Ontology-based Knowledge Management for Comprehensive Geriatric Assessment and Reminiscence Therapy on Social Robots

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Abstract MARIO is an assistive robot that has to support a set of knowledge-intensive tasks aimed at increasing autonomy and reduce loneliness in people with dementia, and supporting caregivers in their activity to assess patients cognitive status. Examples of knowledge-intensive tasks are the Comprehensive Geriatric Assessment (CGA) and the delivery of reminiscence therapy. In order to enable these tasks, MARIO features a set of abilities implemented by pluggable software applications. MARIO's abilities contribute to and benefit from a common knowledge management framework. For example, the ability associated with the CGA retrieves questions to be posed to the patient from the framework and stores the obtained answers and associated relevant metadata. In this work we presents the MARIO knowledge management software framework, which combines robotics with ontology-based approaches and Semantic Web technologies. It consists of (i) a set of interconnected and modularized ontologies, meant to model all knowledge areas that are relevant for MARIO abilities, and (ii) a set of software interfaces that provide high level access to the ontology network and its associated knowledge base. Finally, we demonstrate how the knowledge management framework supports the applications for CGA and reminiscence therapy, implemented on top of the knowledge base.

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1 Introduction

Dementia is a progressive and degenerative syndrome that affects the global cognitive capabilities of an individual, gradually impairing cognition and causing a deterioration of memory, thinking, language, social behaviour and emotional control. The World Health Organization estimates that nowadays around 50 million people are affected by this syndrome worldwide, and this number is expected to triple by 2050.[1] Dementia is thus one of the major challenges for global public health, with psychological and socio-economical effects that extend to caregivers and family members [11]. As there is still no definitive cure for dementia, standard pharmacological therapy is often complemented with non-pharmacological treatments and cognitive rehabilitation therapies that focus on stimulating and maintaining the functional and mental abilities of people with dementia (PWD).

In this general context, the potential of information and communication technology (ICT) in dementia care is increasingly investigated [22]. Specifically, in recent years elderly and dementia care have emerged as the main application fields for Socially Assistive Robotics [13], given the great potential of social robots in supporting people with cognitive impairment and their caregivers [5, 17, 20, 27, 29]. As overviewed in [28], existing robotic technologies for elderly care range from pet-like devices to advanced anthropomorphic mobile robotic assistants. While service robots often focus on providing *physical* support and interaction, a socially assistive robot aims to provide cognitive support through *social* interaction. Companion robots thus aim at providing services and assistive functions to improve daily life, such as interactive media access, events reminding, cognitive training exercises, mentally stimulating games, and communication facilities to enable connectedness with caregivers and relatives. Robots able to provide companionship, support and assistance through social interaction have the potential to combat the impact of loneliness by improving mood and quality of life, and reduce social isolation by enabling PWD to maintain social connectedness [9, 30]. However, in order to perform complex tasks in real environments, socially engage human users and provide personalized support to PWD, a companion robot has to acquire and manage heterogeneous information and data. A fundamental requirement for social robots is thus the ability to capture knowledge from multiple domains and manage it in a form that facilitates sharing, reuse and integration. Hence the need and importance of providing robots with knowledge management frameworks able to handle knowledge from different sources and support multiple tasks and applications.

In recent years, these challenges are increasingly addressed by exploring the potential of ontology-based approaches and Semantic Web methods in supporting robotic applications. Along this path, the H2020 European Project MARIO[2] has investigated the use of autonomous companion robots as cognitive stimulation tools for people with dementia. The MARIO robot and its capabilities are specifically designed to provide support to PWD, their caregivers and related healthcare

[1] http://www.who.int/mediacentre/factsheets/fs362/en/

[2] http://www.mario-project.eu

professionals. Among its unique capabilities, MARIO can help caregivers in the patient assessment process by autonomously performing Comprehensive Geriatric Assessment (CGA) evaluations, and is able to deliver reminiscence therapy through personalized interactive sessions. These capabilities are part of a robotic software framework for companion robots and are supported by a knowledge representation and management framework, where ontology-based knowledge representation techniques and Semantic Web technologies are combined. The overall framework and the applications presented here have been deployed on Kompaï-2 robots, and evaluated and validated during supervised trials in different dementia care environments, including a nursing home (Galway, Ireland), community groups (Stockport, UK) and a geriatric unit in hospital settings (San Giovanni Rotondo, Italy).

In this work we present the ontology-based knowledge management framework for companion robots and we focus on the robotic applications developed on top of the framework for supporting Comprehensive Geriatric Assessment and reminiscence therapy. In Section 2 we first outline the main challenges and requirements related to knowledge management on companion robots for people with dementia, and we provide an introduction to ontologies and Semantic Web principles. An overview of relevant approaches and ontology-based frameworks for robotic applications is provided as well. The MARIO knowledge management framework is discussed in Section 3, focusing on the ontology network and the software framework we designed. We then present the applications for Comprehensive Geriatric Assessment and reminiscence therapy in Section 4 and Section 5 respectively. Finally, Section 6 concludes the paper.

2 Knowledge Management on Social Robots

As robot acceptance and the perception of usefulness for both PWD and caregivers play a fundamental role, different authors have focused on the main requirements and challenges for social robots targeting elderly people with cognitive impairments, as discussed for example in [8, 14, 19, 21].

2.1 Challenges and Requirements

Key functionalities range from the ability to perceive the environment and autonomously move and operate, to the capability of engaging the user in cognitively stimulating entertainment activities. In terms of human-robot interaction, dialogue is considered as one of the most important social interaction abilities for companion robots, and the ability to communicate using natural language emerges as an important requirement. Similarly, the need to provide the robot with the ability to perceive and interpret emotions is recognized, so as to understand the emotional state of the user and react accordingly. Orthogonally to these capabilities, the ability to provide a personalized user experience and adapt to user needs is a major success factor for acceptance of companion robots [10], particularly when designed for PWD. Robot applications should be customizable to meet individual needs and preferences, and should be able to progressively gather user-specific information through a knowledge acquisition and learning phase driven by actual interactions.

In a robotic framework, each subsystem and application accesses a variety of information needed to support its task-specific internal logic, and in turn produces data as part of its processing. Each application can thus exploit knowledge coming from multiple sources, including other subsystems and applications, and produces knowledge that can be used by other components or serve as a basis for data analytics. As an example, the natural language understanding subsystem in charge of processing user's utterances would need access to *(i)* linguistic resources to build a syntactic and semantic representation of textual utterances; *(ii)* user-dependent knowledge for linking language symbols to specific entities; and *(iii)* sentiment-related knowledge to enrich the interpretation with sentiment data. Language interpretation results can then be exploited by the robot control subsystem to, e.g., trigger the appropriate application, or by a running application to select the next action. These decisional steps can also be influenced by combining contextual information with user-specific knowledge, such as user preferences, previous interactions and other data that collectively define the user profile.

To address the requirement of capturing knowledge from multiple domains and managing it in a form that facilitates sharing, reuse and integration, two key elements are needed: *(i)* a common conceptualization of the domains of interest, captured and formalized in shared, extensible representational models where domain concepts and their properties are defined, structured and linked according to a reference knowledge representation framework; *(ii)* a knowledge management framework, supporting the storage in and retrieval from a common knowledge base instantiated with knowledge produced according to the reference models. The need to provide robots with a knowledge representation and management framework able to handle knowledge from different sources (including external data sources and knowledge bases) and support multiple tasks and applications has long been considered in robotics. However, it is only in recent years that the potential of ontology-based knowledge representation approaches and Semantic Web technologies has been considered to address the two aforementioned points in robotic platforms. In the following we first introduce in Section 2.2 the main definitions and background concepts concerning ontologies and Linked Data, and then in Section 2.3 we briefly present notable ontology-based frameworks and initiatives in the robotic domain.

2.2 Ontologies and Linked Data

Historically ontology, listed as part of metaphysics, is the philosophical study of the nature of being, becoming, existence, or reality, as well as the basic categories of being and their relations. Ontology deals with questions concerning what entities exist or can be said to exist, and how such entities can be grouped, related within a hierarchy, and subdivided according to similarities and differences. While the term ontology has been rather confined to the philosophical sphere in the recent past, it has gained a specific role in a variety of fields of Computer Science, such as Artificial Intelligence, Computational Linguistics, and Database Theory and Semantic Web. In Computer Science the term loses part of its metaphysical background and, still keeping a general expectation that the features of the model in an ontology should closely resemble the real world, it is referred as a formal model consisting of a set of types, properties, and relationship types aimed at modeling objects in a certain domain or in the world. In early ’90s Gruber [18] gave an initial and widely accepted definition:

> *An ontology is a formal, explicit specification of a shared conceptualization. An ontology is a description (like a formal specification of a program) of the concepts and relationships that can formally exist for an agent or a community of agents.*

Accordingly, ontologies are used to encode a description of some world (actual, possible, counterfactual, impossible, desired, etc.), for some specific purpose. In the Web of Data, aka the Semantic Web, ontologies have been used as a formalism to define the logical backbone of the Web itself. The language used for designing ontologies in the Web of Data is the Web Ontology Language (OWL) [1]. In the last decade there has been a lot of research for investigating best practices for ontology design and re-use in the Web of Data. Among the others the EU-FP7 NeOn project[3] has provided sound principles and guidelines for designing complex knowledge networks called *ontology networks*. An ontology network is a set of interconnected ontologies. According to [2], the interconnections can be defined in a variety of ways, such as alignments, modularization based on `owl:imports` axioms[4], and versioning. Ontology networks enable modular ontology design in which each module conceptualizes a specific domain and can be designed by using Ontology Design Patterns [16] and pattern-based ontology design methodologies, such as eXtreme Desing [6]. This particular notion of ontologies and their evolving trend towards networked, modular, and interconnected structures has encouraged us to use them as the key technology for dealing with knowledge in MARIO.

While (networked) ontologies define the logical backbone of the Web, the *Linked Data* principles define how data should be published and connected on the Web of Data. Those principles behind are as simple as using HTTP URIs for identifying things, responding to standard lookups (e.g. SPARQL or URI dereferencing) with standard formats (e.g. RDF) and curating cross-links between things. Linked Data provide a formalism to have data organised in MARIO as a knowledge graph. This knowledge graph is modelled by using concepts and relations defined in a pertinent ontology network, as detailed in Section 3.

[3] `http://www.neon-project.org/`

[4] An ontology can import other ontologies in order to gain access to their entities, expressions, and axioms.

2.3 Knowledge Management Frameworks for Robotics

Ontologies and Semantic Web technologies can support the development of robotic systems and applications that deal with knowledge representation, acquisition and reasoning. Furthermore, Semantic Web standards enable the interlinking of local robotic knowledge with available information and resources coming from the Web of Data. This trend has also led to the creation of the IEEE RAS Ontologies for Robotics and Automation Working Group (ORA WG), with the goal of developing a core ontology and an associated methodology for knowledge representation and reasoning in robotics and automation [33].

In this direction, different frameworks have been proposed to model, manage and make available heterogeneous knowledge for robotic systems and applications. Focusing on service robots that operate in indoor environments through perception, planning and action, the ontology-based unified robot knowledge framework (OUR-K) [25] aims at supporting robot intelligence and inference methods by integrating low-level perceptual and behavioural data with high-level knowledge concerning objects, semantic maps, tasks, and contexts. An ontology-based approach is also adopted in the ORO knowledge management platform [24]. The platform stores and processes knowledge represented according to the OpenRobots Common Sense Ontology[5], an OWL ontology based on the OpenCyc upper ontology and extended with the definition of reference concepts for human-robot interaction. When deployed on a robot, the knowledge base can be instantiated with a priori common-sense knowledge and is then used as a “semantic blackboard” where the robotic modules (such as the perception module, the language processing module, the task planner and the execution controller) can store the knowledge they produce and query it back.

Along the same path, research projects and initiatives, such as KnowRob[6], RoboEarth[7] and RoboBrain[8], go beyond local knowledge bases and, also with the emergence of cloud-based robotics, propose Web-scale approaches. KnowRob [37] is a knowledge processing system and semantic framework for integrating information from different sources, including encyclopedic knowledge, common-sense knowledge, robot capabilities, task descriptions, environment models, and object descriptions. Knowledge is represented and formally modeled according to a reference upper ontology, defined using the Web Ontology Language (OWL). The system supports different reasoning capabilities and provides interfaces for accessing and querying the KnowRob ontology and knowledge base. Similarly, the RoboEarth framework [38] provides a web-based knowledge base for robots to access and share semantic representations of actions, object models and environments, augmented with rule-based learning and reasoning capabilities. The RoboEarth knowledge base relies on a reference ontology, as an extension of the KnowRob ontology to *(i)* represent actions and relate them in a temporal hierarchy; *(ii)* describe object

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[5] `https://www.openrobots.org/wiki/oro-ontology`

[6] `http://knowrob.org/`

[7] `http://roboearth.ethz.ch/`

[8] `http://robobrain.me/`

models to support recognition and articulation; and *(iii)* represent map-based environments. An HTTP-based API enables robots to access the knowledge base for uploading, searching and downloading information from and to their local knowledge bases. Along the same path, the RoboBrain knowledge engine [35] aims at learning and sharing knowledge gathered from different sources and existing knowledge bases, including linguistic resources, such as WordNet, image databases, such as ImageNet, and Wikipedia. Although the RoboBrain knowledge base does not explicitly adopt ontologies and Semantic Web technologies, knowledge is represented in a graph structure and stored in a graph database. A REST API enables robots to access RoboBrain as-a-service, to provide and retrieve knowledge on the basis of a specific query language.

3 The MARIO Knowledge Management Framework

At the heart of the MARIO robotic platform, a knowledge management framework provides MARIO abilities with a reference ontology and common knowledge base able to cover all relevant knowledge areas, as well as with mechanisms to interact with such a knowledge base for organizing, accessing and storing knowledge. The framework consists of: *(i)* the MARIO Ontology Network (MON), a set of interconnected and modularized ontologies covering different knowledge areas and defining reference models for representing and structuring the knowledge processed by the robot; *(ii)* a knowledge management system that manages the shared knowledge base and provides high level access to the MON and knowledge base.

3.1 The MARIO Ontology Network

The MARIO Ontology Network has been designed following best design practices and a pattern-based ontology engineering approach, aimed at extensively reusing Ontology Design Patterns (ODPs) [16] for modeling ontologies. The design methodology that we followed is based on an extension of eXtreme Design [6], an agile design methodology for ontology engineering. Such an extension mainly focuses on providing ontology engineers with clear strategies for ontology re-use [34].

In line with the eXtreme Design methodology, the core knowledge areas were identified by analyzing the reference use cases outlined together with domain experts, including professional caregivers from different pilot sites. These uses cases mainly describe actions and behaviors that the robot should perform or select while interacting with the user under different circumstances. At the same time, they include detailed descriptions of the nature of the knowledge that the robot should deal with in order to perform and select actions and behaviors. The process of highlighting the knowledge domains was enabled by the identification from the use cases of a set of *competency questions*, commonly identified as the requirements that an on-

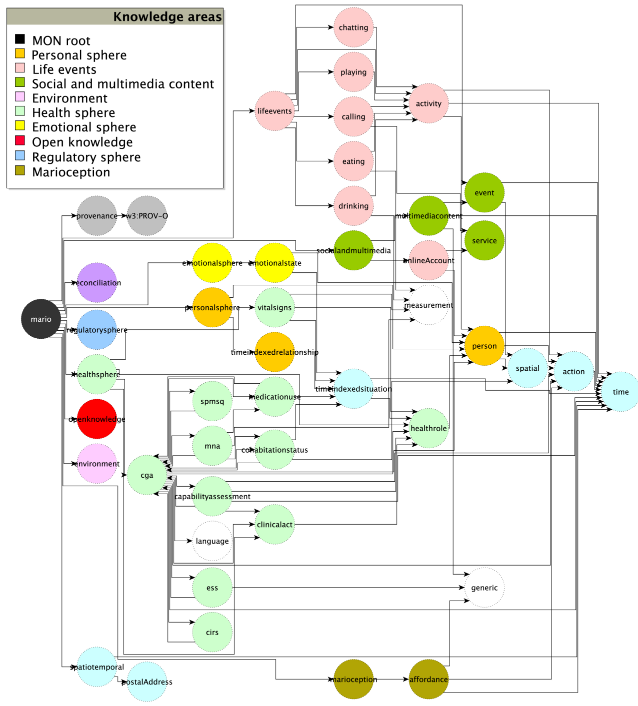

Fig. 1 Knowledge areas and core modules of the MARIO Ontology Network

tology has to address. By iteratively generalizing the knowledge domains, we then identified a set of top-level knowledge areas as a basis for the ontology network.

As shown in Figure 1, the MON was designed as a networked ontology[9] composed of interlinked modules that cover the different knowledge areas relevant to MARIO in order to make it a cognitive agent able to support people with dementia. With respect to the guidelines defined in [34], the strategy we adopted for the development of the MON is the *indirect re-use* of ontology design patterns and alignments. Under this approach, ODPs are used as templates. At the same time, the ontology guarantees interoperability by keeping the appropriate alignments with the external ODPs, and provides extensions that satisfy domain-specific requirements. With this type of reuse, the potential impact of possible changes in the external ontology modules is minimized. Currently, the MON covers 12 knowledge areas and includes 40 modules for representing different knowledge domains, such as lexical knowledge (e.g., natural language lexica and linguistic frames), user- and application-specific knowledge (e.g., user profiles, life events and multimedia con-

[9] as denoted by the arrows, each module can import other modules; the root of the MON and the ontologies part of the network are available at `http://www.ontologydesignpatterns.org/ont/mario/`

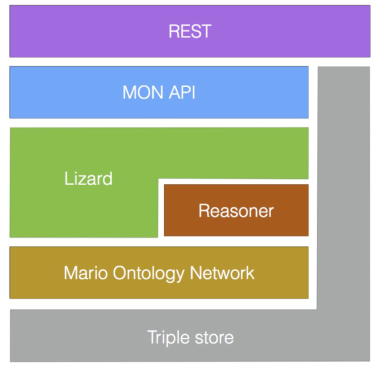

Fig. 2 Layered model and components of the knowledge management system

tent), environmental knowledge (e.g., physical locations and maps), and metadata knowledge (e.g., entity tagging).

3.2 *The Knowledge Management System*

The MON introduced in Section 3.1 serves as a basis for organising in a knowledge base (KB) the knowledge consumed and produced by the applications implementing robot's abilities. These applications, which can be plugged into the platform by means of the REST architectural style, interact with the MON and KB. To this end, a knowledge management system, whose layered conceptual architecture is shown in Figure 2, provides mechanisms for creating and storing knowledge, and for querying and reasoning over the shared knowledge base. These capabilities are abstracted and made available through a set of software interfaces for programmatic, language-independent access.

As shown in Figure 2, while knowledge is concretely expressed by using RDF and managed in a triple store that serves as physical storage, the knowledge management system relies on an Object-RDF mapper called *Lizard*[10], responsible for enabling transparent access to the ontology network and knowledge base by generating a middleware API for client applications. An Object-RDF mapper is a system that exposes the RDF triple sets as sets of resources and seamlessly integrates them into the Object Oriented paradigm. However, differently from existing systems, such as SuRF[11] or ActiveRDF[12] [31], Lizard provides a RESTful layer that enables the access to the knowledge base over HTTP. Basically, Lizard dynamically and automatically generates Java and HTTP REST APIs from the ontology network specification. Those APIs reflect the semantics of the MON, but client applications (i.e., any component of the MARIO robotic framework) can access the knowledge base

[10] available at `https://github.com/anuzzolese/lizard`
[11] `https://pythonhosted.org/SuRF/`
[12] `https://github.com/ActiveRDF/ActiveRDF`

without any prior knowledge of the ontologies used within the system. For example, this avoids client applications to directly deal with OWL and RDF, or to interact with the knowledge base by means of SPARQL queries. Additionally, Lizard embeds an Access Control Management System (ACMS) that enables the setup of specific access policies in order to restrict access to specific knowledge areas (either in read or write mode) only to a set of allowed entities/systems. For example, an application that performs some entertainment activity (e.g., an interactive music player) would not be allowed to access knowledge about user's clinical status. Hence, the ACMS allows Lizard to deal with some important data management aspects regarding data access, security and privacy. As part of the knowledge management system, reasoning services are made available through Lizard as well. The reasoner relies on the Apache Jena Inference engine[13] and provides reasoning capabilities for knowledge consistency checking, classification and enrichment, to infer new knowledge by using the axiomatisations defined in the MON and the knowledge stored in the knowledge base.

Personalization and knowledge acquisition. Enabling the robot to provide personalized support and interactions requires to instantiate the knowledge base with user-specific knowledge, exploited by the applications to adapt to user needs and preferences. To this end, the platform provides a *Caregiver Interface*, as a Web-based Graphical User Interface that supports caregivers and family members in the process of of building a user-specific knowledge graph, centered around user's profile, family/social relationships and life events. The tool also enables the provision and tagging of multimedia objects (such as music files and photos) and the configuration and personalizations of the available applications. Through the interface, the caregiver can set up the Comprehensive Geriatric Assessment sessions and access generated health reports and scores resulting from the assessments, as detailed in Section 4. The tool is responsible for storing the gathered data in the knowledge base, by exploiting the interfaces provided by the knowledge management system.

This user-specific knowledge that has to be explicitly provided is complemented with general purpose background knowledge that supports robot's abilities, such as linguistic resources managed in the local knowledge base, like the multilingual Paraphrase Database (see Section 4), or accessed by linking to external resources like the Framester hub [15].

4 The Comprehensive Geriatric Assessment Application

The Comprehensive Geriatric Assessment (CGA) is a diagnostic process that aims at collecting and analyzing data in order to determine the medical, psychosocial, functional and environmental status of elderly patients, with the goal of improving the diagnostic plan and supporting physicians in the definition of personalized plans for treatment and long-term care.

[13] https://jena.apache.org/documentation/inference/

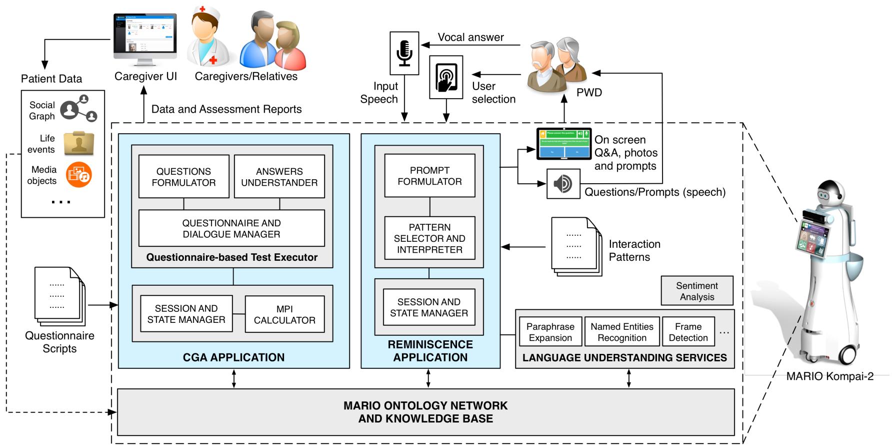

Fig. 3 Architectural model of the CGA and Reminiscence applications

The assessment process. A multidimensional assessment phase is at the heart of the CGA process and represents a critical, time consuming activity for caregivers. To gather information about the patient, physicians rely on a set of widely accepted, internationally validated formal assessment tools and standardized rating scales designed to evaluate patient's functional abilities, physical and mental health, and cognitive status. As part of the assessment tools and procedures, the patient is required to answer questions defined in standardized clinical questionnaires[14] (e.g., about his/her daily life and ability to autonomously perform specific activities). Depending on the answers, a score is given to the patient and evaluated according to a reference rating scale. The assessment enables the evaluation of a Multidimensional Prognostic Index (MPI), a prognostic tool that combines the scores resulting from the questionnaires to derive a single score able to synthetically represent patient's health status and define the severity grade of mortality risk in elderly subjects [32].

A CGA is typically carried out every 6 months and, on average, a questionnaire-based evaluation requires between 20 and 30 minutes per patient to be completed. As most of the total time available to the formal caregiver is consumed to collect information from the patient, the evaluation and definition of a personalized care plan is often performed under time pressure, in particular in the setting of an ambulatory geriatric care unit. Nowadays health professionals increasingly use ICT supporting tools and devices, such as computers and tablets, during the multidimensional assessment phase for recording test results and calculating the corresponding scores. However, it has been observed that these devices and the need to interact with them to input information can represent a "communication barrier" between the caregiver

[14] A standard CGA includes eight assessment tools and scales: Co-habitation status, Medication use, Activities of Daily Living (ADL), Instrumental Activities of Daily Living (IADL), Short Portable Mental Status Questionnaire (SPMSQ), Exton-Smith Scale (ESS), Cumulative Illness Rating Scale (CIRS), and Mini Nutritional Assessment (MNA).

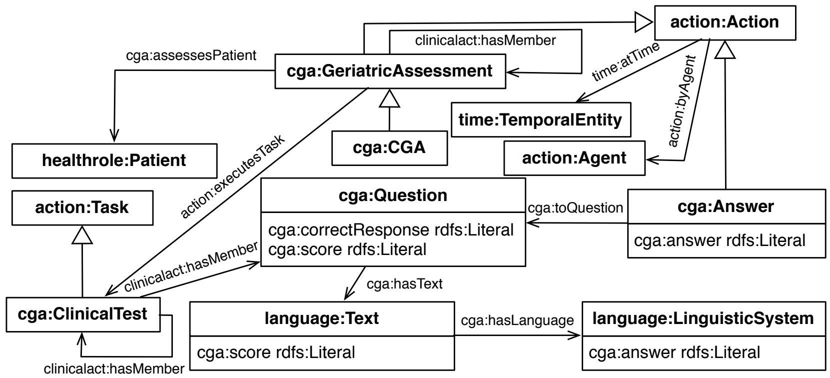

Fig. 4 Graphical representation of the Comprehensive Geriatric Assessment (CGA) ontology

and the patient during clinical interviews [12]. The lack of visual contact with the caregiver can further increase stress and anxiety in frail elderly patients undergoing a cognitive evaluation whose results may potentially impact on their autonomy.

The introduction of a robotic solution able of autonomously performing parts of a CGA is expected to reduce the direct involvement of health professionals in the time-consuming data collection tasks, as well as the perceived tiredness resulting from the performance of repetitive tests. This will enable them to concentrate their efforts on the interpretation of the results and the elaboration of personalized care plans. In the long term, the objective is to enable a continuous monitoring of patient's conditions (e.g., by increasing the frequency of CGA sessions), with an opportunity to early detect relevant changes in the health status. In this direction, the ASSESSTRONIC project[15] and the CLARC framework [3] are investigating robotic solutions for supporting the CGA process.

MARIO's CGA application, whose components are shown in Figure 3, aims at enabling the robot to autonomously perform and manage the execution of the questionnaire-based tests required in the CGA process[16], in order to assist the formal caregivers and physicians in the multidimensional assessment phase and facilitate the evaluation of the Multidimensional Prognostic Index. The CGA application is thus designed to undertake a dialogue-based interaction with the patient, by posing the defined questions and interpreting patient's answers to assign the corresponding scores. Moreover, by recording patient's answers and calculated tests scores, the application can generate health reports for the care staff, to allow them to access, analyze and review test results.

Knowledge base support. The CGA application relies on the CGA ontology module[17] defined as part of the MARIO Ontology Network introduced in Section 3.1.

[15] http://echord.eu/essential_grid/assesstronic/

[16] the described solution manages, in English and Italian, 8 assessment questionnaires as defined in http://www.operapadrepio.it/contenuti/ricerca/pdf/TEST_MPI_en.pdf

[17] http://www.ontologydesignpatterns.org/ont/mario/cga.owl

While some ontologies have been proposed with high-level concepts for representing medical assessments and processes [4, 7], these models are not able to directly represent the results of CGA executions. The CGA ontology we defined, whose graphical representation is shown in Figure 4, follows their approach and specializes the high-level concepts where needed. The CGA ontology provides a high-level conceptual model shared by all the tests included in the CGA process. Specific ontology sub-modules, imported by the CGA ontology, were designed to capture the peculiarities and requirements of the different tests that compose a CGA.

On the one hand, the CGA ontology supports the execution of the assessment process by providing a reference model for storing test information, including questions and their multilingual formulation, expected answers and corresponding scores. On the other hand, it allows storing and recording the data resulting from the assessment sessions, including the answers provided by the patient, test results and calculated scores. As in [4], a patient assessment (i.e., `cga:GeriatricAssessment`) is an action having as participant a `healthrole:Patient` and, as it specializes the class `action:Action`, an `action:Agent` who makes the assessment. The agent can be either a `healthrole:Physician` or another kind of agent (e.g., the MARIO robot). To represent the *description* of how the assessment is to be executed, we rely on the *Task Execution* Ontology Design Pattern. The action `cga:GeriatricAssessment` executes a `cga:ClinicalTest` which provides a “description” of how the assessment has to be executed. A `cga:ClinicalTest` can be composed of other clinical tests or some `cga:Question`. Furthermore, the CGA ontology allows representing information about the answers (i.e., `cga:Answer`) provided by a patient to specific questions. The designed sub-modules specialize the CGA ontology on the basis of the specific requirements of the tests, e.g., the CGA ontology defines the class `cga:GeriatricAssessment` and the sub-modules representing the Activities of Daily Living (ADL) and Instrumental Activities of Daily Living (IADL) questionnaires specialize this class with `ca:CapabilityAssessment`.

CGA sessions. In the CGA application (Figure 3), the *Session and State Manager* manages the overall execution and status of CGA sessions, coordinating the scheduling and performance of the configured tests. It operates on the basis of user profiles and configuration settings defined by the formal caregiver and available in the knowledge base. To access the knowledge base, the CGA module exploits the functionalities and API provided by the knowledge management system introduced in Section 3.2. As CGA tests are typically performed during a clinical encounter (e.g., when the patient is admitted to or discharged from the geriatric unit), a CGA session can be initiated by the caregiver either through the provided graphical interface or by vocally interacting with the robot.

When the application is activated, the *Session and State Manager* initiates and monitors the sequential execution of the specific tests to be performed. Specifically, the *Questionnaire-based Test Executor* is in charge of the execution of questionnaire-driven tests, and is thus responsible for engaging the patient in a dialogue-based interaction, with the aim of gathering information that enables the calculation of assessment scores and prognostic indexes. The dialogue flow is driven by the robot and unfolds on the basis of a continuous question-answer interaction pattern. To this end, the component relies on the speech-based communication capabilities provided by the MARIO framework and operates on the basis of scripted representations of the different questionnaires that are part of the CGA. Dialogue management is driven by the questionnaire structure, which acts as a blueprint for the question-answer interactions and provides the ordering and sequencing of the assessment questions. For a specific test, the corresponding questionnaire script is derived from its description and representation retrieved from the knowledge base.

Basically, the application gradually presents spoken questions to the patient and gathers her vocal responses to be interpreted. Each question formulated by the app and uttered by the robot is contextually shown on the touch screen. Depending on the question type (open-ended or closed-ended question), possible answers may be shown on the screen as well. This enables the patient to provide her answers by directly speaking to the robot or by interacting with the graphical interface. The application relies on natural language understanding capabilities for interpreting patient's utterances representing answers to the evaluation questions. A proper interpretation of provided answers ultimately results in the assignment of a score to each answer. The *Answers Understander* takes as input the textual representation of patient's utterances, as provided by the speech-to-text subsystem. The actual interpretation strategy directly depends on the question and corresponding answer type.

In the case of YES-NO questions (e.g., *"Do you need any help to wash or bathe yourself?"*), which cover most of the items in the CGA questionnaires, patient's answers are matched against regular expression patterns that aim at capturing both positive and negative answers. The patterns were built by exploiting existing linguistic resources, in particular the Paraphrase Database (PPDB)[18], an automatically extracted multilingual database of paraphrases. PPDB has been re-engineered in RDF and included as part of the knowledge base, according to the reference PPDB ontology[19] we defined. In the case of *Wh*-questions, which cover most of the items in the Short Portable Mental Status Questionnaire (e.g., *"What is the date today?"*, *"When were you born?"*, *"Who is the current Pope?"*), the understanding process maps to the task of comparing patient's answers with known properties of named entities, such as persons (including the patient herself, her parents, and well-known present and historical individuals) and dates. These properties can be directly retrieved or derived by querying the knowledge base (e.g., by accessing patient's profile to get her birth day or her mother's maiden name) and then compared with the provided answer. The matching process relies on specialized understanding capabilities that restrict the recognition and interpretation to specific domains, such as locations and numbers, used for example when the user is asked to perform basic math calculations as part of the SPMSQ questionnaire.

Finally, the *MPI Calculator* is responsible for calculating the overall Multidimensional Prognostic Index, taking into account the scores and rating scales resulting from the execution of the assessment tests.

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[18] `http://paraphrase.org/`

[19] `http://w3id.org/ppdb/ontology/ppdb.owl`

5 The Reminiscence Application

Reminiscence therapy is based on verbal interactions that focus on recalling positive memories about people, past activities, experiences and personal events, often with the support of materials such as photos that act as memory triggers. Reminiscence therapy thus targets and aims at stimulating long-term autobiographical memory, which is relatively unaffected by the disease. Reported effects range from increased socialization and self-esteem to improvements in cognition and mood, with a general positive impact on quality of life [26, 39].

As discussed in [23, 36], existing systems for supporting reminiscence aim at improving traditional practice and basically consist of software applications, deployed on desktop/laptop computers or tablets, that act as personalized multimedia systems for the storage and retrieval of digital reminiscence materials. Our approach focuses on robot-enabled delivery of so-called *simple reminiscence* [26], based on a conversational approach and highly focused verbal and visual memory triggers. The application, whose components are shown in Figure 3, is thus specifically designed to actively prompt the PWD and engage her in interactive and personalized reminiscence sessions, where dialogue-based interactions are complemented with multimedia content associated with relevant people, places and life events.

Knowledge base support. Supporting reminiscence requires the availability of user-specific factual knowledge, gathered in the form of a life history from family members and caregivers. In order to represent, structure, store and make available this heterogeneous information, specific ontology modules were defined as part of the MARIO Ontology Network. The ontology modules supporting reminiscence cover three main knowledge areas, i.e., personal sphere, life events and multimedia content. They address the need of representing persons and their basic biographic information, family and social relationships among them, life events, and multimedia objects along with their association with persons, places and life events.

While biographic information covers basic data (e.g., first/last name, birth date and hometown), family and social relationships enable the definition of a social graph for the PWD. User profiles can be further enriched with the definition of life events on the basis of a generalized representational schema, which includes the primary properties of a life event and relies on the *time-indexed situation* ontology design pattern. In addition to a title and a textual description, a life event is characterized by *(i)* a temporal dimension, to allow representing events that occurred in a specific date (e.g., a marriage) or over a period of time (e.g., attendance to college); *(ii)* a set of participants, to express the participation of potentially multiple persons in the event; *(iii)* a location where the event took place; *(iv)* a set of multimedia objects (photos, videos, etc.) associated with the event. Starting from this generic representational structure, the need to specialize life events to cover specific domains led us to narrow down the scope of the modeling approach and adopt a frame-based representational structure. Specific life events and their properties are modeled as *frames*, to cover typical domains including work and education (e.g., school attendance and working experiences), personal and family events (such as a marriage and the birth of a child), and living and travel experiences. A *frame* provides a schema for conceptualizing the description of an event type and its participants in terms of *frame elements* or *semantic roles* [15]. For example, a marriage involves two persons participating as *partners*, and takes place in a specific *location* and *date*. Similarly, a birth event includes an *offspring* (the person that was born) and involves two persons as *mother* and *father*, along with the *birth place* and *date*.

The association between media objects and other entities relies on a semantic tagging approach, as defined in a *tagging* ontology module[20] designed so that any object (including frames or even named graphs) can be used to categorize or describe the entity being tagged. This allows defining, for example, life events and persons as tags for an image, in addition to simple properties expressing when and where a photo was taken.

Reminiscence sessions. User-specific knowledge is directly exploited by the application for engaging the patient in reminiscence sessions. A reminiscence session can be triggered as a result of a direct request issued by the user, either through the GUI provided by the MARIO framework and available on the touchscreen, or via vocal commands, exploiting the multimodal interaction capabilities provided by the robot. Specifically, a dialogue-based reminiscence session is driven by an extensible repertoire of *interaction patterns*, that allow the application to prompt the user through specific questions and triggers, associated with media objects such as images that are contextually shown on the touchscreen available onboard the robot.

An *interaction pattern* consists of: *(i)* a *precondition*, with constraints expressed as queries over the knowledge base, defining under which conditions the prompt can be instantiated and used; *(ii)* a parametric *prompting question* to be used for triggering reminiscence, represented as a partially-formulated prompt template containing variables to be instantiated with data from the knowledge base; *(iii)* a set of queries over the knowledge base providing a binding for the variables in the prompting question. On the basis of these patterns, the main step in the application logic consists of contextually identifying the applicable patterns, by accessing the knowledge base to evaluate their preconditions and instantiate the corresponding prompt. As visual memory triggers are fundamental for reminiscence, the patterns are always evaluated taking into account the availability of an image that will be shown to the user while the prompt is uttered by the robot through its text-to-speech capabilities.

Prompting questions are defined to cover the aforementioned knowledge elements, including life event types, people and tagged media objects. As informally shown in Figure 5, given a photo with information on where it was taken, and who appears in the picture, examples of parametric prompting questions that also exploit family/social relationships include *"Is that your* `{familyRelationship}` `{personName}` *in the photo with you?"* or *"That's you* `{patientName}` *in the photo with your* `{familyRelationship}` `{personName}`*. Where was this taken?"*. Similarly, the association between photos and life events can be exploited to formulate questions about the event. Assuming, for example, that there is a marriage event where the PWD is one of the partners, prompting questions, such as

[20] `http://www.ontologydesignpatterns.org/ont/mario/tagging.owl`

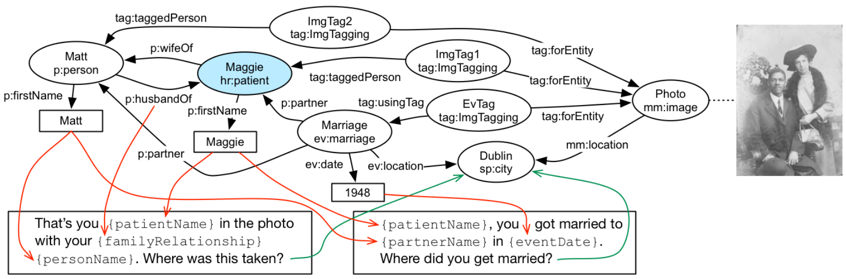

Fig. 5 Example of prompting questions formulation from user-specific knowledge graph

"`{patientName}`*, you got married to* `{partnerName}` *in* `{eventDate}`*. Where did you get married?"*, can be formulated.

In these examples, prompting questions take the form of targeted questions that assume a specific, known answer, from a simple positive/negative reply to the identification of specific persons, places, dates or events. In the case of prompts formulated as targeted questions, the interaction patterns are extended by defining the answer type (e.g., a yes/no answer, a person, a date, etc.), the actual expected answer (by referencing a concrete entity in the knowledge base, such as a specific person or location), and utterance templates that are used by the robot depending on whether user's reply matches the expected answer or not. These additional elements are used by the application in the user answer processing step, where the capabilities of the natural language understanding subsystem are used. Targeted questions with specific answers constrain the language interpretation domain: the interpretation maps to the task of named entity recognition and linking with respect to the knowledge base, to identify mentions of named entities (e.g., a person or a location) in user's utterance and check the correspondence with the entity representing the expected answer. Depending on the outcome of this step, the robot can reply with a confirmation and encouragement if the answer is correct, or otherwise provide the patient with intermediate hints or the expected answer.

As an approach based on repeated questions can create stress and anxiety and be inappropriate for people with cognitive impairments, prompting questions can also be defined as open-ended prompts that aim at stimulating conversation. So for example, considering again a picture related to a marriage event, the robot can use prompts like *"*`{patientName}`*, you got married to* `{partnerName}` *in* `{eventDate}`*. Tell me about you wedding day! What was it like?"*. Similarly, given a picture of one of patient's children, prompts like *"*`{patientName}`*, this is your* `{childRelationship}` `{childName}` *in this nice picture. What was* `{childName}` *like as a child?"*. When dealing with this type of prompts, the interpretation of user's replies adopts a different strategy and relies on *sentiment analysis* capabilities. Basically, the application attempts identify the polarity of user's utterances, to recognize whether the visual and verbal prompt is eliciting a positive, neutral or negative mood or reaction from the person. The interaction patterns are extended in this case by defining utterance templates for the different polarities, so that the robot can, e.g., encourage the user to tell more about the subject if the reaction is positive, or otherwise propose to move to another picture.

The selection of the interaction patterns is thus a dynamic process, driven by patient's replies and reactions, and by traversing the links in the knowledge graph on the basis of the dialogue context and history. So, for example, a question about when a photo was taken can be followed by a question concerning a person that appears in the picture, and then move to a life event where the person participated in, and so on, exploiting the properties of and links between the entities in the knowledge base. Similarly, sentiment data can influence the selection process as well: for example, a negative reaction to a picture concerning an event or showing a specific person may lead to avoid subsequent prompts with images about the same event or with that person. Moreover, sentiment data emerging from the interactions can be associated with the concerned entities (pictures, people, events, etc.) and stored in the knowledge base. This knowledge is then used in subsequent reminiscence sessions so that, for example, photos that generated a positive reaction are favored in the selection process, whereas those causing negative reactions are less likely to be reproposed.

6 Conclusions

Social robots can become useful tools in dementia care, improving patient's daily life and caregivers' work practices. We focused on the challenges and possible solutions for multi-domain knowledge management on companion robots, as a prerequisite for the development of applications based on knowledge sharing and reuse. In the MARIO project, we explored an ontology-based approach and Semantic Web technologies for knowledge representation and management. This approach and technologies support innovative applications that enable the robot to autonomously perform Comprehensive Geriatric Assessment and deliver personalized reminiscence therapy. Although ongoing trials in different dementia care settings confirm the validity of the approach, an in-depth analysis of qualitative and quantitative data collected from patients and caregivers will enable a multidisciplinary evaluation.

Acknowledgements The research leading to these results has received funding from the European Union Horizon 2020 – The Framework Programme for Research and Innovation (2014-2020) under grant agreement 643808 Project MARIO "Managing active and healthy aging with use of caring service robots".

References

1. OWL 2 Web Ontology Language Document Overview. W3C Recommendation (2009). URL `http://www.w3.org/TR/owl2-overview/`
2. Allocca, C., d'Aquin, M., Motta, E.: DOOR - towards a formalization of ontology relations. In: Proceedings of the International Conference on Knowledge Engineering and Ontology

Development, pp. 13–20 (2009)
3. Bandera, A., Bandera, J.P., Bustos, P., Calderita, L.V., nas, A.D., Fernández, F., Fuentetaja, R., García-Olaya, A., García-Polo, F.J., González, J.C., Iglesias, A., Manso, L.J., Marfil, R., Pulido, J.C., Reuther, C., Romero-Garcés, A., Suárez, C.: CLARC: a Robotic Architecture for Comprehensive Geriatric Assessment. In: 17th Workshop of Physical Agents (2016)
4. Batrancourt, B., Dojat, M., Gibaud, B., Kassel, G.: A core ontology of instruments used for neurological, behavioral and cognitive assessments. In: Proceedings of the 6th International Conference on Formal Ontology in Information Systems, pp. 185–198 (2010)
5. Bemelmans, R., Gelderblom, G.J., Jonker, P., de Witte, L.: Socially Assistive Robots in Elderly Care: A Systematic Review into Effects and Effectiveness. J Am Med Dir Assoc **13**(2), 114–120.e1 (2012)
6. Blomqvist, E., Presutti, V., Daga, E., Gangemi, A.: Experimenting with eXtreme Design. In: Proceedings of the 17th International Conference on Knowledge Engineering and Management by the Masses, EKAW'10, pp. 120–134. Springer-Verlag, Berlin, Heidelberg (2010)
7. Bouamrane, M.M., Rector, A., Hurrell, M.: Development of an ontology for a preoperative risk assessment clinical decision support system. In: Proceedings of 22nd IEEE International Symposium on Computer-Based Medical Systems, pp. 1–6 (2009)
8. Bruno, B., Mastrogiovanni, F., Sgorbissa, A.: Functional requirements and design issues for a socially assistive robot for elderly people with mild cognitive impairments. In: 2013 IEEE RO-MAN, pp. 768–773 (2013)
9. Casey, D., Felzmann, H., Pegman, G., Kouroupetroglou, C., Murphy, K., Koumpis, A., Whelan, S.: What People with Dementia Want: Designing MARIO an Acceptable Robot Companion. In: K. Miesenberger, C. Bühler, P. Penaz (eds.) Computers Helping People with Special Needs, pp. 318–325. Springer International Publishing, Cham (2016)
10. Dautenhahn, K.: Robots we like to live with?! - a developmental perspective on a personalized, life-long robot companion. In: RO-MAN 2004. 13th IEEE International Workshop on Robot and Human Interactive Communication, pp. 17–22 (2004)
11. Etters, L., Goodall, D., Harrison, B.E.: Caregiver burden among dementia patient caregivers: a review of the literature. J Am Acad Nurse Pract **20**(8), 423–428 (2008)
12. European Coordination Hub for Open Robotics Development (ECHORD++): Robotics for the Comprehensive Geriatric Assessment (CGA) Challenge (2015). URL `http://echord.eu/portal/ProposalDocuments/download/9`
13. Feil-Seifer, D., Matarić, M.J.: Socially Assistive Robotics. IEEE Robot Autom Mag **18**(1), 24–31 (2011)
14. Fong, T., Nourbakhsh, I., Dautenhahn, K.: A survey of socially interactive robots. Rob Auton Syst **42**(34), 143–166 (2003)
15. Gangemi, A., Alam, M., Asprino, L., Presutti, V., Recupero, D.R.: Framester: A Wide Coverage Linguistic Linked Data Hub. In: 20th International Conference on Knowledge Engineering and Knowledge Management, pp. 239–254 (2016)
16. Gangemi, A., Presutti, V.: Ontology Design Patterns. In: S. Staab, R. Studer (eds.) Handbook on Ontologies, pp. 221–243. Springer Berlin Heidelberg, Berlin, Heidelberg (2009)
17. Gross, H.M., Schroeter, C., Mueller, S., Volkhardt, M., Einhorn, E., Bley, A., Martin, C., Langner, T., Merten, M.: Progress in developing a socially assistive mobile home robot companion for the elderly with mild cognitive impairment. In: 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2430–2437 (2011)
18. Gruber, T.: A translation approach to portable ontology specifications. Knowl Acquis **5**(2), 199–220 (1993)
19. Heerink, M., Kröse, B., Evers, V., Wielinga, B.: Assessing Acceptance of Assistive Social Agent Technology by Older Adults: the Almere Model. Int J Soc Robot **2**(4), 361–375 (2010)
20. Huschilt, J., Clune, L.: The Use of Socially Assistive Robots for Dementia Care. J Gerontol Nurs **38**(10), 15–19 (2012)
21. Korchut, A., Szklener, S., Abdelnour, C., Tantinya, N., Hernandez-Farigola, J., Ribes, J.C., Skrobas, U., Grabowska-Aleksandrowicz, K., Szczęśniak-Stańczyk, D., Rejdak, K.: Challenges for Service Robots-Requirements of Elderly Adults with Cognitive Impairments. Front Neurol **8**, 228 (2017)

22. Lauriks, S., Reinersmann, A., der Roest, H.V., Meiland, F., Davies, R., Moelaert, F., Mulvenna, M., Nugent, C., Droes, R.: Review of ICT-based services for identified unmet needs in people with dementia. Ageing Res Rev **6**(3), 223–246 (2007)
23. Lazar, A., Thompson, H., Demiris, G.: A systematic review of the use of technology for reminiscence therapy. Health Educ Behav **41**(1 Suppl), 51S–61S (2014)
24. Lemaignan, S., Ros, R., Mösenlechner, L., Alami, R., Beetz, M.: ORO, a knowledge management platform for cognitive architectures in robotics. In: 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3548–3553 (2010)
25. Lim, G.H., Suh, I.H., Suh, H.: Ontology-Based Unified Robot Knowledge for Service Robots in Indoor Environments. IEEE Trans Syst Man Cybern A Syst Human **41**(3), 492–509 (2011)
26. Lin, Y.C., Dai, Y.T., Hwang, S.L.: The effect of reminiscence on the elderly population: a systematic review. Public Health Nurs **20**(4), 297–306 (2003)
27. Marti, P., Bacigalupo, M., Giusti, L., Mennecozzi, C., Shibata, T.: Socially Assistive Robotics in the Treatment of Behavioural and Psychological Symptoms of Dementia. In: The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, pp. 483–488 (2006)
28. Martinez-Martin, E., del Pobil, A.P.: Personal Robot Assistants for Elderly Care: An Overview. In: A. Costa, V. Julian, P. Novais (eds.) Personal Assistants: Emerging Computational Technologies, pp. 77–91. Springer International Publishing, Cham (2018)
29. Mordoch, E., Osterreicher, A., Guse, L., Roger, K., Thompson, G.: Use of social commitment robots in the care of elderly people with dementia: A literature review. Maturitas **74**(1), 14–20 (2013)
30. Moyle, W., Cooke, M., Beattie, E., Jones, C., Klein, B., Cook, G., Gray, C.: Exploring the effect of companion robots on emotional expression in older adults with dementia: a pilot randomized controlled trial. J Gerontol Nurs **39**(5), 46–53 (2013)
31. Oren, E., Heitmann, B., Decker, S.: ActiveRDF: Embedding Semantic Web data into object-oriented languages. Web Semant **6**(3), 191–202 (2008)
32. Pilotto, A., Sancarlo, D., Panza, F., Paris, F., D'Onofrio, G., Cascavilla, L., Addante, F., Seripa, D., Solfrizzi, V., Dallapiccola, B., Franceschi, M., Ferrucci, L.: The Multidimensional Prognostic Index (MPI), based on a comprehensive geriatric assessment predicts short- and long-term mortality in hospitalized older patients with dementia. J Alzheimers Dis **18**(1), 191–199 (2009)
33. Prestes, E., Carbonera, J.L., Fiorini, S.R., Jorge, V.A.M., Abel, M., Madhavan, R., Locoro, A., Goncalves, P., Barreto, M.E., Habib, M., Chibani, A., Gérard, S., Amirat, Y., Schlenoff, C.: Towards a core ontology for robotics and automation. Rob Auton Syst **61**(11), 1193–1204 (2013)
34. Presutti, V., Lodi, G., Nuzzolese, A., Gangemi, A., Peroni, S., Asprino, L.: The Role of Ontology Design Patterns in Linked Data Projects. In: I. Comyn-Wattiau, K. Tanaka, I.Y. Song, S. Yamamoto, M. Saeki (eds.) Conceptual Modeling, pp. 113–121. Springer International Publishing, Cham (2016)
35. Saxena, A., Jain, A., Sener, O., Jami, A., Misra, D.K., Koppula, H.S.: RoboBrain: Large-Scale Knowledge Engine for Robots. ArXiv e-prints (2015). URL `http://arxiv.org/abs/1412.0691v2`
36. Subramaniam, P., Woods, B.: Towards the Therapeutic Use of Information and Communication Technology in Reminiscence Work for People with Dementia: a Systematic Review. Int J Comput Healthc **1**(2), 106–125 (2010)
37. Tenorth, M., Beetz, M.: KnowRob: A knowledge processing infrastructure for cognition-enabled robots. Int J Robotics Res **32**(5), 566–590 (2013)
38. Tenorth, M., Perzylo, A.C., Lafrenz, R., Beetz, M.: Representation and Exchange of Knowledge About Actions, Objects, and Environments in the RoboEarth Framework. IEEE Trans Autom Sci Eng **10**(3), 643–651 (2013)
39. Woods, B., Spector, A., Jones, C., Orrell, M., Davies, S.: Reminiscence therapy for dementia. Cochrane Database Syst Rev (2) (2005)