudur, R.R., Blackler, A., Mahar, D., Popovic, V.: The effects of cognitive ageing on use of complex interfaces, pp. 22–26. Paper presented at the OZCHI, Brisbane (2010)
37. Gudur R.R., Backler A.L., Popovic V., Mahar D.P.: Ageing and use of complex product interfaces. In: Norbert R., Lin–Lin C., Pieter J.S. (eds) Proceedings of 4th World Conference on Design Research, Delft, the Netherlands, 31 October–4 November (2011)



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Universal Remote Delivery of Rehabilitation: Validation with Seniors' Joint Rehabilitation Therapy

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Universal Remote Delivery of Rehabilitation: Validation with Seniors' Joint Rehabilitation Therapy

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Remote rehabilitation applications still have limited deployment. The path to achieve greater user acceptance and adherence lies in the provision of solutions in their real-life context. Such acceptance is gained through flexibility provided in terms of location, client device, interaction means, and content.

This article presents a universal remote rehabilitation delivery approach supporting the introduced flexibility needs. Furthermore, an implementation of the approach in joint rehabilitation for the elderly is described.

The approach has been evaluated in a real scenario within Donostia Hospital. The usability evaluation results show the validity of the approach and the acceptance of the developed human–computer interaction paradigm.

KEYWORDS Abstract user interfaces, inertial sensors, joint rehabilitation, seniors, telerehabilitation, universal access, universal remote console (URC), virtual humans

INTRODUCTION

It is undisputed that during the last few decades the use of user-centered design methodologies (International Organization for Standardization 2010) in service

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development has led to greater acceptation of the developed human–computer interaction (HCI) solutions and the services themselves.

Despite the achievements and advances in the user acceptance of technological products and services and their interaction, the shift toward multi-environment service consumption limits traditional systems' deployment (Burrell et al. 2000). From a design point of view, the main limitations of these services are (1) the limited consideration of the user's real-life context (e.g., not considering user's needs and preferences changes from a home scenario to a work scenario or to an on-the-go scenario) and (2) the lack of an architecture support to provide the required flexibility in terms of location, client device, interaction means, and content (Hong and Landay 2001).

One of the main application areas of these advanced services is the remote provision of health services. The number of people aged over 65 is projected to grow from an estimated 524 million in 2010 to nearly 1.5 billion in 2050 worldwide (World Health Organization 2011). This trend has a direct impact on the sustainability of health systems, in maintaining both public policies and the required budgets. As a result of these global trends and the need to provide individual attention, a tendency toward resource and patient care staff overload in hospitals is occurring and is especially true for rehabilitation, because it is generally characterized by repetitive encounters over a long time period with low intensity (Parmanto and Saptono 2009).

Parting from this motivation scenario, telerehabilitation is defined as the use of telecommunications to provide remote rehabilitation services (Brienza and McCue 2013). Brienza and McCue (2013) presented a study that defends the benefits of providing rehabilitation services in the natural environment (where patients live, work, and/or interact socially) rather than in the clinical setting. The aforementioned authors described a collection of studies reporting the benefits of rehabilitation service provisioning in the patient's own environment, in terms of increased functional outcome, enhanced patient satisfaction, reduction in needed therapy duration and cost, and pathology specific benefits.

One of the main beneficiaries of telerehabilitation, according to its challenges and market trends (Simpson 2013), is people with disabilities. The main challenges observed by the study are the high number of people with disabilities (increased by the society getting older), the diversity of needs and preferences of each person, and their economic limitations.

In order to answer the demand of a remote rehabilitation service that will adapt to the requirements and needs of these large and diverse user groups and their real-life usage contexts, it is necessary to define a universal remote rehabilitation delivery architecture (Winters 2013).

The objective of this article is to introduce an approach to support the universal remote rehabilitation delivery. Furthermore, the research also covers the implementation for validating the approach focused on seniors' knee replacement rehabilitation therapy. This implementation targets the increased treatment adherence through the use of realistic avatars as the human–computer interaction paradigm and the use of a portable high-definition tracking system for precise joint angle measurement and monitoring.

The article is arranged as follows: in the next section a survey of the current body of work related to present article's objectives is presented. Then, the proposed architecture approach is described. Next, the implementation for the validating of the approach is reported. Then, the evaluation methodology and the obtained results are presented. Finally, the conclusions and the future work are discussed.

STATE OF THE ART

In the following subsection, the evolution of the telerehabilitation architectures will be studied. Next, focusing on the implementation of the approach for elderly users, the most accurate HCI paradigms for seniors will be analyzed. Finally, joint rehabilitation assessment technologies will be revised.

Evolution of the Telerehabilitation Architectures

In general, telerehabilitation applications fall into two main categories. The first application type is called *real-time interactivity* application. Traditionally this application type has been achieved through videoconference means. The second type of application works using an asynchronous communication and is known as *store-and-forward* application. This application type stores the therapy and forwards it to the patient. Similarly, the therapy results are stored and forwarded to the therapist.

The evolution of real-time interactivity applications from analogue to digital technologies has enabled the implementation of applications such as the shared whiteboard. The evolution of store-and-forward applications includes simple communications such as e-mail, Web solutions using Java applet/ActiveX (Reinkensmeyer et al. 2002), and more conceptual evolution toward service-oriented architectures (Mougharbel et al. 2009). The evolution toward service-oriented architectures and future Internet architectures (Światek et al. 2012) opens new opportunities that will benefit from the potential highlights of cloud technologies.

Among telerehabilitation's main challenges, the provision of universal access is one of the most important ones (Simpson 2013). Feng and Winters (2007) have worked on the universality of telerehabilitation architectures. Their work is based on the universal remote console (URC) standard. This standard defines an abstract user interface layer called the *user interface socket* and allows the development of pluggable user interfaces for any type of user. Their approach has some limitations: the integration of new interaction device protocols is limited; it is not possible to deploy non-URC controllers; and solutions that access more than one service are not addressed.

Older Adult-Centered Interaction Technologies

Motivated by the point that television (TV) is present in most homes and watching TV is one of the activities that takes up most people's leisure time (Eurostat European Comission 2012), TV has been actively researched for service deployments, especially for older adults.

With the evolution of information and communications technologies (ICT) and their incremental adoption by seniors, applications targeting the elderly have been developed for the PC and more recently for the mobile devices. Regarding telerehabilitation, PC-based solutions were initially developed recently evolving to TV-based game consoles and to mobile terminals. European citizens' ICT usage (European Commission 2008) evidence the need for an architecture that supports users' real-life context and its multidevice usage nature.

With regards to the type of content used to instruct rehabilitation follow-up at home, usually it is limited to a set of instructions provided to the patient informally or through printed material.

Initial telerehabilitation developments focused on videoconference applications (Nakamura et al. 1999). Later, with the aim to increase patients' motivation and objectivize their evolution, research advanced to gaming rehabilitation. Gaming rehabilitation's natural evolution has been the use of game consoles (Deutsch et al. 2008). The next big step has been in virtual reality (VR). Development of VR environments and interactive technology has led to a variety of applications focused specifically in the areas of disability, therapy, health, and rehabilitation (Nap and Diaz-Orueta 2013).

Research on HCI for seniors centered on VR technology have shown that virtual humans ameliorate seniors interaction with machines (Ortiz et al. 2007), Within the health sector, virtual humans have been adapted to advice army members (Rizzo et al. 2010).

Rehabilitation Assessment

Traditionally, physical rehabilitation assessment has been based on assessment scales and manual tools such as the goniometer and the dynamometer. With the emergence of VR and gaming rehabilitation, a wide variety of robotic systems specifically targeted at rehabilitation have been developed and have confirmed their therapeutic benefits (Kwakkel et al. 2008). The elevated cost of such robot-based therapies makes them unachievable for home rehabilitation.

Hence, interface devices (computer mouse, joystick, force sensor, cyber glove) that were not designed with rehabilitation in mind have been tested as an alternative for interaction and navigation within VR-based rehabilitation. Johnson et al. (2007) reported the use of a conventional force-reflecting joystick, a modified joystick therapy platform, and a steering wheel platform with stroke subjects. In recent years, with evolution of the main game console controllers to wireless and gesture technologies including motion-sensing technologies, there has been an active research area testing the validity of these devices for rehabilitation (Deutsch et al. 2008).

In regards to the rehabilitation of joints, different technologies are used for position sensing (Zheng et al. 2005), movement analysis (Zhou and Hu 2004), and joint angle estimation. Zheng et al. (2005) identified non-vision-based inertial sensors as the best suitable technology for home rehabilitation, due to the information they can provide for clinical assessment, their small size, and their relatively low cost and easy interface with computers. Recently, affordable and easy-to-install vision systems, such as the Kinect, have been used for joint rehabilitation assessment. However, as research by Bo et al. (2011) has underlined, the Kinect presents irregular performance in nonstructured environments. These authors underlined that the inertial sensor can also suffer from data corruption and suggested that this could be fixed by complementing it with information from the Kinect or by integrating inertial sensors with magnetometers.

PROPOSED APPROACH

This section introduces the technology required and adopted in our approach to enable user interaction solutions exchangeability and personalization.

The URC Framework

The URC framework (International Organization for Standardization 2008) is a five-part international standard (ISO/IEC 24752) published in 2008. This standard specifies a user interface socket (UI socket) that enables decoupling the user interfaces (UIs) from the target device or services and works as an interaction point for pluggable user interfaces. The framework also specifies resource servers as repositories for any kind of user interface and resource necessary for interacting with appliances and services to be shared among the user community.

Furthermore, the universal control hub (UCH) overcomes the transition to a URC-enabled world by implementing a gateway-oriented architecture of the URC framework (Zimmermann and Vanderheiden 2007). The UCH connects both URC and non-URC compatible controllers and target devices/services bridging across multiple targets and target platforms and providing a choice of user interfaces for various controller platforms.

Universal Remote Rehabilitation Delivery Architecture

The architecture proposed in this article for universal remote rehabilitation delivery is made up of three layers: the user layer, the cloud layer, and the hospital layer. For an improved understanding, the proposed architecture is depicted in Figure 1.

The user layer defines a common approximation for the different service consumption contexts that users have to deal with in their real lives (e.g., home context, hospital context, or on the go). Each service consumption context client is composed of a UCH middleware, a tracking solution, and a user interface. The UCH enables UI personalization and easy upgrading through its UI plug-and-play feature. In addition, the definition of a common interface specification for the different tracking systems in the UCH enables the seamless exchange of the tracking systems. Following a UCH middleware-based architecture approach, the system can be easily extended with new services (e.g., health services, home control) in the future and user interfaces that span across several services or targets can be deployed.

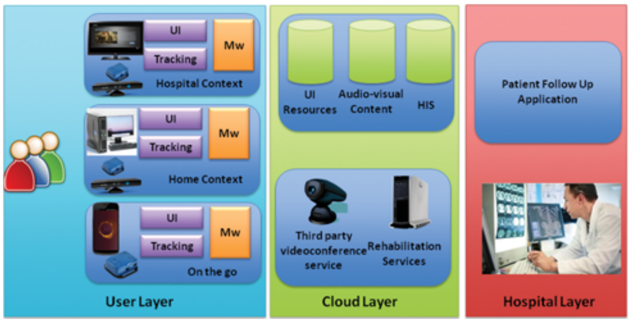

FIGURE 1 Proposed system architecture.

The cloud layer is responsible for ensuring the scalability of the services and it is composed of the following blocks: the UI resources repository and the audio-visual content repository, the rehabilitation services, and the hospital information system.

The UI repository follows the resource server concept introduced as part of the URC ecosystem (OpenURC Alliance 2013a) and implements the interface and guidelines provided by the OpenURC Alliance (OpenURC Alliance 2013b). This technology enables to incrementally support users with different needs and preferences and to upgrade UI elements or complete UIs based on users' capabilities and context evolution or maintenance tasks.

The developed audio-visual content repository supports different modalities, in order to meet all users' needs and preferences. Apart from a static repository, the most advanced scenario is targeting the fusion of the prescribed exercise content with the user's exercise tracking representation in the same audio-visual content.

The rehabilitation services can include basic to more complex services. The baseline services must include the support for therapy prescription and results assessment functionalities for the medical professional and the therapy load and results submission functionalities for the patient. These services can be extended to include other actors involved in the care cycle or provide new functionalities to the involved actors.

In order to provide open interfaces for third-party developments and make sure that the implementation is hospital information system independent, the rehabilitation services must be defined following Web Services Description Language specifications. The integration of videoconference can be provided as part of the rehabilitation services or externally as depicted in Figure 1.

The main element of the hospital layer is the follow-up application, which implements the medical professionals' client to access rehabilitation services. The functionalities to be implemented for such a client include rehabilitation therapy prescription and patient's therapy execution tracking results revision.

In summary, the inclusion of the UCH technology in the architecture approach enables the easy personalization of UIs, allows using URC and non-URC controller technologies (choice of client device), maximizes available interaction capabilities, and provides a platform for adding new services in the future.

The presented approach proposes an architecture for service provision in users' real-life contexts (starting rehabilitation at hospital, moving home, and providing the chance to continue outdoors or while on the go). Apart from the localization choice, the solution allows having different service functionalities in each UI, providing the required service functionalities per scenario.

IMPLEMENTATION

The implementation to validate the approach has been developed for knee replacement rehabilitation and more specifically for the postsurgical teletraining of body joints. The implementation has been focused on seniors, the user group suffering this pathology most.

On the service layer, the initial rehabilitation services implementation includes four web services: (WS1) rehabilitation therapy prescription, (WS2) load therapy exercises, (WS3) send exercise monitoring, and (WS4) load therapy monitoring and historical services.

The rehabilitation workflow is detailed in the following: First, the medical professional (medical doctor or therapist) prescribes a therapy through the WS1 service. Later, the patient loads the therapy and the assigned multimedia content using the WS2 service, realizes the exercises while being monitored, and the monitoring is updated to the cloud through the WS3 service. Finally, the rehabilitator loads the therapy monitoring for assessment using the WS4 service. Figure 2 shows a conceptual diagram of the developed web services.

Skype videoconferencing was selected as the third-party videoconference service and it has been integrated through SkypeKit API (Zivkov et al. 2012).

On the user layer, the following services have been integrated with the UCH middleware: (WS2) load therapy exercises and (WS3) send exercise monitoring. In addition, the inertial sensor-based tracking system and the required modules for the virtual human–based interaction technology have been integrated with the UCH.

On the hospital layer, a patient follow-up application has been implemented that has been integrated with (WS1) rehabilitation therapy prescription and (WS4) load therapy monitoring and historical services. The following subsections detail the UI concept developed for seniors and the selected tracking solution. The implementation

FIGURE 2 Conceptual diagram with the developed rehabilitation services.

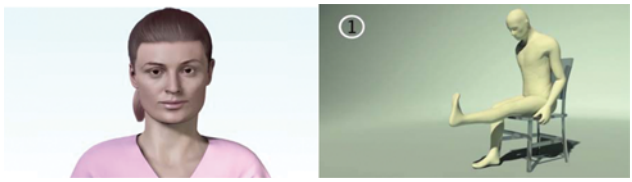

FIGURE 3 Virtual human—based rehabilitation therapy guidance.

of the cloud layer has been done on locally hosted servers, but porting to cloud service, such as the Amazon EC2, is planned to provide scalability and high availability and decrease system maintenance tasks.

Virtual Human—Guided Rehabilitation Therapy

A realistic virtual human deployed on TV was selected as the user interface interaction concept for the seniors' telerehabilitation therapy guidance. In order to achieve older adults' acceptance and have them follow a virtual therapist's instructions, a familiar and convincing look was specifically designed in collaboration with medical professionals. The voice of the virtual therapist was selected from a casting to meet the therapist profile in mind. For the dummy virtual human reproducing the exercises, a simple model was selected to avoid stigmatization. The developed virtual therapist and dummy concepts are shown in Figure 3.

Portable Inertial Sensors for Joint Angle Assessment

Precise joint angle measurement is required for specific rehabilitation therapy (elbow, shoulder, etc.) assessments. In addition to a precise and reliable solution, a home rehabilitation deployment should keep at the minimum the number of device technologies used, configuration needs, and costs. As suggested by the literature analysis, the approach's implementation has made use of a device that integrates the inertial sensors with magnetometers (STT Systems 2013). The selected solution provides precise orientations, angular velocities, and accelerations in real time and has been integrated with the UCH middleware through its Bluetooth connectivity and serial port profile implementation.

Information received from the inertial sensors is locally processed to calculate each flexion/extension angle for the selected biomechanical model. For the approach's implementation, left and right knee biomechanical models have been used. Then, the prescribed exercise repetition is assigned with the processed joint angle time—history data set and uploaded to the cloud using the defined rehabilitation service. Alarms per maximum/minimum joint angle flexion/extension can be defined currently to ease rehabilitation assessment by the therapist. Additionally, work is being carried out to identify underactivity and the recognition of evolution trends to suggest to the medical professional the need for a therapy/rehabilitation phase change.

EVALUATION

The developed system was evaluated with 13 medical professionals and 19 patients in the period January 2013 to July 2013. The recruited medical professionals' profiles were rehabilitation specific, evenly distributed between medical doctors and physiotherapists. Their experience was quite diverse, ranging from low (1–2 years), to medium (5–10 years), to high (20–30 years). With regards to patients, the sample was composed of 10 males and 9 females with an age range from 50 to 79 ($x = 69.31$; SD = 7.38), from the city of Donostia—San Sebastian (Spain), and its surroundings. The sample was composed of patients who had recently undergone knee replacement at Donostia Hospital. Only 15.79% had no formal education, 57.89% had completed primary education, and 26.32% had finished secondary education. Regarding the technology usage habits, 52.63% did not make use of connected devices, 21.05% used computers, 15.79% used tablets, and 26.32% reported having smart TVs but not making much use of their advanced features.

The technical setup on the patient side was composed of a TV set with the virtual therapist content as the HCI technology and with the inertial sensors for therapy execution monitoring. The sensors were identified with stickers numbered 1 and 2 and instructions with clarifying pictures were provided to the patient. For the therapist, patients' visual information was shown on a laptop, including a 3D representation of the exercise execution and 2D graphics of achieved joint angles in time.

For the therapists, a special meeting was arranged where the system was introduced. Therapists were then invited to a room where a prototype of the client was presented to them. Next they were asked to complete a usability questionnaire. Additionally, focus groups were set up to collect more information and detect improvement areas. For the patients, the technical setup was similar, but the system was tested by the patients and the monitoring results were reviewed by a therapist. The evaluation was explained to them by the therapist and they were administered a consent form for acceptance to participate in the evaluation session. Afterwards, sociodemographical data was captured and they were allowed to practice using the system. After the patients completed four therapy sessions, programmed for different days, they were asked to complete a usability questionnaire for the designed audiovisual content paradigm and look, tracking system, and acceptance of the developed system.

RESULTS

Medical professionals were very positive regarding the virtual therapist for therapy guidance though the simplicity of the dummy virtual human presenting the exercises was found to be a possible limiting factor for engaging with patients. One of the main comments from the virtual therapist was why recordings of real people could not be used instead of the virtual therapist. Some of the professionals also stated that the virtual therapist looked too serious and lacked empathy with the patient. Regarding the dummy virtual human, they thought that it should reflect the user's effort and

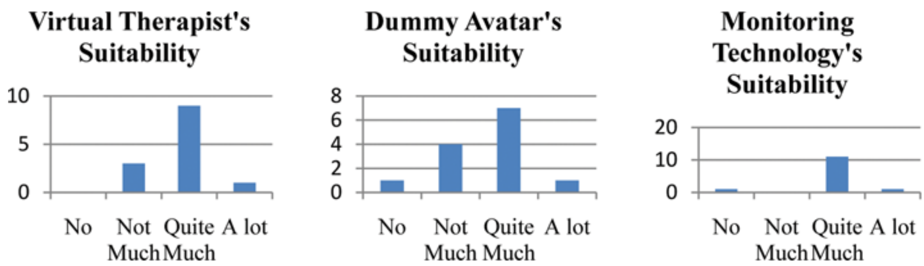

FIGURE 4 Graphical representation of the medical professionals' answers to questions regarding the solution's suitability.

pain, it should be dressed, and it should highlight the areas used in each exercise. Regarding the inertial sensors, they were identified as providing precise information but therapists were afraid that senior patients might not being able to put them on correctly. In general, the therapists conceived the solution as a valid, motivating, and complementary tool for outpatient rehabilitation at clinical facilities. Figure 4 presents therapist results regarding the solution's suitability.

Patients showed good acceptance of both evaluated virtual humans (therapist, dummy). The virtual therapist's design acceptance was confirmed with comments including patients considering it a serious and adequate character or patients requesting for more exercises. Concerning the dummy virtual human, patients expressed that it was easy to follow, but it was considered too simple to engage with. Regarding the inertial sensors, the patients had almost no problem in wearing them following the instructions provided. Figure 5 presents patient results regarding the solution's suitability and the perceived ease of putting the sensors on.

Concerning the marketability of the product (attitude toward product consumption), the therapists clearly understood the evaluated system as complementary and noted its potential to improve patient progress. Additionally, the patients reported that this system could improve their motivation to exercise. Figure 6 presents results related to marketability of the product.

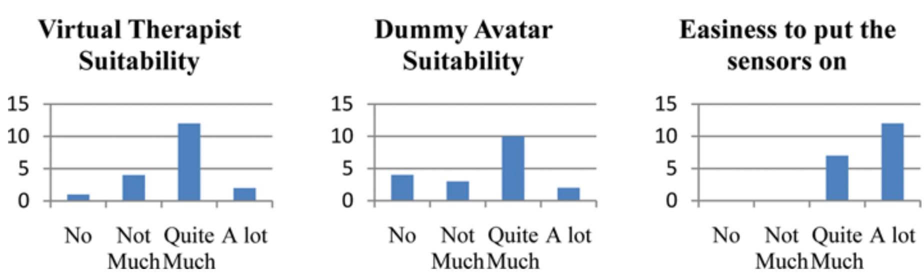

FIGURE 5 Graphical representation of the patients' answers to questions related to the solution's suitability.

FIGURE 6 Product's complementarity and expected progress improvement compared to traditional therapy from professionals' perspective (left, middle). Patients' view on motivation improvement using this product (right).

CONCLUSIONS

This article has presented an architectural proposal, an implementation to validate such a proposal, and the corresponding evaluation results of a universal remote rehabilitation delivery system that considers the user's real-life context. For the patients' client controllers a UCH middleware (i.e., gateway oriented architecture implementation of the ISO/IEC 24752 URC standard) was used. Following this approach, limitations of previous URC-based rehabilitation works were overcome. The presented approach enables the use of URC and non-URC controller technologies, enabling the exchange of interaction and monitoring devices for rehabilitation and providing a platform for deploying new services in the future.

Furthermore, the provision of the rehabilitation services through standardized Web interfaces enables deployment with different hospital information systems without changing the rest of the implementation. Open standard-based Web service interfaces additionally enable third-party developers to easily develop new solutions/modules. Moreover, migration from the locally hosted server to cloud-based services ensures scalability and high availability and decreases system maintenance tasks.

The implementation for validation of the proposed architecture approach was developed on the older adults' joint rehabilitation therapy. Following state-of-the-art research results, a TV-based virtual human has been selected for rehabilitation therapy guidance for seniors. A high-fidelity virtual therapist (visual model and voice) and a dummy avatar reproducing the prescribed exercises were defined and developed in tight collaboration with therapists. Concerning the therapy progress assessment, the literature review on tracking devices for precisely measuring joint angles revealed two main options from which integration of magnetometers with inertial sensors was selected because they require the fewest devices and configuration needs as well as low home rehabilitation system costs.

Both medical professionals and patients positively rated the approach's implementation. Patient acceptance of the implementation for validating the approach confirms the proposed architecture and its implementation. Enhancements were requested with regards to the dummy virtual human reproducing the exercises, whose simplicity was identified as a possible limiting factor in patient engagement. Some therapists also requested that the expression of the virtual therapist should be relaxed in order to improve its empathy with the patient. Evaluation has shown that the patients had no problem with putting the inertial sensors on using the instructions provided.

FUTURE WORK

Responding to the evaluation results, the personalization of the dummy virtual human to the patient and exercise is being researched to increase patient identification with the virtual human in order to increase the targeted engagement. Furthermore, audio-visual content and automatic placement detection are being developed to guide seniors in the correct placement of the sensors. The authors' research is oriented toward the adaptation of the developed virtual reality concepts to the patients' needs, preferences, and therapy progress.

Regarding the proposed approach, the objective is to implement additional services starting from AAL (Ambient Assisted Living) and telehealth services. Self-management of chronic conditions is another application area where telerehabilitation has the potential to exceed that of traditional care and management strategies. Concurrently, security and performance implementations are being implemented to prepare the system for real-world deployment. Concerning research on the architecture approach, the aim is to move service integration to the Web service side through the upcoming ISO/IEC 24752—Part 6. This upcoming standard defines URC-enriched Web services through naming convention. Implementation of this part will require simpler middleware implementations, therefore benefiting resource-constrained device deployments.

Last but not least, in order to take into account the patient's real-life context, a methodology is needed in order to define which functionalities of the service will be implemented in each potential scenario.

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REFERENCES

Bo, A. P. L., M. Hayashibe, and P. Poignet. "Joint Angle Estimation in Rehabilitation with Inertial Sensors and Its Integration with Kinect." In *Engineering in Medicine and Biology Society Annual International Conference*, edited by N. Lovell, 3479–83. Boston: IEEE, 2011.

Brienza, D. M. and M. McCue. "Introduction to Telerehabilitation." In *Telerehabilitation*, edited by S. Kumar and E. R. Cohn, 1–11. London: Springer-Verlag, 2013.

Burrell, J., P. Treadwell, and G. K. Gay. "Designing for Context: Usability in a Ubiquitous Environment." In *Proceedings of the 2000 Conference on Universal Usability*, edited by J. Thomas, 80–84. New York: ACM, 2000.

Deutsch, J. E., M. Borbely, J. Filler, K. Huhn, and P. Guarrera-Bowlby. "Use of a Low-Cost, Commercially Available Gaming Console (Wii) for Rehabilitation of an Adolescent with Cerebral Palsy." *Physical Therapy* 88, no. 10 (2008): 1196–207.

European Commission. *Seniorwatch 2—Assessment of the Senior Market for ICT Progress and Developments*. Brussels, Belgium: European Commission, 2008.

Eurostat European Commission. *Standard EuroBarometer 78—Media Use in the European Union*. Brussels, Belgium: European Commission, 2012.

Feng, X. and J. M. Winters. "An Interactive Framework for Personalized Computer-Assisted Neurorehabilitation." *IEEE Transactions on Information Technology in Biomedicine* 11, no. 5 (2007): 518–26.

Hong, J. I. and J. A. Landay. "An Infrastructure Approach to Context-Aware Computing." *Human–Computer Interaction* 16, no. 2 (2001): 287–303.

International Organization for Standardization. *ISO/IEC 24752:2008—Information Technology—User Interfaces—Universal Remote Console (5 Parts)*. Geneva, Switzerland: International Organization for Standardization, 2008.

International Organization for Standardization. *ISO 9241-210:2010 Ergonomics of Human–System Interaction—Part 210: Human-Centred Design for Interactive Systems*. Geneva, Switzerland: International Organization for Standardization, 2010.

Johnson, M., X. Feng, L. Johnson, and J. Winters. "Potential of a Suite of Robot/Computer-Assisted Motivating Systems for Personalized, Home-Based, Stroke Rehabilitation." *Journal of NeuroEngineering and Rehabilitation* 4, no. 6 (2007): 1–17.

Kwakkel, G., B. J. Kollen, and H. I. Krebs. "Effects of Robot-Assisted Therapy on Upper Limb Recovery after Stroke: A Systematic Review." *Neurorehabilitation and Neural Repair* 22, no. 2 (2008): 111–21.

Mougharbel, I., N. Miskawi, and A. Abdallah. "Towards a Service Oriented Architecture (SOA) for Tele-Rehabilitation." In *Ambient Assistive Health and Wellness Management in the Heart of the City*, vol. 5597, edited by M. Mokhtari, I. Khalil, J. Bauchet, D. Zhang, and C. Nugent, 253–56. Berlin: Springer-Verlag, 2009.

Nakamura, K., T. Takano, and C. Akao. "The Effectiveness of Videophones in Home Healthcare for the Elderly." *Medical Care* 37, no. 2 (1999): 117–25.

Nap, H. H. and U. Diaz-Orueta. "Rehabilitation Gaming." In *Serious Games for Healthcare: Applications and Implications*, edited by S. Arnab, I. Dunwell, and K. Debattista, 50–75. New York: IGI Global, 2013.

OpenURC Alliance. 2013a. "Resource Server HTTP Interface 1.0." Available at: http://openurc.org/TR/res-serv-http1.0/ (accessed September 27, 2013).

OpenURC Alliance. 2013b. "URC Technical Primer 1.0." Available at: http://openurc.org/TR/urc-tech-primer1.0/ (accessed September 27, 2013).

Ortiz, A., M. P. Carretero, D. Oyarzun, J. J. Yanguas, C. Buiza, M. F. Gonzalez, and I. Etxeberria. "Elderly Users in Ambient Intelligence: Does an Avatar Improve the Interaction?" In *Proceedings of the 9th Conference on User Interfaces for All*, edited by C. Stephanidis and M. Pieper, 99–114. Berlin: Springer-Verlag, 2007.

Parmanto, B. and A. Saptono. "Telerehabilitation: State-of-the-Art from an Informatics Perspective." *International Journal of TeleRehabilitation* 1, no. 1 (2009): 73–84.

Reinkensmeyer, D. J., C. T. Pang, J. A. Nessler, and C. C. Painter. "Web-Based Telerehabilitation for the Upper Extremity after Stroke." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 10, no. 2 (2002): 102–8.

Rizzo, A. A., B. S. Lange, J. G. Buckwalter, E. Forbell, J. Kim, K. Sagae, J. Williams, B. O. Rothbaum, J. Difede, G. Reger, T. Parsons, P. Kenny. "SimCoach: An Intelligent Virtual Human System for Providing Healthcare Information and Support." In *Proceedings of the 8th International Conference on Disability, Virtual Reality and Associated Technologies,* edited by P. Sharkey and J. Sánchez, 213–21. Viña del Mar/Valparaiso, Chile: The University of Reading, 2010.

Simpson, J. "Challenges and Trends Driving Telerehabilitation." In *Telerehabilitation*, edited by S. Kumar and E. R. Cohn, 13–27. London: Springer-Verlag, 2013.
STT Systems. 2013. "IBS Sensor." Available at: http://www.stt.es/en/products/inertial-sensor/ibs-sensor/hardware/ (accessed September 27, 2013).
Światek, P., K. Juszczyszyn, K. Brzostowski, J. Drapala, and A. Grzech. "Supporting Content, Context and User Awareness in Future Internet Applications." In *The Future Internet*, vol. 7281, edited by F. Álvarez, F. Cleary, P. Daras, et al., 154–65. Berlin: Springer, 2012.
Winters, J. M. "Telerehabilitation Interface Strategies for Enhancing Access to Health Services for Persons with Diverse Abilities and Preferences." In *Telerehabilitation*, edited by S. Kumar and E. R. Cohn, 55–78. London: Springer-Verlag, 2013.
World Health Organization. *Global Health and Aging*. Geneva, Switzerland: World Health Organization, 2011.
Zheng, H., N. Black, and N. Harris. "Position-Sensing Technologies for Movement Analysis in Stroke Rehabilitation." *Medical and Biological Engineering and Computing* 43, no. 4 (2005): 413–20.
Zhou, H. and H. Hu. *A Survey Human Movement Tracking and a Research Proposal*. Technical Report CSM-420. Colchester, UK: Department of Computer Sciences, University of Essex, 2004.
Zimmermann, G. and G. Vanderheiden. "The Universal Control Hub: An Open Platform for Remote User Interfaces in the Digital Home." In *Human–Computer Interaction*, vol. 4551, edited by J. A. Jacko, 1040–49. Berlin: Springer, 2007.
Zivkov, D., M. Davidovic, M. Vidovic, N. Zmukic, and A. Andelkovic. "Integration of Skype Client and Performance Analysts on Television Platform." In *Proceedings of the 35th International Convention MIPRO*, edited by P. Biljanovic, Z. Butkovic, K. Skala, et al., 479–82. Opatija, Croatia: IEEE, 2012.