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A review of smart homes—Present state and future challenges

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ABSTRACT

In the era of information technology, the elderly and disabled can be monitored with numerous intelligent devices. Sensors can be implanted into their home for continuous mobility assistance and non-obtrusive disease prevention. Modern sensor-embedded houses, or smart houses, cannot only assist people with reduced physical functions but help resolve the social isolation they face. They are capable of providing assistance without limiting or disturbing the resident's daily routine, giving him or her greater comfort, pleasure, and well-being. This article presents an international selection of leading smart home projects, as well as the associated technologies of wearable/implantable monitoring systems and assistive robotics. The latter are often designed as components of the larger smart home environment. The paper will conclude by discussing future challenges of the domain.

1. Introduction

According to French INSEE figures, 16.4% of the French population is in the "over 65" age group and an additional 8% are over 75; furthermore, these proportions are likely to increase. As a result, the ratio of persons aged 16–65 to those aged 65 and over will decrease from over 3:1 (its value in the 1990s) to about 2:1 by the year 2040 [1]. Similar demographic changes are taking place in most European countries, the U.S.A., and Japan. Overall, this trend suggests that by 2050 approximately 20% of the world population [2] will be at least 60 years old.

One way to avoid institutionalizing older persons (or at least to defer it as long as possible) and reduce spiraling medical costs is through technology. We wish to not only cure illness, but also promote wellness in all stages of life. In particular, technology can help persons age at home in safety and independence. For many years, home automation has been considered a highly promising field for developing electronic technologies. Even as early as the eighties, several applications were being considered to enhance personal comfort and safety. Although some of these solutions were highly sophisticated, the home market has lagged the telecommunications and automotive markets—two industries where the role of electronics has continually grown more important. Households spent a large fraction of their income on cars, computers, etc. and very little is left for home automation devices. Still, it is worth mentioning progress in certain areas:

- *Remote management*: data associated with energy (gas and power), water, and telecommunications expenses can now be transmitted to the utility company without anybody going on site. As for home comfort systems, heating, air conditioning, ventilation, lighting, and doors and windows can all be automated and manipulated by remote control. Various electrical appliances such as washing machines,

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dishwashers, refrigerators, and cooking devices can be programmed to carry out their tasks. Radios and TV sets, as well as other entertainment devices, can be connected to share programming channels.
- *Elderly assistance*: ever since the eighties, the elderly have benefited from devices that signal assistance services. Miniature transmitters can be worn around the neck or wrist, or carried in a pocket, allowing an individual to signal danger or request help simply by pressing a button. In effect, the device is an emergency telephone connected to a professional service center or a family member.

In what ways has change taken place?

- Personal computers (PCs) are increasingly available, allowing people to access the Internet. In 2004, according to French INSEE figures [1], 45% of French households had a microcomputer and 7% had an Internet connection.
- There has been rapid development of miniature, autonomous, and wireless sensors. It is now much easier to capture the information needed for implementation of home care services.
- Passive and active "tags" are being used more and more often. These are smart, wireless mini-chips that can sense and act by data transmission. They may be tied to a physical space, a machine, a device, a production line, or a human body.
- Cellular phones can be fitted with a global positioning system (GPS), or in the future with the European Galileo tracking system. These can be used to establish a permanent link between one's home and the outdoors, easing interactions and interconnections between various agents who are either monitoring or being monitored.

Thus, ambitious smart homes can be examined from the perspectives of comfort, leisure, and safety. This article aims to identify and describe a selection of leading smart home projects throughout the world. Some independent but related technologies are considered, including wearable/implantable systems and assistive, interactive robots. The paper concludes by summarizing future challenges in the domain.

2. Nomenclature

Telemedicine is defined as "the use of audio, video, and other telecommunications and electronic information processing technologies for the transmission of information and data relevant to the diagnosis and treatment of medical conditions, or to provide health services or aid health care personnel at distant sites" [3]. Originally, the term described mainly consultation services delivered through interactive video. In the Internet and multimedia era, this domain has evolved a much broader scope ranging from health promotion to disease prevention. As well as being used for patient education, telemedicine networks now include clinical decision databases, electronic patient records, artificial intelligence, and administrative support. For this reason, the term *telehealth* is preferred: it describes "the full array of technologies, networks and healthcare services provided through telecommunication, including delivery of educational programs, collaborative research, patient consultation and other services provided with the purpose of improving health" [4]. The term *home telehealth* refers to "the use of telecommunications by a home care provider to link patients or customers to one or more out-of-home sources of care information, education, or service by means of telephones, computers, interactive television, or some combination of each" [5].

A few years ago the term *eHealth* appeared, defined by Eysenbach as "An emerging field in the intersection of medical informatics, public health and business, referring to the health services and information delivered or enhanced through the Internet and related technologies. In a broader sense, the term characterizes not only a technical development, but also a state-of-mind, a way of thinking, an attitude, and a commitment to networked, global thinking, to improve health care locally, regionally, and worldwide by using information and communication technology" [6].

Home healthcare in the U.S.A. refers to individual healthcare and social services such as nursing, rehabilitation, social work and health assistance, when provided to patients in their place of residence or some other home-like setting. *Telehomecare*, a specific type of telemedicine, uses a mixture of telecommunication and videoconferencing technologies to enable communication between a healthcare provider at their clinic and a patient at their home. This interaction is called a "*virtual visit*", as opposed to the term "*actual visit*" which is used to describe traditional "face to face" interactions. A virtual visit can now include physical assessment of the patient through heart, lung and bowel sounds, as well as vital signs such as blood pressure and pulse [7].

Demiris introduces the concept of *home-based eHealth*, which includes both telehomecare and the *smart home*. In this context, the second term refers to unobtrusive disease prevention and monitoring of residents who may not receive other forms of home care, such as the disabled or elderly [7].

Various *assistive devices* are available in all task domains [8]. This term is used for systems that have been designed to fulfill a single function. A fully *integrated system* is a device with multiple functions controlled through a single human-machine interface; household integrated systems have been described for at least several decades [9,10]. Cooper and Keating use the term *integrated home systems*. Thus, a number of alternative and equivalent names are used to describe the full integration of consumer electronics: home systems, integrated home systems, smart houses, and intelligent homes. "All approaches in the field of integrated home systems enable communication between different consumer electronic devices in the home so that they can cooperate, and thus function as a system rather than as a collection of independent devices" [11].

The term *rehabilitation integrated system* refers to a group of rehabilitation assistance devices (usually electronic). When brought together, they can provide disabled individuals with better access and ergonomics [12]. Integrating assistive technologies in this manner allows people with disabilities to more fully participate in society.

Latin languages may use the word *domotics*, meaning *automation of the house* [13]. In English the concept is generally referred to as the *smart house* [14]. In this paper, the terms "home", "house", "household", and "housing" are considered synonymous; “housing” has the additional sense of dwellings in general. *Smart house* is commonly used to refer to any living or working environment that has been carefully constructed to assist people in carrying out required activities.

3. Review of projects

The smart home concept is a promising and cost-effective way of improving access to home care for the elderly and disabled. Many research and development projects are ongoing, funded by international and governmental organizations. Note that some of the following smart homes have been designed to address a specific physical or mental disability.

Smart homes can be classified according to the types of equipment and systems installed. The major targets are improving comfort, dealing with medical rehabilitation, monitoring mobility and physiological parameters, and delivering therapy. Technologies exist to help people deal with a reduction or loss of mobility, vision, hearing, and cognitive ability; to continuously monitor vital parameters; to reduce accidents by anticipating risky situations; and to deliver therapy through wearable biomedical sensors. All these systems maintain a certain level of independence, thus providing a better quality of life for the resident and his close relatives. However, the recipients of smart homes are not just those with severe pathologies or chronic illness; there are also those who simply want a better quality of life. For example, services enabling the “virtual visit” are particularly important in rural areas [15–17].

A block diagram of a smart system is shown in Fig. 1. The functions that can be implemented in a smart home with adequate equipment, devices, or specific appliances are shown in Table 1. In the following section, some specific projects will be presented. The selected projects have been deemed among the most significant from an international perspective, but the list is not exhaustive. The smart homes discussed below, along with their equipment, key algorithms, and functions, are summarized in Table 2.

3.1. *Smart homes*

A number of smart homes have now been developed. Beyond issues of comfort and leisure, they are mainly intended to monitor elderly subjects with motor, visual, auditory or cognitive disabilities [18–21]. In each case the house and its various electrical appliances have been fitted with sensors, actuators, and/or biomedical monitors. The devices operate in a network, which is sometimes connected to a remote center for data collection and processing. The remote center diagnoses the ongoing situation and initiates assistance procedures.

3.1.1. *In the U.S.A.*

In Boulder, Colorado an “adaptive” house has been developed that uses neural networks to control temperature, heating, and lighting without previous programming by the residents. This system, called ACHE, attempts to economize energy resources while respecting the lifestyle and desires of its inhabitants. ACHE continuously monitors the environment and observes actions taken by the residents (using the lights, adjusting the thermostat). From these data, it infers patterns

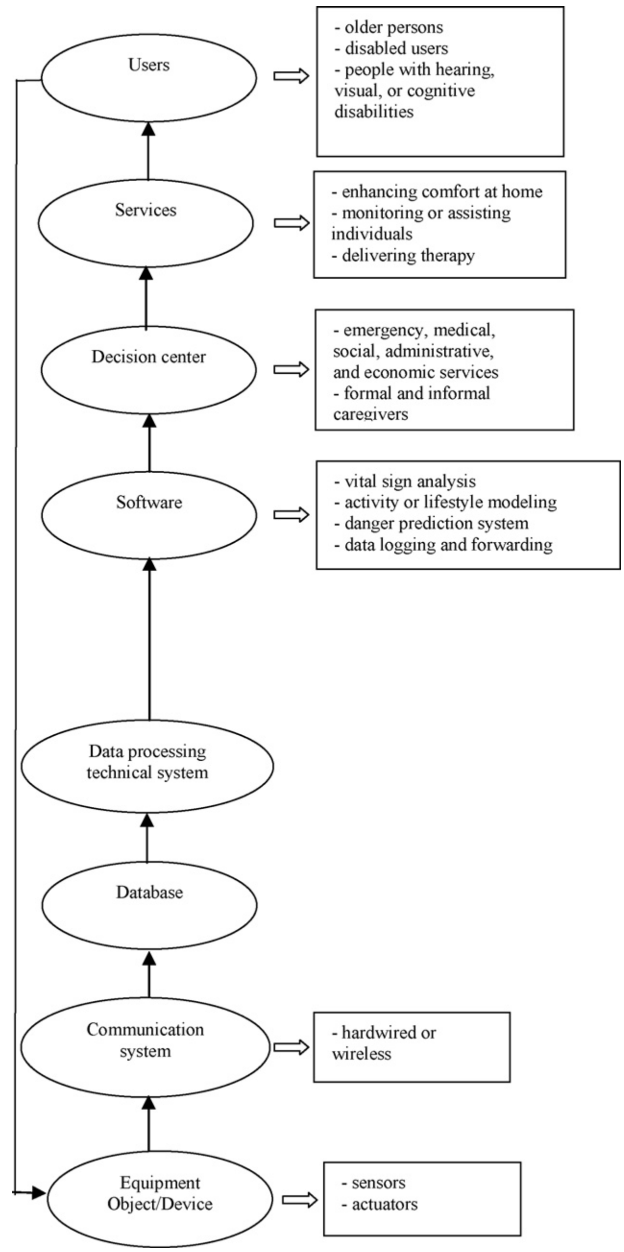

Fig. 1 – General organization of a smart system.

in the home and uses *reinforcement learning*, a stochastic form of dynamic programming that samples trajectories in state space, to predict future behavior [22].

The MavHome project (University of Texas, Arlington) aims to create a home that acts as a rational agent, trying to maximize the comfort of its inhabitants while minimizing operation costs. The agent must be able to sense and predict the occupants’ mobility habits and their use of electrical appliances. The goal is to construct a universal predictor (or estimator) of user mobility. The so-called LeZi method, a technique of information theory, is used to create a probabilistic model predicting the inhabitant’s typical path segments, comfort management scheme, and appliance use. Specifically, the Active LeZi (ALZ) algorithm calculates the probability of every possible action occurring in the currently observed sequence,

Table 1 – Functions that can be implemented in the smart houses and the equipments, objects or appliances used

Author	System description	Method
Mozer [22]	Sensors	Artificial neural networks
Das et al. [23,24]	Sensors	Modeling resident activity based on their past movements; LeZi algorithm
Helal et al. [25,26]	Ultrasonic location tracking sensors, smart floor	Accurate location calculation
Lesser et al. [27]	Robot, home appliances	Intelligent agents
Kidd et al. [28]	Ultrasonic sensors, RF technology, video, floor sensors	Pattern recognition, artificial vision techniques; Hidden Markov models
Krumm et al. [29] and Brumitt et al. [30]	Multi-camera, badge	Image analysis, statistical representation
Intille [31]	Sensors	Context decision computing
Tapia et al. [32]	Sensors	Context decision computing
Rantz et al. [33]	Sensor network, robotics	Comparison between stored sensor data and predefined urgency Artificial intelligent entities (medication dispenser)
Elite Care [34]	Digital technologies	Gathering, storing and transmitting health information
Adami et al. [35]	Wrist actigraph	Lifestyle monitoring, especially time spent in and out of bed
Mihailidis et al. [36]	Vision-based system	Computer vision, artificial intelligence (AI)
Yamaguchi et al. [37] and Tamura et al. [38]	Sensors, magnetic switches, health	Monitoring motor behavior and bed temperature, data processing
Matsuoka et al. [40]	Sensors, video camera,	Statistical analysis of activity time series
Isoda et al. [41]	Sensors, RFID-tagged objects, sensor floor	Spatio-temporal representation of user states and user decisions
Yamazaki et al. [42]	Sensors, cameras, microphones, robots	Detection of human behaviors and activities
Andoh et al. [43]	Sensors (pneumatic microphone, air cushion, pressure sensor)	Vital signs (pulse, respiration, movement) analyzed through Fuzzy logic
Masuda et al. [44]	Sensor (air pressure)	Simple signal analysis
Nishida et al. [45]	Sensors	Assessment of physiological signs
Noguchi et al. [46]	Sensors	Summarization of daily action data
Ha et al. [47]	Sensors	Location-recognition algorithm
Ma et al. [48]	Sensors	Case-based reasoning
Orpwood et al. [49]	Sensors	Home devices
Williams et al. [50]	Sensors	Simple data analysis
Barnes et al. [51]	IR sensors, magnetic switches	Statistical detection of abnormal inactivity or household appliance use
Perry et al. [52]	Sensors, magnetic switches	Locating a person and determining their current activity
Vermeulen et al. [53] and Harrington et al. [54]	Model house equipped with devices for home automation	Active safety alarm (button on pendant)
Hagen et al. [55] and Adlam et al. [56]	Sensors	Home appliances (cooker, night light)
Elger et al. [57] and Deafblind Interna-tional.org [58]	Sensors, actuators	Home automation
Virone et al. [59] and Lebellego et al. [60]	IR sensors, magnetic switches	Statistics, probability theory
Guillén et al. [61]	Sensors, TV	Assessment of physiological signs
Tuomisto et al. [62] and Korhonen et al. [63]	Sensors	Statistical analysis of physiological signs
Chan et al. [64–70]	IR sensors	Statistics, artificial neural networks
Campo et al. [71]	IR sensors	Statistics, artificial neural networks
Celler et al. [72,73]	Sensors	Assessment of resident's mobility and physiological signs
West et al. [74]	Sensors, reed switches	Statistical model for anxiety
Riedel et al. [75]	Video tracking system	Spatial recognition (chemotatic model)
Diegel et al. [76]	Sensors	Statistics, pattern recognition, activity duration threshold

and predicts the action with the highest probability [23]. MavHome combines several technologies: databases, multimedia computing, artificial intelligence, mobile computing, and robotics [24].

In Florida, Helal et al. have developed a smart home project known as the "GatorTech Smart House". It is based on a number of individual smart devices: mailbox, entrance door, bed, bath, floor, etc. The bathroom mirror is used as reminder device. All these components are fitted with sensors and actuators and connected to an operational platform designed to optimize the comfort and safety of an older person [25]. The "GatorTech Smart House" also uses a high-precision ultrasonic tracking system to locate occupants, evaluate their mobility habits, and better control the environment. An in-laboratory mockup of the house is described in reference [26]. It is inhabited by Matilda, a test dummy. Two beacons are placed on Matilda's shoulders, and a smart phone is attached to her left hand. Triangulation provides the subject's location.

The University of Massachusetts at Amherst multi-agent systems laboratory has developed a distributed set of autonomous home control agents, and deployed them in a simulated intelligent home environment [27]. Their goal is to automate some of the tasks currently performed by humans, with an eye towards improving efficiency and quality of service. The simulated intelligent home consists of four rooms joined by a common hallway: a bedroom, a living room, a bathroom, and a kitchen. Various intelligent agents (WaterHeater, CoffeeMaker, AirConditioner, DishWasher, VacuumCleaner, etc.) control the home environment. Moreover, a robot is used to fetch items and to move goods from one location to another. The agents reason about their assigned task, and quantify the value of candidate actions based on the resident's wishes and the availability of resources. An agent's repertoire of primitive actions is defined by a set of discrete probability distributions in terms of duration, quality, and cost. The intelligent agents must interact and coordinate over shared resources (for example, the DishWasher agent uses electricity and hot water). The task modeling and allocation framework models and quantifies resources, agent interactions, task interactions, and the performance characteristics of primitive actions so that agents can reason about the trade-offs of different courses of action and adapt their behavior to the changing environment. The laboratory also built and designed the Multi-Agent Survivability Simulator (MASS) and the Java Agent Framework as tools for evaluating the agents and their coordination.

In the Aware Home Research Initiative at the Georgia Institute of Technology, an interdisciplinary team of researchers built a three-story, 5040 ft^2 home that functions as a living laboratory for the design, development, and evaluation of future domestic technologies [28]. The smart floor senses an individual's footsteps, which allows the home to build a model based on the user's habits and behavior. A number of mathematical tools are used to create and evaluate the behavioral model: hidden Markov models, simple feature-vector averaging, and neural networks. Their main goal is to enable the elderly to remain in familiar surroundings as they age, not only to improve their quality of life but also to lengthen their life. Researchers on the Aware Home project have also developed a system of tracking and sensing technologies to help find frequently lost objects such as wallets, glasses, and remote controls. Each object is given a small radio-frequency (RF) tag. The user interacts with the system via LCD touch panels placed strategically throughout the house. The system guides the user to the lost object using audio cues.

Microsoft's EasyLiving project, based on "context aware computing", uses tracking video to monitor residents. Images from the video feed are analyzed and processed using distributed computing. The system identifies people-shaped clusters of blobs in real time, allowing the system to follow individuals through the house. Residents are recognized through an active badge system. The EasyLiving Geometric Model provides sub-meter localization of entities in the

Table 2 – Smart homes or systems with their equipments, key algorithms and functions used

Function	Equipment/Device/Object

To support	Disabled users
	  Rehabilitation robotics
	  Companion robot
	  Wheelchair
	  Specialized interface
	  Synthetic voice generation for control and command
	Visually impaired subjects
	  Tactile screen
	  Sensitive remote control
	  Audible beacon
	Hearing-impaired subjects
	  Visible alarm
	  Teletype machine
	  Electronic display screen
	  Numerical documents

To monitor	Lifestyle
	  Fixed systems
	    Infrared sensors
	  Wearable systems
	    Active badge
	    Accelerometer
	  Physiological Signs (external or in vivo sensors)
	    EEG (syncope, epileptic seizure, sleep disorder, etc.)
	    EMG
	    Heart rate
	    Temperature
	    Blood oxygen saturation
	    Blood pressure
	    Glucose

To deliver therapy	Therapeutic devices
	  Delivery of current to abort or forestall epileptic seizures
	  Tremor suppression
	  Drug delivery
	  Hormone delivery (e.g., insulin)
	  Active or orthotic boots (podiatry)
	  Robotic devices for bimanual physical therapy

Comfort	Intelligent household devices
	  Dishwasher, washing machine, refrigerator
	  Stovetop, cooker
	Smart objects
	  Mailbox
	  Closet
	  Mirror
	Intelligent house equipment
	  Presence/motion sensors
	  Video camera
	  Magnetic switches
	  Humidity, gas, and light sensors
	Smart leisure equipment
	  TV, home cinema programs
	Interactive communication systems
	  Communication with friends and family in case of emergency
	Intelligent environmental control equipment
	  Windows and doors

Table 2 – (*Continued*)

Function	Equipment/Device/Object
	Heating
	Lighting
	Air conditioning
	Ventilation
	Physical activity
	Fitness devices

environment. Measurements are used to define geometric relationships between the entities (people, devices, places and things) needed for a particular interaction. In an example scenario, the resident (Tom) wishes to start playing music. The smart home uses its geometric world knowledge to select those speakers and other components which are most suitable for the task, based on Tom's current location. Thus, Tom is able to focus only on the decisions that require his input: the music itself. Current development is focused on more fully integrating the various devices and providing a coherent user experience. Their research progresses on a variety of fronts, including middleware development (to facilitate distributed computing), geometric world modeling (to provide location-based context), computer perception (to gather data about world state), and better service description (to support decomposition of device control, internal logic, and user interface) [29,30].

The House_n group at MIT, or "the house of the future", proposes a smart services delivery system that conducts qualitative and quantitative studies on the relationships between environmental factors and the behavior of the subject. The system consists of three components: a set of state-change sensors used to collect data about the use of objects, a context-aware experience sampling tool (ESM) used by the subject to label his activities, and pattern recognition and classification algorithms for recognizing activities. The user model is based on a training data set. In practical tests, the sensors were installed on pieces of furniture, kitchen appliances, bathroom appliances, and the washing machine. The subjects were given a personal digital assistant (PDA) running the ESM software at the start of the study, and asked to collect their activity data. A naïve Bayesian network approach is used to train the model and predict user activities. The authors of this study concluded that while the model's accuracy for some activities is better than chance, it is not as high as expected. Their main problems were the low quality and number of activity labels, and the small training set of 2 weeks. They expect that by collecting training data over a period of months, generating higher quality activity labels by video observation or other methods, and improving the information collection boards and sensors, they will be able to greatly improve the accuracy of the model [31,32].

The "Aging in Place" project, at the University of Missouri-Colombia, offers a long-term care model for seniors who want supportive health care services in a home environment of their choice. The "Aging in Place" project consists of two complementary initiatives: Senior Care and TigerPlace. Senior Care was initially designed to provide community-based support and health services, including an environmental component, to the residents of TigerPlace. It now serves occupants of other private and public senior residences, and some seniors' private homes in Boone County, Missouri. The project is characterized by interdisciplinary research, innovative educational programs, and an ideal practice environment for health care providers; the overall goal is to implement better ways of caring for older people who wish to "age in place" [33]. The TigerPlace residence, designed in collaboration with the American Corporation of Sikeston, Missouri, uses a network of wireless sensors connected to small computers. Some sensors measure proximity and motion, while others sense weight on a mat, hear calls, or assess a variety of vital signs. The system is designed to notice functional decline and call for an intervention in case something goes wrong. An important aspect of the project is training older participants to accept and use the technology. TigerPlace opened in 2004, and is located just a few miles from the MU campus.

Elite CARE (creating an autonomy-risk equilibrium) is an assisted living facility in Portland, Oregon using smart home technologies. It is inhabited by retirees, some of whom suffer from dementia or Alzheimer's disease [34]. The aim is to prolong independence and help the staff identify health problems early. Health information is processed in real time using digital technologies, including the Internet. The system detects behavioral cues indicating change in an individual's physical or cognitive condition, enhances social networks via electronic mail, and regulates ambient conditions. Researchers at Oregon Health and Science University associated with the Elite CARE project have developed a method of unobtrusively monitoring the residents' sleep characteristics. The data permit estimation of each resident's bedtime and wake-up time, as well as their position shifts during sleep [35].

In Toronto, Canada, Mihailidis et al. have developed a vision-based system capable of tracking the gross and fine motor movements of older adults. The vision system consists of three agents: sensing, planning, and prompting. The sensing agent was developed using a Sony video camera and a Matrox Meteor II frame grabber installed on a 2.4-GHz personal computer. Both statistics-based and physics-based methods of segmenting skin color in digital images are used for face and hand tracking in real time. The main goal of this technology is not just to recognize and track the hand positions associated with each activity of daily living (ADL) step, but also to do so discreetly—the better to support a policy of aging-in-place [36].

3.1.2. *In Asia*

In Japan, about 15 smart houses are being developed. They usually aim to maximize the use of assistive technologies, enabling older people to live at home by creating a smart and comfortable environment. The Japanese Ministry of International Trade and Industry built 13 examples called "Welfare Techno-Houses (WTH)". The objective of these *care houses* is to improve the quality of life of both elderly people and their caregivers. The WTHs have been used as a test bed for new diagnostic technologies as well as the evaluation of residents' living conditions. The researchers collect data on residents' health and physiological signs by equipping the bathroom with fully automated medical devices. Their physical activity is monitored by equipping the rooms with infrared (IR) sensors and the doors with magnetic switches. Many weeks of raw data on an experimental subject's localization, ECG, and bed temperature are now available [37,38].

The smart house of Dr. Matsuoka, based in Osaka, automatically detects unusual events that may be caused by disease or an accident through its 167 sensors. Seventeen electrical appliances are also fitted with sensors (refrigerator, TV set, rice cooker, air conditioning, etc.). Each sensor is associated with one or more activities: getting up, going to bed, preparing meals, having a wash, working in an office, and so on. Matsuoka uses a two-step method to translate the raw sensor signals into behavioral data. Each time-segment of sensor data is to be associated with one of a limited number of living states, and the similarity of series in the same category is evaluated. The method used to construct the states is principal component analysis, which reduces high-dimensional data sets to a manageable number of independent linear combinations [39]. Thus, the first step extracts principal components from vectors of sensor data obtained within a specified time window. The second step identifies statistical clusters in the complete sensor data based on the principal component decomposition. There are only two free parameters in this analysis: the number of principal components sought, and the distance permitted between clusters. The method was verified using a 1-year observation of a four-person family interacting with the system. Unusual states were detected a total of 73 times during this period. Based on the family's testimony, 19 of these events coincided with a real change in their habitual behavior. The cases of agreement included staying up late and going out at night, for example [40].

One multimedia laboratory, NTT DoCoMo, has developed a system for modeling and recognizing personal behavior based on sensors and Radio Frequency Identification (RFID)-tagged objects, which has been tested in an experimental house. The daily activity of the resident is modeled as a sequence of states describing their varying contexts. (The user's state is represented by attributes expressing which objects are in the user's vicinity, and how long they remain there. The user's absolute position is another attribute.) Behavior modeling is learning-based: the raw data obtained from the RFID tags and sensors are classified into "typical" states by constructing a decision tree. The user's behavioral context at any given moment is obtained by matching the most recently detected states to previously defined task models. The authors concluded that their system is an effective way of acquiring the user's spatio-temporal context [41].

The Ubiquitous Home project (sometimes called the smart home or sensor-embedded house) serves as a test facility for the creation of useful new services directed towards linking devices, sensors, and appliances through data networks [42]. It is a real-life apartment, comprising a living room, dining room/kitchen, study, master bedroom, washroom, bathroom, and a Japanese-style room for extended family members. There is also a computer room, named the Network Operating Center, which is located between the Japanese room and the rest of the apartment. The Ubiquitous Home is equipped with a number of sensors to monitor human activities. Each room has enough cameras and microphones to gather complete audiovisual data. The residents' privacy is therefore a big issue for the authors of the project. Pressure sensors in the floor track the residents' movement and locate furniture. To gather further data on movements in the house, IR sensors are installed above each room entrance and at foot level in the kitchen and corridor. Two RFID systems are used to identify the residents, one active and the other passive. The former uses 315 MHz waves, while the latter operates in the 2.45 GHz band. Active scanners are located above the ceiling of each room, and detect RFID tags whenever a subject enters. Passive system antennas are embedded inside the walls around each room entrance, and read out data on the tag when a person passes through. An RFID tag is also attached to each article a resident removes from the Ubiquitous Home. Four accelerometers or vibration sensors are placed beneath the corners of the bedroom floor, and are used to detect human behavior. Plasma panels, liquid crystal displays, and speakers provide residents with audiovisual programs. Visible robots are introduced for certain home services, and the house itself can be considered an unconscious robot. (That is, the whole test bed controls appliances on the home network based on its sensor information.) The goal of the Ubiquitous Home is to help residents take advantage of user-adaptation technologies. The visible robot makes itself known to the residents, and serves as an intermediary between the inhabitants and the unconscious robot (i.e., the house).

Researchers are currently observing real human activity in the Ubiquitous Home, and using this information to develop technologies capable of extrapolating user intention from sensor data. The services provided to the residents include TV program recommendations, a cooking recipe display, and a forgotten-property check service. (An RFID tag is attached to each article that the resident removes from the smart home. In addition, articles that he *should* bring outside with him are listed. Whenever he leaves, he can easily verify which articles may still be needed using an RFID tag reader installed at the entrance.) In the near future they hope to construct the more ambitious Universal City: a next-generation intelligent living environment hospitable to everyone, including the elderly, disabled and children.

In Tokyo, Andoh et al. have designed a highly sophisticated sleep monitoring system based on vital sign analysis: breathing, heart rate, snoring, and body movement. The mattress is equipped with electronic devices (pneumatic microphone sensor named air cushion sensor and pressure sensor) and connected through a serial link to a PC. The researchers have built the algorithm which can estimate a sleep stage of sleeping human by analyzing his measured heart rate and included it in the PC [43].

In Nara (Japan), Masuda et al. have developed an monitoring system for home-visit rehabilitation therapists. The system uses existing public and mobile phones, minimizing and simplifying its requirements for measurement and transmission technology. The system does not constrain the resident, and is silent in operation. It is composed of an air-filled mat, a single measurement unit, and a bridge unit which handles the connections. When a subject lies on the mat, his heartbeat and respiratory movements cause perturbations in the air pressure. These data are easily acquired by a pressure sensor, and have low-frequency characteristics that are easily separated from environmental noise. Through an appropriate filtering process, both heart rate and respiratory rate are easily estimated. It allows therapists to plan and evaluate long-term rehabilitation schedules by measuring and exploiting heart/respiratory data [44].

In Ibaraki (Japan), Nishida et al. have developed the intelligent environmental system named sensorized environment for life (SELF). The project allows a person to maintain his or her health through a "self-communication" analysis based on objective data. Data on their physiological status is currently obtained using a model SELF-bedroom: the bed includes a pressure sensor array, and the ceiling light has a microphone to detect breathing sounds (measuring air flow at the mouth and nose). The washstand contains cameras, a two-way mirror, and a monitor displaying a digitized visual representation of the person. Several physiological parameters can be assessed using these data: posture, body movement, breath curve, oxygen in the blood, airflow at the mouth and nose, and apnea. Healthcare support is based on a comparison between the resident's physiological status and a human model. SELF stores and analyzes the physiological data, then advises the person on how to maintain his or her health based on daily behavior.

Self-communication thus refers to externalizing and correcting the resident's self-image in an objective manner by observing and reporting the subject's daily behavior. There are three independent self-communication functions: "soft" interaction (i.e., normal daily behavior), human objectification, and the creation of a useful report [45].

Noguchi et al. have built another sensing room at the University of Tokyo; the system collects quantitative data on human daily actions, then learns from and analyzes the data. The goal of this project is simply to support the person in her/his daily life. The system has three main components: data collection, data processing, and the integration of processed data. The states of the floor, bed, table and switches are recorded by the sensing modules of the room. The combination of these data is defined as the "room state". An algorithm named "summarization" was also developed, which segments the accumulated sensor data at points where the outputs change drastically. The segments are matched with and assigned to "room states". The algorithm also tries to eliminate redundant states that have changed only slightly. The system includes switch sensors on a number of appliances, in addition to the table, chair and bed. These sensors are sufficient to detect whether a human is standing or sleeping, to detect the position of their hands on the table, and to detect the positions of objects on the table. The freezer, refrigerator, microwave, toaster, windows, and chest of drawers are all equipped with switch sensors to detect whether their doors are open or closed [46].

A collaboration of two Korean universities has developed a location system based on pyroelectric (P) IR sensors. The test bed is a room measuring 4 m × 4 m × 2.5 m. Twelve PIR sensors are located on the ceiling. The researchers aim to build a smart home capable of detecting the resident's lifestyle and state of health, in order to better anticipate their needs and offer appropriate services. A performance evaluation using this test bed has already been carried out. Their next step will be to develop an algorithm that can determine the location and trajectory of multiple residents simultaneously [47].

Ma et al. have developed a context-awareness project implementing case-based reasoning (CBR). To provide more appropriate services, this technique relies on previous interactions and experiences to find solutions for current problems (changing the TV channel, adjusting the air conditioning and lighting, etc.) corresponding to user preferences. In CBR systems a database is used to store the cases, which are defined in terms of sensor data. The degree of correspondence between two similar data structures (i.e., the current state and a previously observed state) can easily be quantified. New solutions are proposed based on the nearest neighbor past state. In a smart home, the system would adopt any manual adjustments of the environment as revisions of the case data. Thus, the user can modify the data and the system will adapt [48].

3.1.3. *In Europe*

Many smart houses have been developed in Europe; their usual goal is to support elderly persons living at home.

Gloucester's Smart House project is funded by UK Government Engineering and Physical Sciences research Council, the European Commission, Gloucester Social Services and the Barnwood Trust. Dementia Voice Housing 21 and the Bath Institute of Medical Engineering are leading the project, which is geared towards helping subjects suffering from dementia. Most items in the house are continuously monitored through sensors (for example, the indoor environment, bathwater temperature, etc.) [49].

CarerNet, designed in the United Kingdom, deploys various telecare and "hospital at home" services such as a home emergency alarm, access to community health information, and ambulatory monitoring [50]. In addition to therapy units, CarerNet includes a sensor set, a sensor bus, an intelligent monitoring system, and a control unit. CarerNet incorporates many functions: collecting physiological data (ECG, photoplethysmograph, spirometry, temperature, galvanic skin response, colorimetry, and pulse), determining the patient's lifestyle (through passive IR sensors, accelerometers, inductive badges, smart IR badges, and piezoelectric sensors), and environmental awareness (thermometer, microphone, IR smoke alarm). Certain elements of the communication network lie entirely within the client's local environment: the HomeLAN and the Body Area Network (BAN). The system's distributed intelligence is based on the following: smart sensors, smart therapy units, the "body-hub", a Local Intelligence Unit, and the client's healthcare record. As a case study, a prototype CarerNet system was used to monitor an individual who had undergone brain surgery after suffering from a subarachnoid hemorrhage in the left hemisphere due to an aneurysm.

The smart house designed by British Telecom and Anchor Trust in England monitors the activity of the subject using interior IR sensors, magnetic contacts on the entrance doors (to detect when the user enters and leaves their home), and another contact on the refrigerator door. A temperature sensor is placed in the main living area to monitor the ambient temperature [51]. Based on its observations of the resident's lifestyle, the smart house triggers an alarm in case of abnormality. The Millennium Home has been developed from this project as a way of supporting the elderly in their homes. The main issue at hand is creating a more sophisticated and sensitive approach to monitoring activity and modeling behavior, in order to better control the alarms. In addition, the Millennium Home provides the user with a quick and easy mechanism to cancel false alarms and more rapid response to a real emergency. The lifestyle monitoring system also supports some of the independent-living needs of older users. The technical infrastructure includes passive IR sensors to detect movement, pressure sensors under the chairs and bed, and burglar alarm-style sensors on the windows and front door to detect when they are opened. The system includes adjustable timers to remind the resident of medications, and temperature sensors to check that the home is not getting too cold or too warm for the resident's health. Finally, it incorporates a computer-activated telephone, loudspeaker, TV screen, and interactive dialogue system between the user and their caregiver [52].

In 1994, in Eindhoven a model house was built according to the demands of the Dutch Senior Citizens Label. Since 1995, several other model houses have been placed in cities of the Netherlands. These are likewise equipped with monitoring and assistive technologies. Motion detection sensors measure the resident's activity, and alert service providers to suspicious inactivity and break-ins. A button-based call system completes the security system. Electronic actuators control lighting, heating, and the cooker. The main purpose of this project is to use information technology to facilitate communication among the elderly, their caregivers, and service providers [53,54].

The ENABLE project focuses on subjects suffering from mild to moderate dementia, demonstrating the impact of assistive technology on their quality of life. Several devices have been installed in the ENABLE project apartments. Two devices designed to increase the independence of people with dementia have been formally evaluated [55,56].

In Tønsberg, Norway, the two-room SmartBo ("bo" means "nest" in Swedish) house has been built for the elderly. SmartBo is high-tech, comfortable, and warm. All the main systems (lighting, doors, windows, shutters, etc.) are controlled automatically, with an alarm in case something goes wrong [57,58].

The HIS project in Grenoble is an apartment with IR sensors for measurement of the individual's activity. These data are transmitted via a CAN network to a personal computer [59,60]. Weight and vital sign sensors are also connected to the network for data processing, and an alarm is transmitted in case of danger. The computer software defines profiles for the patient's agitation, mobility, and occupation. The algorithms were validated using simulated data.

In Spain, a multimedia platform has been developed to support patients that need specific health support at home. The platform runs on an integrated services digital network, using Internet protocols and videoconferencing standards H.320 and H.323. A standard TV set is used for patient–caregiver interaction. The platform is composed of two parts. The first is the home station, which consists of the videoconferencing-data processing module (a PC integrated into the audiovisual environment of the home, with standard USB and RS232 ports) and a recording module for vital signs (blood pressure, temperature, ECG, pulse oximetry). Data from the sensors are transferred to the PC via a serial cable. The second component of the platform is the caregiver's medical center, which is composed of a call center, one or more medical workstations, a database management system, and peripherals such as a printer and scanner. The following functions are performed by the medical center workstation: videoconferencing with a customized clinical protocol, control of remote monitoring functions, communication, and medicine prescription. This home multimedia platform was tested on real patients: mostly gynecology patients, but also a few students and two pregnant women [61].

A similar home health station, called TERVA, has been developed in Finland. The TERVA system monitors physiological and psychological health through vital sign measurements (arterial blood pressure, heart rate, body temperature) and the outpatient's long-term behavioral diary, respectively (data on mood and emotional responses; use of tobacco, alcohol, coffee, and tea). The system is controlled through a laptop computer and the measurement modules are controlled via a dedicated user interface. Data from the measurement devices are transmitted to the computer via a serial interface (RS232). The system includes a blood pressure monitor, a thermometer, an ECG and activity monitoring device, a scale to measure body weight, a static charge-sensitive bed, a diary, and the laptop software used to initiate and manage bedside measurements of the subject [62]. The TERVA research team explored the diurnal and weekly rhythms of health-related variables in 14 healthy men for 2 months using the following data reduction statistical methods: artifact filtering, computation of derived parameters, and windowing to allow comparison of variables with widely differing sampling rates (consider the difference between one sample per heartbeat for the RR interval, and one sample per day for body weight) [63].

Our own project, PROSAFE as shown in Fig. 2, has been developed as a means of continuously monitoring the motor behavior of older subjects. The goals of PROSAFE are twofold: to support autonomous living, and to sound an alarm in case of emergency [64–70]. The motion sensors are pyroelectric IR devices with binary output. Several hospital rooms in a long-stay setting for the elderly have been equipped with the system. A wireless version of the system using the 868 MHz band has also been designed. To assess the mobility and activity of a subject, the whole system must be switched on: motion sensors, data acquisition card, and PC. The data are stored in the PC, which runs software to assess the subject's mobility and activity. Our first study used neural networks to predict the presences and absences of a subject using simulated data [64]. This approach was then validated using several months of observation data on real subjects. Statistical results on periods of mobility, night activity, and immobility for several such subjects are given in references [65,66]. An elderly patient's repetitive trajectory was compared to several specific cases, to find the subject's most representative indoor displacement pattern [67].

Finally, ERGDOM is a smart, multi-criteria management system that minimizes the cost of comfort and heat-related energy expenses. A network of IR presence sensors is distributed throughout the house, allowing the system to collect data on the occupant's motions. It applies an automatic learning procedure based on continuous observation of the users' habits, and integrates any adjustments introduced by the occupant through the house's interface terminal. The living habits of the occupant are represented as the proba-

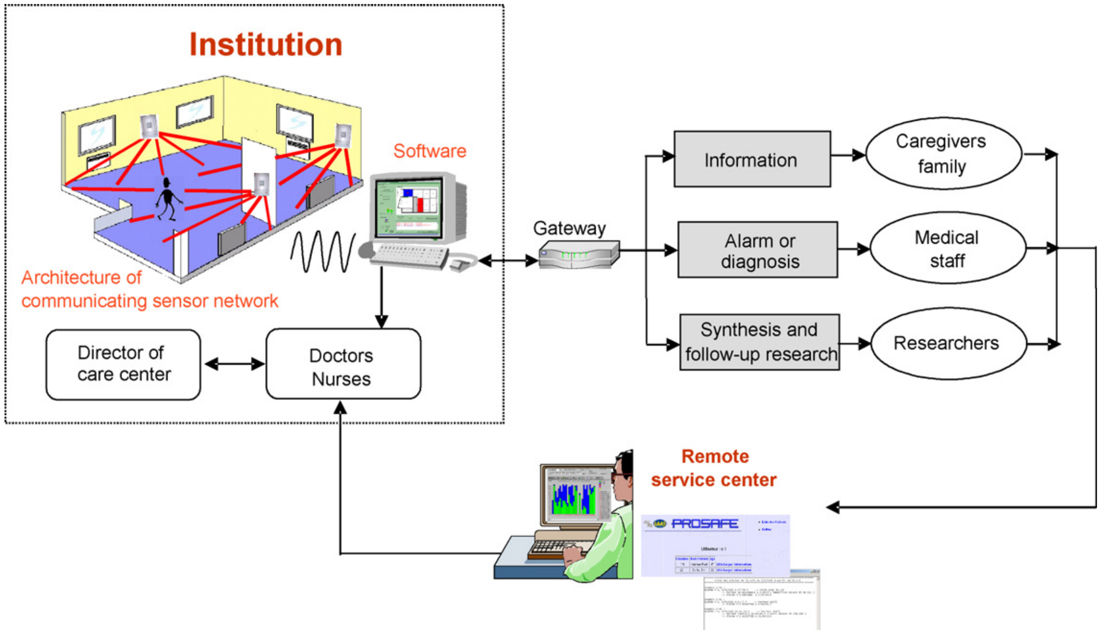

Fig. 2 – General organization of the PROSAFE project.

bility of occupying each place at the same time each day. By systematically comparing this model to the ongoing situation, the system is able to automatically adjust the heating system [71].

3.1.4. *In Australia*

Celler et al. have designed a system that monitors a subject's interactions with his home environment. The house is equipped with IR sensors, light sensors, temperature sensors, microphones, a central power meter, appliance power meters, and pressure sensors. All these data are transmitted using an Echelon LonWorks PLT-10 power line transceiver module. Biological signs (ECG, pulse, blood oxygen saturation, blood pressure, and blood glucose) are also collected [72,73].

Another team is investigating whether anxiety can be detected by reviewing a person's household activity profile. Their results are presented in terms of simple "using the kitchen" scenarios: for example, the less he uses his cooker the more anxious he is [74]. The subject's movements are studied using a model inspired by *Escherichia coli* chemotaxis studies, which is capable of handling noisy data. The researchers believe that this model can be used to recognize activities of similar length captured by a video tracking system within the constraints of a smart house environment [75].

3.1.5. *In New Zealand*

A smart house system has been built that can learn the user's habits and make intelligent decisions based on these patterns. A health monitoring system measures and classifies the daily routine, and at the same time each day measures physiological signs such as systolic and diastolic blood pressure, mean arterial pressure, pulse arrhythmia, lung capacity, blood sugar, weight, temperature, and body fat. The computer detects late or missing readings, and if other data are available can make an educated guess as to the cause. Once the data have been classified, the computer can decide whether a reading falls outside its alert threshold. It can also modify this threshold as more user data are gathered. That is, the intelligent health system defines a normal range of activity and physiology based on the user's health measurement habits, but tightens this range over time as it learns. The system has been shown to improve the user's medication and health care compliance rate [76].

3.2. *Wearable and implantable systems*

Wearable and *in vivo* implantable health systems can be used both indoors and outdoors to monitor people 24 h a day and 7 days a week. Such systems are not just for monitoring, however; they can also to affect vital functions and deliver therapy. These devices have the potential to greatly enhance comfort, health, and the efficiency of disease prevention. If vital functions are maintained at a normal level, complications and hospitalization can be avoided. These biomedical sensors are usually worked into textiles, equipped with data storage and a wireless transceiver system. The data are sent to a central processing unit, for example a medical center able to diagnose the situation and organize assistance if needed. Wearable and *in vivo* systems must be easy to operate, small in size, and unobtrusive. In addition, they must be waterproof and possess a long battery life. They must automatically collect their measurements, without the intervention of a third party. They should provide total confidentiality and reliable data. These systems can take the form of a textile garment [77], a wrist-worn device [78,79], a ring [80], a system attached to the belt [81], an over-the-shoulder pouch, a small box worn on the patient's head [82], a chest belt (for stress monitoring) [83], a glucose sensor with a needle [84], etc.

3.2.1. In the U.S.A.

There are a number of projects featuring a garment with several sensors: LifeShirt (Vivometrics) [85,86], SenseWear Pro ArmBand (BodyMedia, Inc.) [87] and SmartShirt [77,88]. All these garments are comfortable and washable; the biomedical sensors are included in the fabric. This technique offers numerous advantages: the sensors are unobtrusive, and not difficult to install. Made with Lycra fabric, LifeShirt measures several physiological parameters: ECG/EOG, frequency of leg movement, temperature, end tidal CO_2, blood oxygen saturation, blood pressure, and coughs. It also includes sensors for plethysmographic respiration. Data are recorded in a small, belt-worn cellular device, where they are encrypted and sent to the VivoMetrics Data Center. There the data are decrypted, scanned for artifacts, and placed in a database. Summary reports can then be generated for the user. The SenseWear garment includes six sensors: a two-axis accelerometer; three thermometers to measure body temperature, skin temperature, and ambient temperature; a psycho-galvanic sensor to assess the patient's mood; and a heart rate sensor. The garment contains a radio and a data port for communication, and uses a proprietary data transfer protocol. The battery is rechargeable, with a lifetime of about 3 days for one version of the garment. The SmartShirt is a research project targeting the public at large. It is used to monitor the carrier's heartbeats, ECG, breathing, body temperature, and vital functions, warning the carrier and a physician if there is a problem. The system collects analog signals through a grid of conductive fiber sensors knitted into the garment. A connector passes the analog signals to a small personal controller, which is carried in the pocket of the T-shirt. The personal controller digitizes and transmits the signal to a Bluetooth or Zigbee receiver, which in turn is connected to a base station where the data are collected, displayed, and stored.

In Boston, Moy et al. have developed a monitoring system for patients with chronic obstructive pulmonary disease (COPD). While the patient performs tasks, the system keeps track of their motor functions using accelerometers. The goal of the project is to assess the cumulative impact of free-living activity on COPD sufferers in both clinical care and clinical trials [89].

MIT (Cambridge, MA) has developed an ambulatory, telemetric, continuous health-monitoring device. It is a ring-shaped array of miniaturized sensors based on advanced photoplethysmographic techniques. The device is able to continuously monitor variations in a patient's heart rate and blood oxygen saturation. The first prototype contains an optical sensor unit, analog and digital processing units, and an RF transmitter, encapsulated in a compact housing and powered by a small battery. The ring's microcomputer controls all the devices (LED modulation, data acquisition) and performs low-level signal processing (filtering and bi-directional RF communication). The sensor signals are sampled at 100 Hz, then transmitted to a PDA or cellular phone carried by the patient. The RF link has a transfer rate of 105 kbps and a carrier frequency of 915 MHz. The cellular phone accesses a Web site for information storage and clinical diagnosis [80].

Prof. Waterhouse has developed a wearable EEG tool for characterizing seizures and seizure-like events in patients suffering from epilepsy. This commercially available system consists of several electrodes (to be attached to the patient's head) and a recording unit which may be attached to a belt or carried in an over-the-shoulder pouch. Most models weigh about 2–3 pounds, including the hard drive and battery pack, and take up only 450–550 cm^3, approximately the size of a portable CD player. An important future direction for this technology is developing its ability to not just diagnose but detect seizures. Such devices could initiate an automated intervention, such as drug or current delivery [82].

A stress-monitoring biomedical sensor using a distributed wireless intelligent system has been developed in Huntsville. The system quantifies stress in terms of heart rate variability, using these data to predict stress resistance prior to and during physical exercise. Its wireless intelligent sensors (WISE) form a BAN. The WISE are microcontroller-based, intelligent physiological sensors that carry out low-level signal processing in real time as well as data acquisition. The BAN is organized as a client-server network, with a single personal server (PS) and multiple WISE clients. A PDA-based mobile gateway (MOGUL) device reduces power consumption of the wireless transceiver on the PS. The PS-MOGUL connection uses standard 900 MHz RF modules rather than Bluetooth, which requires three to five times the power. The connection between MOGUL and Internet can be implemented using Bluetooth, IEEE 802.11, IR, or a USB cradle [83].

An implantable glucose sensor for diabetics has been created based on the "enzyme electrode" principle. The sensor includes three electrodes, and measures a current proportional to the glucose concentration. (Glucose is converted to hydrogen peroxide in an immobilized glucose oxidase layer, generating ions.) The sensor current is transmitted at a fixed interval (which may be set to 4, 32, or 256 s) to a remote receiver. The transmission interval can be varied to match the needs of the experiment, for example to minimize power consumption in the case of long-term experiments. (At the lowest frequency, the battery can last for up to 1.5 years; this mode has been used for the long-term evaluation of implantable glucose sensors.) The receiver detects and demodulates these transmissions, relaying the data to a PC interface card using a 300–500 Hz RF signal. The custom interface card allows any PC to program the receiver and handle the transmitted data [90].

Another device, named GlucoWatch, provides non-invasive, frequent, automatic measurements for patients suffering from diabetes. The device uses the novel sampling technique of reverse iontophoresis to extract glucose from the skin, where it is detected by an amperometric biomedical sensor. The GlucoWatch Biographer includes a microprocessor to control operations and convert the sensor data to glucose readings, two independent potentiostats to operate the amperometric biomedical sensors, and a galvanostat to manage the iontophoresis. The Biographer also has onboard memory, a liquid-crystal display, and a standard serial port [79,91].

The intra-corporeal microstimulator developed at University of Michigan is a functional device for neuromuscular stimulation. It is small enough to be implanted into paralyzed muscle groups via a 12-gauge hypodermic needle. Power, data, and control are all supplied from the outside by RF telemetry (radio transponders and actuators) using an amplitude-modulated, 2 MHz carrier wave generated using a class-E transmitter. The implant is hermetically packaged in a custom-made glass capsule [92].

NASA's Jet Propulsion Laboratory (Pasadena, California) has developed biotelemetric units resembling large pills, which are proposed for physiological monitoring of the gastrointestinal tract. After swallowing, the pill passes through the gastrointestinal tract in about 24 h. It conveys sensor readings to an exterior monitor by radio. The pill is interrogated with a hand-held radio transceiver, and derives its power from the radio beam emitted by the transceiver. It could include reservoirs and actuators to deliver one or more drugs to designated sites. It measures the interior body temperature, and senses the presence of blood, bacteria, and chemicals [93].

Mechatronic devices are a promising class of solutions in physical and occupational therapy. This technology, based on thin film, force-resistive sensors, was originally developed for pediatric therapy. A force-sensing glove made from the film is used to assist the therapist in muscle testing. In addition to the thin film sensor glove, the base design requires a portable computing platform and specialized components for sensor integration. A PDA with integrated wireless communication is sufficient to upload and download data and compare tests. In a similar vein, a new "active boot" has been constructed to assist children with cerebral palsy. These patients have spastic diplegia, which typically manifests as toe walking. The boot can assist them in walking and gradually rehabilitate associated muscle groups [94].

3.2.2. *In Asia*

A Taiwanese team has developed a wearable sensor capable of measuring ECG, body temperature, and body humidity. The system processes data in a multi-agent architecture with three components: a personal nursing agent (the mobile device), an agent studio, and a central bulletin board. The system is subdivided into several zones, each representing an independent working group; agents from different zones can communicate with each other via the central bulletin board. A zone typically consists of one agent studio and several personal nursing agents. The personal nursing agent carries the patient's ID and password. The agent studio manages both room devices and personal nursing agents. It communicates with the personal nursing agents through the IEEE 802.11b wireless network protocol [95].

Another system is being developed in Korea and Japan for tracking and measuring patient activity. It is composed of a Linux-based PDA, a sensing module that includes an 8-bit microcontroller, a biaxial accelerometer, a digital compass sensor, an angular velocity sensor, and miscellaneous electrical parts (9-V battery, power regulator, RS-232 signal converter, connectors, etc.). Transitions between predefined zones are detected automatically, and various postures can also be recognized such as standing up and moving about. The nearest-neighbor method is used to find a subject's current location [96].

A team at Jichi Medical School's Department of Cardiology (Tochigi, Japan) uses a mobile device to assess blood pressure for prevention of cardiovascular diseases [97].

A project at Waseda University in Tokyo has developed a wireless ECG monitoring device composed of a low-consumption sensor on the individual's chest and a relay transmitter located on the wrist. Data are transmitted to the relay through an a.c. microcurrent flowing through the tissue of the body. The monitoring device consists of an ECG detection circuit, a PWM modulator, and a carrier wave oscillator. The sampling frequency is 900 Hz, and the carrier frequency is 70 kHz. The relay transmitter has a differential amplifier, a band-pass filter, a waveform shaping circuit, a PWM demodulator and an FM modulator [98].

At Ritsumeikan University (Kusatsu, Japan), researchers are developing a device to monitor the user's location and his or her gait outdoors. Two piezoresistive accelerometers measure the posture of the subject. A GPS receiver provides the current location of the user. (The GPS sensor receives information from space satellites orbiting the Earth, and calculates its position, altitude and velocity once every second.) A biosignal memory device and small battery-driven computer are combined into a wearable unit called MICRO (Medical Information Collection Robot), which is used as an acceleration data logger [99].

An *in vivo* drug delivery system has been developed in Waseda University, Tokyo. It is based on an endoradiosonde, or radio pill, a small transmitter that can be swallowed to monitor digestive tract parameters such as pressure, temperature, and pH. The system is composed of an RF power transmitter, receiver, and controller [100,101].

3.2.3. *In Europe*

The goal of the WEALTHY project is to assist a patient during rehabilitation and professional workers during risky activity. The wireless system is a garment with embedded textile sensors that monitor the individual's biomechanical, physiological, and/or clinical sensitive parameters. The garment alerts its user or emergency services if a situation becomes dangerous. The system is capable of monitoring ECG rhythm, blood pressure, respiratory rate, O_2 saturation, motion (body position, body movement), skin temperature, and core temperature. The 'smart cloth' also incorporates a strain sensor based on piezoresistive yarn, and fabric electrodes realized with metallic yarn. GPRS and Bluetooth are used to transmit the data for diagnosis and alerts [102].

In France, the VTAMN garment project (supported by RNTS) aims to create a "second skin" that includes all connections, wires, and biomedical sensors in the fabric. The T-shirt includes smooth, dry ECG electrodes, a sensor to detect falls, a temperature sensor, a breathing rate sensor, a GPS receiver, a GSM/GPRS data transmission module, and a hands-free communication system [103].

The MARSIAN project is developing a smart glove for non-invasive multiparametric measurements of the autonomous nervous system. This can be combined with other smart clothing using a wrist device. The MARSIAN wrist system supplies real-time information acquisition, processing, and wireless transmission. The smart glove measures skin resistance and potential, and includes a microsensor for measurement of skin temperature. Additional sensors measure microcirculation in the skin of the hand. Additional smart clothing can be used to measure the user's respiration rate and pattern. The main research topics in this project are raising the vigilance level and improving task-related responses to odor, taste, touch, vision and sound as well as environmental and thermal comfort. They also carry out comparisons between unconscious and verbal reactions as part of a study on behavior and stress [104].

The system called MagIC (Maglietta Interattiva Computerizzata) was developed in Milan. It is a textile-based system for unobtrusive monitoring of cardio respiratory and motion signals during spontaneous behavior. The sensory component is a vest that measures ECG and respiratory activity. The system includes a portable electronic board for motion detection, data preprocessing, and wireless communication with a remote monitoring station [105].

The AMON project has developed biomedical sensors to measure vital signs such as heart rate, ECG, blood oxygen rate and skin temperature; some GPS/GPRS technology is also included. A global system for mobile communication (GSM) transceiver is integrated into the device. Measurements from the wrist unit are sent to the telemedicine center (TMC) and processed by trained medical personnel. The TMC system consists of a Java server platform and a windows workstation. It permits caregivers to directly communicate with patients through the wrist-worn device [106].

Korhonen et al. have developed the Vivago watch, a Finnish project, monitors user activity in terms of micro and macro motions, skin temperature and conductivity. The level of activity is determined by counting accelerations in excess of a given threshold within a 1-min interval. It is mainly used as a warning system for elderly and chronically ill patients. It sends information about the user's activity level, faints, and falls to caregivers or a care center. A prototype exists for a ubiquitous computing-enabled home, with an IP-based home network and an OSGi-compliant server. Various non-IP peripherals use a device proxy, which can connect to the network using any proprietary method (e.g., a RS232 or SoapBox wireless interface). Applications run on the home server as OSGi bundles. In the prototype, information on appliances is available via PDA or a TV with a wireless mouse [78,107].

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The CRIM Laboratory at Scuola Superiore Sant'Anna (Pontedera, Pisa, Italy) has developed a new generation of microcontroller-based, multi-channel, telemetry platform systems for *in vivo* monitoring of physiological parameters. The implantable system consists mainly of a transceiver, a pressure sensor, and a telemetric link. The data stream is encoded before transmission, allowing the receiver to interface directly with a standard serial communication port. The telemetric link is capable of sending information through biological tissue (bovine spleen, liver, lung, heart, etc. were placed in a phantom to simulate the human body *in vitro*). Transmitter units with gastric pressure sensors have been implanted and tested in two 25 kg female pigs. The selected carrier frequency of 433.92 MHz and the low transmission power (30mW/m^2) meet international safety standards for electromagnetic field exposure. The small size of the electronic circuit is suitable for minimally invasive diagnosis tests such as gastroesophageus pressure, pH, and glucose levels, according to the biomedical sensors chosen [108].

A project named DRIFTS, supported by the European Union, has developed wearable active orthoses that suppress upper-limb tremors while preserving natural movement. This project is multidisciplinary, drawing on research in the neurological sciences, neural control of movement, biomechanics, signal processing and control, sensors and actuator technologies, ergonomics, and modern textiles [81].

A miniaturized silicon MEMS (Micro Electro Mechanical System), developed in Germany, has been added to sensor chips based on common enzymatic and electrochemical principles. The goal of this work is to continuously control glucose levels in patients with diabetes mellitus [109].

The MobiHealth project, also supported by the European Union (5th Research Framework), allows diverse medical sensors to communicate via wireless connections. This technology enables the live transmission of vital signals to healthcare providers over public wireless networks. The MobiHealth system has been successfully deployed on UMTS and GPRS networks. The MobiHealth patient/user is equipped with various sensors for vital signs such as blood pressure, pulse rate, and ECG, which are interconnected via a BAN. A mobile base unit (MBU), the central point of the healthcare BAN, acts as a gateway: it aggregates the vital measurements (intra-BAN communication is based on Bluetooth and Zigbee) and transmits them to a back-end system (extra-BAN communication is based on GPRS and UMTS). The back end may be physically located on the health broker's premises, or accessed through the wireless services provider. Once the data are sent to the health care broker, trained medical personnel will monitor them. Automated monitoring and patient feedback, however, are not in the scope of the project [110].

Healthy Aims, supported by the European Union's FP6 project (2002–2006), includes 6 small and medium-sized enterprises operating in 9 member countries. The partners are developing a range of intelligent medical implants and ambulatory measurement systems to help the elderly and disabled. The devices will communicate with each other through a BAN, and send information to the outside world for interpretation and diagnosis. The project is funded under the IST Micro system program. Among the products currently being developed are a cochlear implant, a retinal implant and glaucoma sensor, a functional electrical stimulation (FES) device for the upper limbs, a sphincter sensor for oesophageal and urological applications, an implantable intracranial pressure sensor, and an inertial measurement unit that can detect body motion and trigger the FES [111].

3.3. *Assistive and interactive robotics*

Smart homes are often associated with robotics, as shown in the projects described below. The robots in these homes may provide useful services and/or act as companions to ease the burden of social isolation [27,33,42]. There are two principal research directions in robotics: task-oriented robots that can help humans by doing work in a specific environment, and interaction-oriented robots that participate in human society. The most highly developed robots working in human society today are those in industry, where they perform highly specialized tasks in the place of humans, clean public spaces, etc.

Rehabilitation robots are built to assist the elderly, the disabled, and children. This aspect of robotics is now moving from position control to force control, making them more effective workers. In this discipline, however, the user interface is of great importance. Robotic systems allow the elderly to lead more independent lives. With the advent of new technologies, robotic systems can be commanded using whatever body movements are easiest for the owner; for example, switches can be operated using residual digits, the shoulder, or the feet. Patients who tremble or suffer from poor motor control can use speech recognition systems or modified keyboards; computers can even learn to recognize and interpret eye movements. In terms of emotional interactions, humanoid robots could serve as companions and pet robots could be a source of entertainment.

3.3.1. *In the U.S.A.*

Mobile robot technologies are being explored in the new discipline of rehabilitation robotics. The NavChair system, for example, was developed to be fully autonomous in specialized environments. It uses a navigation method based on Vector Field Histograms (Minimum VFH), which allows the system to adapt to instantaneous needs of the user while retaining autonomy of function. Joystick movements indicate the rider's intended direction, but this input is considered along with data from the wheelchair sensors so that obstacles can be avoided. The chair still moves in the intended direction, but it may choose an indirect route [112].

Krovi et al. have added two cooperating arms to a wheelchair. The arms not only help the user manipulate objects, but can also assist a person through a door, over an obstacle, or up steps. In addition, his prototype is a *legged* vehicle that remains capable of locomotion in environments where wheeled or tracked vehicles cannot be used (cluttered rooms, for example). It is a truly omnidirectional vehicle with active suspension, providing superior mobility even in difficult terrain or soil conditions (sand, clay, gravel, rocks, etc.). The legs can be re-configured, giving the chair additional versatility. When the wheelchair is stationary, one of its legs can be used as a manipulator for simple tasks such as pushing open doors and reaching for objects [113].

The Nursebot project was conceived in 1998 by a multidisciplinary collaboration of health care professionals and computer scientists from three universities. It aims to develop mobile robotic assistants for nurses and the elderly in various settings. The Nursebot's principal tasks consist of reminding people about routine activities such as eating, drinking, taking medicine, and using the bathroom, and guiding them through their environment. Two autonomous mobile robots have been developed to assist residents of the Longwood Retirement Community in Oakmont, PA, where field tests have been conducted. The robots, named "Flo" and "Pearl", are equipped with autonomous navigation systems, speech recognition and synthesis software, fast image capture and compression software for online video streaming, and face detection and tracking software [114,115].

Finally, a project at the University of California, Berkeley has developed robotic assistants for bimanual physical therapy. The prototypes were designed to measure and assist the user with transport tasks, and provide them with a bimanual squeezing task [116].

3.3.2. *In Europe*

In the European Union, TIDE ("Technology Initiative for the Disabled and Elderly") projects are aimed at promoting research and development into assistive technology so as to improve the quality of life for the disabled and elderly. Two other important research directions of this initiative are enhancing existing commercial products and services that compensate for impaired function, and designing special interfaces for commonly used equipment. Three TIDE projects have resulted in highly autonomous robotic wheelchair systems: the OMNI (Office wheelchair with high Manoeuvrability and Navigation Intelligence, for people with severe handicaps) [117], the SENARIO (Sensor-aided Intelligent Wheelchair Navigation System) [118] and MOVAID [119,120]. Meanwhile, non-TIDE projects have resulted in the MANUS [121] and CALL [122] systems.

The OMNI grants control to persons with severe or multiple physical disabilities by providing omnidirectional mobility. The chair can move in any direction, and its linear motion can be combined with a rotation around any given point (including, of course, the center of the wheelchair). In addition, ultrasonic and IR sensors analyze the environment and allow the wheelchair to avoid obstacles. The system is equipped with a modular human-machine interface to better support a range of devices and user abilities. Environmental control completes the system [117].

The SENARIO is a sensor-aided navigation system with obstacle avoidance and path-planning functions. It can operate in two modes: semiautonomous and fully autonomous. In the semiautonomous mode, the system accepts commands to move in a given direction or take a specific action (e.g., go ahead, turn right) but prevents dangerous conditions and avoids obstacles during execution. The fully autonomous mode is similar to the semiautonomous mode, but includes "go to the goal" commands (e.g., go to washroom) [118].

The MOVAID project aims to give the disabled and elderly more comfortable access to and control of common consumer products such as food preparation and cleaning equipment [119,120]. For individuals who are severely disabled or bedridden, a modular mobile robotic assistance system can be instructed through activity workstations. A long-term goal of this project is interpreting and reproducing the human central nervous system, which would lead to the development of fully humanoid robot assistants [123].

For some users, a new interface is sufficient to control home appliances. M3S (multiple master multiple slave) interfaces, for example, can be controlled by other (possibly robotic) M3S-based systems as well as by the user. This technology issues from a TIDE project to enable flexible and reliable communication among devices made by different manufacturers [124].

MANUS is a wheelchair-mounted manipulator suitable for everyday tasks. With MANUS, the user can pick up objects from the floor, get plates from shelves, pour a glass of water, open the refrigerator, etc. The MANUS arm is telescopic and mounted on a rotating base unit, and can be attached to a wide range of commercial wheelchairs [121].

The CALL Center's smart wheelchair was developed for the education and therapy of children who cannot operate conventional powered wheelchairs [122].

Finally, Caldwell et al. have developed a mobile robot with twin arms in the laboratory environment. Such a robot could have a wide range of domestic applications: loading a washing machine or unloading a tumble dryer, performing simple cleaning and service tasks through long-distance teleoperation, testing and maintenance, surveillance and emergency intervention (e.g., fire detection and firefighting), etc. [125,126].

3.3.3. *In Asia*

Wakaumi et al. (Japan) have developed an autonomous wheelchair that follows guide tracks embedded in the floor. With this wheelchair, the simple operation of pressing a button locks the motion onto a magnetic ferrite lane; this function allows the severely disabled to move both indoors and outdoors. For increased comfort, a nonlinear signal-processing circuit and pulse-steering drive provide smooth operation. In addition, for convenience and safety purposes, it incorporates IR sensor-based functions for, "running" to a desired destination and collision avoidance [127].

Sato et al. have developed the "Robotic room": a robot-enabled environment that delivers many useful services to its residents in order to ease their daily life. The robotic sickroom is equipped with a smart bed containing pressure sensors for physiological information, respiration, pulse measurements, and a ceiling camera that can monitor breathing by watching the chest of a patient. (The latter is an example of unconstrained behavioral measurement.) A long-reach robotic arm attached to the wall can bring food and drugs to the subject [128].

In Korea, there is a smart house project for the elderly and disabled named Intelligent Sweet Home. It includes a smart "robotic" bed fitted with a "smart hand", an intelligent wheelchair, and a robotic hoist to transfer the user between the bed and wheelchair. The goal is to help the subject with all manner of motions: getting a book, reading a newspaper, putting items back on the shelf, etc. A number of man-machine interfaces have also been proposed for the automatic control of its electrical appliances [129,130]. A steward robot with human-friendly interactions has been developed to help guide the resident in operating all the subsystems of the Intelligent Sweet Home [131].

The concept of emotionally interactive entertainment robots is a fairly recent development. Their purpose in the smart home would be to increase the emotional comfort of people living alone [132,133]. Current entertainment robots are mechatronic devices that express animal-like behavior. Interactive humanoid robots are one of the latest trends. The humanoid robot "Robovie", for example, can generate almost all the physical gestures required for human-robot communication and uses rich sensory information to interact with humans. The goal of such robots is not to execute a particular task, but to behave as a human partner might in daily life. That is, it interacts and communicates as a human with another human [134].

4. Future challenges

Continued progress and cost reduction in electronics, information technology, and communication technology have made smart home projects feasible and cost-effective. This review shows that many projects are still in the prototype stage, but will soon make the transition from research to viable industrial products. We now propose a list of future challenges that researchers must overcome. This list is not intended to be exhaustive, but to provide a basis for debate by identifying items that still hinder and restrict smart home development. We hope that resolving these problems will lead to a practical, sustainable and successful diffusion of smart homes among the general public. Their introduction will go a long way towards helping people age in place independently.

4.1. *User needs, acceptability and satisfaction*

As early as 1997, CNRS-SPI (France's "National Center for Scientific Research—Science for Engineering") called on a group of experts [135] on smart homes to better identify research issues in the field and define priorities. The group suggested that the roles of various actors (including but not limited to users and providers) needed to be better defined. Some of their recommendations follow.

- First, consider the subjects themselves: the sick, convalescent, elderly, and disabled have a clear need for this technology, which will help them express their needs and guide their choices. It may be assumed that there exist prospects for improving the quality of care and comfort of these people in their home. Of course, one must avoid using technologies that are not suitable to their needs; these have to be identified and excluded as early as possible.
- The subject's immediate surroundings are also important: family and neighbors, voluntary activities, and the organizations cooperating with health care professionals. Then there are the physicians and hospital teams diagnosing the subject, and the whole array of formal caregivers. All these actors have their own needs, and will play a major role in determining the conditions of an efficient health care system.
- The manufacturers and commercial actors must build, disseminate, and maintain products that satisfy all these needs.

Satisfying the needs of the user is a major challenge in research and development on smart houses. If a given need is not perfectly conceived early in the process, it will not be incorporated into the design. This is a complex and ambiguous subject, open to interpretation [136]. It is equally important to include the user when designing user-friendly technological systems. Indeed, user satisfaction and acceptance (usability) have become an important topic of several studies in telemedicine [16,137–140]. However, these studies mainly conclude that further work is needed on certain problems: the types of consultations appropriate for virtual visits, ways of improving patient-doctor communication, the patient's perception of long-distance care, and the limitations of telemedicine in clinical practice.

Satisfaction with telehealth services must be explored from the provider's point of view as well as the client's. A study on patient satisfaction with a Minnesota telehomecare system showed that those who receive a virtual visit are less often transferred to a higher level of care, which may reduce costs. What's more, they perceived their virtual visits as equal to or better than standard care (the latter opinion being more likely when both kinds of care were provided). The results clearly show that virtual visits are helpful, and might substitute for actual visits in the future–although of course more research is necessary [141].

In a pilot study of telemedicine in Korea, it was shown that among 50 patients selected to answer satisfaction-related questions the number of clinic visits per month decreased significantly from 0.64 to 0.42 ($p < 0.05$) after the introduction of telemedicine. Seventy-two percent of these patients were satisfied with the service, but their location was an important factor. Subjects living in their own homes were much more satisfied with the service (82%) than those living in nursing homes (50%). Among the types of services delivered, medical consultations (100%) and physical therapy (83%) were the most highly appreciated [142].

4.2. *Reliability and efficiency of sensory systems and data processing software*

One of the major problems encountered in smart houses remains the reliability of measurement systems. As the mobility, activity and vital signs of a monitored subject will be processed by algorithms to detect and signal dangerous situations, the accuracy of the input data is paramount.

In terms of mobility and activity, the goal is to locate a person within their home and model their habitual movements. An alarm is triggered when the person deviates from this routine by more than some predefined threshold. The house can be equipped with IR motion sensors [51,52,59,64,70,71,72] and pressure sensors [28,42]; alternatively, the subject might carry a beacon [26] or an accelerometer and compass [96]. In a room equipped with IR and pressure sensors, the person will be located only when they pass through a detection zone. If a beacon is carried, their position is calculated by triangulation with respect to the fixed sensors in each room. A less discreet system consists of spotting the person with video cameras [29,36,45]. Their location must be calculated in this case by processing image captures.

Several methods are used for deciding when an alarm should be triggered: neural networks [32,64], Markov chains [31,32], machine learning and predictive algorithms [24], decision trees [41], statistical models [65,69], probabilistic models [32,59,60], classification [67,76], etc. Other more unusual techniques have also been used to trigger the alarm, such as a chemotactic model based on the supervised prior classification of activity sequences [75] and calculation of the subject's anxiety level [74]. In the latter case, the user's interactions with devices in the house serve as a predictor of health.

In all these cases, it is necessary to measure a *lifestyle*: the person being monitored must have consistent habits in the first place for the system to work. One must also account for and anticipate deviations from this lifestyle such as vacations, unforeseen absences, and other exceptional events.

The IR sensors (and pressure sensors in the case of a "smart floor") also present the following technical problem: detection of the subject's presence is only effective they live alone. What's more, the IR method runs into difficulties when several sensors are placed in close proximity. A subject will often trigger several adjacent sensors at once when he enters their zone. This can introduce errors into the calculation of their position, which become particularly important when the subject's trajectory must be determined [67,69]. In the case of a personal beacon or multi-camera/multi-person tracking, an identifying badge must also be carried [26,29,30].

Another way of monitoring a patient's state of health is to place medical sensors in a garment [77,85–88], watch [78,79], jewel [80], chest belt [83], etc. All these biomedical sensors are electronic systems, which may or may not include mechanical parts and/or data processing software. A number of vital signs can be monitored in this manner: arterial pressure, ECG, EEG, body temperature, O_2 saturation, pulse, etc. Certain sensors are also capable of delivering therapy [93]. Others are ingested or implanted into the patient [93,100,101,108]—for example, electronic systems capable of measuring the ambient pressure. Some of these systems can be equipped with reservoirs, so that they can deliver chemical substances for therapy. Finally, the MARSIAN glove mentioned earlier can be used to monitor a patient's physiological response to stress, odors, tastes, failures of vigilance, etc. [104]

To sum up, all these home care systems must

- provide reliable positioning and measurement of vital signs;
- have a reliable algorithm for evaluating the patient's "lifestyle";
- trigger an alarm in case of danger;
- correctly interpret the vital signs through automated software or a competent medical professional, so that deficient function can be recognized;
- organize emergency response rapidly and effectively in case of need.

As for rehabilitation robots, these devices must be adapted to the handicap of the person requiring their services. The system should be easy to learn, reliable, and user-friendly. The automation of robotic systems should not require complex manipulation on the user's part. Rather, it should compensate for their handicap in the least traumatic manner possible. Finally, the use of robotic systems should under no circumstances increase the risk of accidents.

4.3. *Standardization of information and communication systems*

The authors mentioned in this review have used a wide variety of communication networks to organize multi-sensor personal monitoring systems. Some of these networks are hardwired through RS232 links [61,65], buses [59,60,72,143,144], or even the power-line system for controlling lighting, fans, and electrical outlets [22,145]. Others are wireless, using digital mobile phones [44], 802.11 [94], 868 MHz [70], Bluetooth, IR, or a USB cradle [83]. Still other types of communication exist: RS485 [146], FIP [147], Profibus [148], etc. Each depends on either an industrial protocol (possibly proprietary) or an academic equivalent such as the Michigan Parallel Standard [149,150].

In Europe, the so-called "domotic buses" (Elbus, Batibus, EHS) have long suffered from the lack of a common standard. (LonWorks, the American equivalent, is more commonly accepted.) This lack, which has long delayed the penetration of electronic systems and services into the domicile, has now been corrected by the introduction of Konnex [151]. This standard promotes interoperability among the various existing buses.

In smart home applications, ease of use, cost, and bandpass are the most important criteria. On this basis, the ideal network medium is doubtless the immaterial (radio, IR, ultrasound, microwaves, etc.). This choice offers several advantages: mobility of components, ease of installation, and simplicity of reconfiguration. Several bands may be used for interior applications (433 MHz, 868 MHz, 2.4 GHz, IR, etc.). The transfer rates achievable in these bands (~1 Mbps in the 2.4 GHz radio band, for example) are more than sufficient to support a multi-sensor monitoring system.

Important progress has been achieved in the production of miniaturized devices capable of network communication through standard protocols (Bluetooth 802.15.1 [152], Zigbee 802.15.4 [153], or WiFi 802.11 [154]) and having an autonomous power supply. Thus, while a wide range of communication systems has been proposed, the challenge of interoperability among different systems remains. It is necessary to establish the most suitable communication infrastructure for a given personal monitoring system.

One study carried out in the U.S.A. presents a system that addresses these usability issues. Different standards were applied for plug-and play interoperability, reconfigurability, wireless communication, and medical data exchange [155]. In this project, 2.4 GHz Bluetooth was used to support plug-and-play operations such as inquiry, connection, disconnection, and networking. For representing and exchanging high-level medical data, the IEEE 1073 standard for medical device interoperability was adopted. (This group of standards is also called the medical information bus (MIB), but was renamed to "the ISO/IEEE 1073 standards" in an effort at internationalization [156].) The IEEE 1073 standards provide "interconnection and interoperability of medical devices and computerized healthcare information systems" for acute care in bedside environments. The authors of this project showed that it is feasible to implement MIB-based devices while achieving the ease of use usually associated with plug-and-play features, including reconfigurability and scalability of the wireless body area network [155].

Laxminarayan and Istepanian [157] has addressed some of the issues and scenarios regarding the next generation (3G) of mobile telemedicine systems. Current mobile systems have some significant drawbacks that prevent the widespread diffusion and globalization of telemedical services:

- operational incompatibility between telemedicine network services and current mobile standards;
- the high cost of satellite links between global mobile devices;
- the limited data transfer rate of current mobile telephones (9.6 kb/s) compared to the costly new ISDN land links (up to 2Mb/s);
- the limited Internet functionality due to current bandwidth limitations.

According to the authors, the next generation of wireless and Internet solutions will resolve many of these problems, changing the structure of telemedical and healthcare delivery systems [157].

As Koch emphasizes, there is also a lack of standards for combining incompatible information systems—for example, inter-profession document sharing [158].

4.4. *Legal issues*

Smart homes and telemedicine have been around for less than 100 years, an insignificant period compared to the history of traditional medicine. The new techniques are becoming more or less accepted in countries where much research is being conducted into sustainable alternatives to traditional care. When it comes to distributed health care, however, a state has to protect its citizens from the possibility of malpractice. While information and communication technology have improved access to health care, policy makers should enact laws to (1) ensure that citizens have a high quality of care, and (2) anticipate the legal conflicts that could arise between recipients and providers of remote care. For example, long-distance medical personnel might be held accountable for misinterpreting the client's vital signs and symptoms. If a client in country B is examined by a medical worker in country A, what would happen in the case of an incorrect diagnosis? Which jurisdiction should be applied? Should the doctor be judged in A or B, if the patient lives in B and the doctor violates the laws of B? [159] According to Cwiek et al., the impact of telemedicine's progress in the U.S.A. has been diminished by anachronistic state licensing laws, which limit the practice of medicine to state geographic boundaries. He recommends that the practice of telemedicine should be licensed differently than the practice of traditional medicine. A national licensure model for telemedicine should be advanced, but the political and constitutional hurdles may be too great to overcome [160]. The courts lack legal precedent to respond to malpractice claims in the telemedicine domain.

Providers of telemedicine in the U.S.A. are limiting their liability by clarifying doctor licensure issues, revising doctor credentialing procedures, establishing standards, safeguarding computerized medical data, and videotaping telemedical procedures. As the field progresses, we are also learning more about the impact of telemedicine on malpractice insurance rates [161]. Daly argues that licensure and liability rules present formidable obstacles to the expansion of telemedicine, while failing to provide sufficient protection to clients. This problem has prevented the benefits of telemedicine from reaching many people in need [162]. Sable concluded that the obstacles to widespread implementation of telemedicine in the U.S.A. include the lack of standardization in telemedicine components, confusing legal issues and licensure requirements, and poor reimbursement [163].

To move forward, it is necessary for the states to adopt mutual recognition of licenses and define a universal standard of care [162]. Practicing medicine without a license in the patient's state is currently prohibited, whether the physician is treating the patient in person or from a distant location. The advent of telemedicine has crystallized the tension between the states' twin goals of protecting patients from incompetent physicians and protecting their own physicians from out-of-state competition on the one hand, and the desire to ensure access to the highest-quality medical advice and treatment available on the other [164].

In Canada, the use of telehealth services is increasing across the country; many new programs and networks are being established. Against a backdrop of major health care restructuring, both in Ontario and across Canada, telehealth is being practiced in a legal vacuum. There is no specific legislation in Canada, and apparently no initiatives to provide it with legal foundations. Donadue et al. have suggested that telehealth practitioners call for a regulatory paradigm to ensure accountability, establish acceptable parameters for encounters and reimbursement, and clarify uncertainties surrounding the new field. Until Ontario and the other Canadian jurisdictions take steps to address these issues, however, the status of telehealth in Canada will remain as it is today [165].

In Japan, Doctor's Act no. 20 stipulates that diagnosis and treatment should only be provided by examining the patient directly. Physicians long wondered whether telemedicine was allowed under this law, and the resulting uncertainty greatly hindered the growth of telemedicine in Japan. On 24 December 1997, however, the Ministry of Health and Welfare (MHW) released a statement that appeared to permit telemedicine under current law. In March 1998, the MHW announced that physicians could request a fee in some cases where they only communicated with the patient over a network [166].

In the E.U., four countries (Germany, Finland, Portugal, and Norway) have made it known that telemedicine is explicitly recognized by their laws and regulations. Among the 11 remaining countries, four (Denmark, the Netherlands, Spain, and Sweden) have affirmed that their general legislation also applies to telemedicine. This is probably also true of the remaining EU countries [167]. In Finland, Harkke et al. [168] analyzed the fact that cyber-medicine has the potential to reach anyone with access to a computer. As in the U.S.A., one of the main challenges in practicing telemedicine is reconciling the various standards and legal rules that apply to physicians treating subjects outside the country in which they hold a license. Every country regulates the practice of medicine within its borders in a different manner. Normally a physician must either obtain a license valid in the patient's territory, or choose not to practice e-health outside her own borders. Furthermore, the patient may run high risks since anyone can pose as a doctor over the Internet. Although the practice of telemedicine has been considered in some jurisdictions, there are no legal provisions for physicians entering a state via the Internet. Any e-health licensure system that hopes to regulate the Internet will have to take a wider approach.

Another important issue concerns the relationship established between physician and patient in the cyber world. Their interactions are limited by a computer screen. According to Harkke et al. [168], the following problems are important to consider:

- The physician's liability in case of malpractice needs to be clarified in terms of civil law. The patient has to be protected, and cyber physicians must be able to quantify their risk.
- The relationship between physicians and insurance companies may need to be modified.
- Should the physician by judged in their state of residence, or by other states in which they operate?
- Privacy laws should be adapted to face the challenge of ensuring the privacy and security of patient data.
- The roles of electronic decision support systems, medical software, and data collection systems in determining responsibility need to be clarified.

4.5. *Ethical issues*

The user's private life must be protected, but his habitation is made porous and public whenever medical data are passed on to the hospital, to a physician or nurse's office, or to a telehealth monitoring center. The barrier that separates his home from the public domain vanishes. It is important to verify that the lines of communication are safe and secure, that they ensure perfect confidentiality, and that it is impossible for a third party to intercept the data on purpose or by accident. Furthermore, the transmitted data must be flawless and uncorrupted to ensure its correct interpretation and high-quality care. On the provider side, medical confidentiality must be maintained. One example of a potential telecommunication problem is the fax, which can be seen by anyone having access to the fax machine [169]. Procedures and processes must be in place to ensure that patient data can only be accessed by those authorized to view it. Automatic encryption should be mandatory for any transmission of identified patient information. Web-based security systems must be implemented if patient data are to be transmitted via the web [170].

Telemedicine reduces the burden of travel, thus reducing stress on the individual being monitored and receiving care at home. However, the distance can generate additional concerns: the user must take charge of his own health care to a greater extent, which may adversely affect his psychological well-being. Technology also downplays the human factor in any personal relationship, including that between the doctor and patient. Virtual visits threaten to turn physicians and nurses into distant medical technicians, cutting off the close contact between recipient and provider and the trust such contact engenders. Thus, the benefits of remote monitoring must be carefully evaluated against respect for privacy, confidentiality, and security. To this we may add moral and human ethical issues, and the added well-being of a patient being treated at home rather than in a hospital or some other impersonal institution [7,171–174].

A physician or caregiver practicing telemedicine must ensure that his patient is aware of the proposed relationship, and obtain consent from the patient to participate in any telemedicine study. In the U.S.A. a code of ethics was prepared at the “e-Health Ethics Summit”, which convened in Washington DC on 31 January 2000–2 February 2000. The summit, organized by the Internet Healthcare Coalition and hosted by the World Health Organization/Pan-American Health Organization (WHO/PAHO), was attended by about 50 experts from all over the world. A draft of the e-Health Code of Ethics was released online for public consultation [175]. The final version of the Code sets forth guiding principles under eight main headings: candor, honesty, quality, informed consent, privacy, professionalism, responsible partnering, and accountability [176]. In Japan people are also aware of ethics issues in telehealth [40,44]. For example, the wireless system monitoring both heart rate and respiratory rate for home-visit rehabilitation described earlier was being developed and tested while the hospital’s ethics council approved the experiment, and patients and family gave their oral and written consent. In this experiment, strong data encryption was performed in the physical layer [44]. Another example is the life activities monitoring system developed in Osaka. The system was built with a great many sensors [167], with the goal of understanding individual living behaviors and noticing unusual conditions. This project has received the approval of the Ethical Committee on Human Research at AIST Kansai; they also obtained the subject’s informed consent [40].

4.6. *Cost effectiveness, socioeconomic impact*

Roughly speaking, remote monitoring of vital parameters and/or mobility is more cost-effective than placing people in a healthcare institution. People sometimes need to reach a distant location to get even basic medical care. Inhabitants of an area without its own healthcare center or hospital may be better served by remote monitoring, with the help of caregivers that are specially trained in this approach and health devices connected to an automated monitoring center. In this case an “actual visit”, or a visit to the hospital, is only required in emergencies or after the remote caregiver has checked all available health factors. In the literature on smart homes, there are no real studies on the socioeconomic impact of using such systems to take care of aged or disabled persons. Allen et al. carried out a retrospective review of nursing charts and clinical records in the U.S.A. Their objective data, abstracted from these records, include patient assessments, demographic information, teaching activities, and interventions. They conclude that 46% of on-site nursing activities could be replaced by telenursing, greatly reducing the cost of care [177].

With respect to the Kaiser-Permanente Tele-Home Health Research Project, in an experimental study conducted in Sacramento, California from May 1996 to October 1997, Johnston et al. showed that remote video technology was well received by patients, capable of maintaining their quality of care, and produced cost savings. The outcomes measured in this study include quality of care, access to care, patient satisfaction, and costs. The mean number of home visits per patient was 9.8 in the intervention group (with remote video technology) and 11.1 in the control group. The mean number of phone visits was 1.0 in the intervention group, and 0.5 in the control group. Patients in the intervention group had an average of 3.9 video visits per year. The average direct annual cost of home health services summed to $1830 in the intervention group and $1167 in the control group. The mean cost of all other care (including rehospitalizations), however, was $1948 in the intervention group as opposed to $2674 in the control group. The study concluded that use of remote video technology for home health care yielded somewhat lower cost savings than expected, because the potential of virtual visits to reduce the number of actual visits had not been fully realized [178].

In Pennsylvania, Dansky et al. showed that the total cost per patient per episode, including hospitalization, was lower for telehomecare patients than for the control group patients. This result supports the Kaiser-Permanente study [179]. Bynum et al. evaluated the cost savings to patients of a telehealth project run by the University of Arkansas for Medical Sciences during 1998–2002. Their results show that telemedicine leads to significant savings in travel distance, missed days at work, and family expenses [180].

Jennett et al., in a recent Canadian study, show the socioeconomic impact of telehealth on residents of Alberta and Canada as a whole [181,182]. Telehealth was found to provide improve quality of life, bringing important health benefits and socio-economic advantages in the form of reduced costs and utilization of the public health care system. While a variety of quantitative outcome measures can be found in the literature (access, quality of life, satisfaction, and cost), no studies attempt to identify or define specific socio-economic indicators. At the time this report was published, there was also no agreement on which quantitative or qualitative measures are most appropriate, or of the most value, in evaluating telehealth applications. Cost, cost savings, and cost effectiveness are common to many studies, but individual measurements of these variables are inconsistent. Many studies use estimates of these quantities as a proxy for in-depth economic analysis. Rather, the benefits and costs of remote care should be evaluated in terms of its impact on the health system and society. The Jennett et al. study concludes that telehealth promotes change, enhances health care, and is an innovative means of health care delivery.

Kun (New Jersey, U.S.A.) explores the costs and technologies involved in telehealth services. Based on a comparison between the average cost per day (or per visit) of various healthcare alternatives, Kun concludes that enormous savings could be realized by delivering care directly to the home through telemedicine. A hospital inpatient in the U.S.A. costs $820 per day, while a nursing home costs $100. The average cost of a house call is $74, while a telemedicine “virtual visit” costs only $30 [183].

An economic evaluation of the Japanese telehealth system has been conducted, comparing four regions. Tsuji et al. analyzed the benefits of various services in terms of an index named willingness to pay (WTP). The real cost to use a service is attributed (in exact monetary terms) to factors such as anxiety in day-to-day life, stabilization of illness, and enhancement of health awareness in addition to simple medical expenditures. This study makes it clear that telehealth systems are useful for consultations and maintaining the health of elderly and chronically ill (but stable) patients, but *not* for curing disease. The psychological benefit of being monitored by a medical institution 24 h a day (i.e., sense of relief) is difficult to estimate in concrete monetary terms [184,185]. Another of their papers has evaluated the economic benefits of telemedicine and factors for its promotion. In this work economic benefits are defined in two ways: WTP and willingness to undertake (WTU). A 15-question survey, distributed to the 622 Japanese medical institutions that use telemedicine, reports approximately 35% satisfaction. The estimated WTP was $35.23 for teleradiology and $165 for telepathology. The estimated economic benefits of these services over 1 year were $1.27 million for teleradiology and $278,600 for telepathology. The annual WTU figures are $10 million for teleradiology and $393,400 for telepathology [186].

In the U.K., the total savings realized by replacing actual visits with virtual visits have been estimated by extrapolating the results of more limited studies. According to one study [187] based on the town of Croydon (population 325,000), for example, virtual visits generated savings of 1 million pounds per year. Extrapolating this figure to the country's population of 64 million gives a figure of 200 million pounds per year. A U.K. report [188] concluded that a typical Community Health National Health Service Trust could replace 15% of home visits with telecare, for savings of 1.26 million pounds in the first year alone. A review of home nursing reached the similar conclusion that 14–16% of visits could be replaced by telecare services [189].

4.7. *Reimbursement*

The U.S.A. lacks a unified health care system; regulations are managed at the state level. Each state cooperates with the federal government to provide (high-risk) health insurance to the elderly, people with heavy disabilities, and poverty-stricken individuals. Some health care exists for the poor, but global health care coverage is not mandatory. Furthermore, the costs of the health system are managed by private insurance companies. The majority of American people (58%) enjoy private health insurance through their employers, who pay for some or all of its cost as a benefit. A small minority (less than 3%) benefits from a public health care system comparable to the French "*Sécurité Sociale*" [190]. Two such systems exist, Medicare and Medicaid. The first one covers medical expenses of the elderly, with a high fee for each reimbursement. The second covers patients whose standard of living is below the poverty threshold. This system covers almost every expense, but repays doctors badly. As an alternative to the private insurance model, "Managed Care Organizations" (for-profit companies trading on the stock market) build and operate health care centers where paying members can go for consultation. A significant proportion of Americans with modest revenues, however, have no health insurance coverage at all [191].

Following passage of the 1997 Balanced Budget Act, Medicare issued rules permitting very limited reimbursement for telemedicine. Medicare would pay the cost of live teleconsultations for rural beneficiaries living in federally recognized Health Practice Shortage areas. The Health Care Financing Administration (CMS) projected that the cost of this initiative in 1999 would lie between $60 million and $690 million. In reality, the policy has had a chilling effect on the use of telemedicine by Medicare recipients; few senior citizens benefited from the practice [192]. In 2001, the Medicare, Medicaid and SCHIP Benefits Improvement and Protection Act (Public Law no. 106-554) loosened Medicare reimbursement rules. The situation for telemedicine now depends on the state where the patient lives [193,194].

In Japan, the costs of telehealth are paid by individual users and public funds such as tax and medical insurance. Tsuji et al. suggest that use of the telehealth system should be reimbursed by medical insurance [185].

Within the E.U., telemedicine is not reimbursed by either public or private health insurance in eight countries. National health insurance reimburses the service in four countries, however: Germany, Greece, Norway, and Finland. The portion paid is especially high for medical imaging services [167]. In France "*la Sécurité Sociale*", a public heath care organism, manages and insures all the health care expenses of citizens [190]. In principle, it should cover smart homes and telehealth services as well. To date, however, telemedicine is not a common practice in France. Remote care of patients is rare or nonexistent. Telemedicine for home care is still in the research stage [195]; the term refers mainly to information exchange [196] or data transfers [197] between experts.

4.8. *Smart home diffusion*

In the U.S.A., a few assisted living facilities (Senior Care, Tiger Place, and Elite Care) have implemented information and communication technologies to help take care of their elderly residents [33,34]. Some also use robotics [33]. Remote surveillance systems, however, are more often used and tested in the context of research. In one organization, about a hundred patients suffering from chronic illness have a videosurveillance system installed in their home [178]. Telehomecare stations constructed by ATI have been installed in the homes of 86 patients. The station consists of a camera with a close-up lens, two medical sensors (sphygmomanometer and stethoscope), and two large buttons for recording the patient's response to audiovisual cues. At the communicating clinic, a PC station allows the nurse to capture and manipulate images acquired by the patient's camera. The patient station and clinic station are linked using ordinary telephone lines and a standard modem [179].

In Japan, several household appliance manufacturers such as Fujitsu, Hitachi, NEC, Sanyo, and Panasonic are now selling remote monitoring systems; their current prices range from US$ 2000 to 3000. When used consistently, these simple devices display the status of a chronic disease in graphs that can be used for diagnosis and consultation. The systems also encourage patients to take more interest in their own health. Some systems are equipped with a simple voice function so that a doctor can talk with the patient while examining the data. Seventy-six local governments in Japan operate telehealth systems, including Kiwa Town in Mie Prefecture, Tadami Town and Nishi-Aizu Town in Fukushima Prefecture, and Manmoku Village in Gunma Prefecture. The total number of devices in use throughout the country amounted to more than 8100 in August 2000, making Japan's telemedicine system the largest in the world [184]. A system named "Urara", invented and manufactured by Nasa Corporation, was adopted in Kamishi City. Its terminals are equipped with memory, an electronic sphygmomanometer, an electrocardiograph, an electronic signboard, and two buttons for answering questions with "yes" or "no". The system does not transmit visual or audio data, however, and is not particularly cheap at about US$ 2000. Vital data such as weight (which must be input by the user) are saved in local memory, to be transmitted at night when telephone charges become lower [185].

Private organizations or insurance companies provide remote monitoring in Europe, especially in France, Spain, and the Netherlands. The company "TeleAlarm Group" provides a variety of products, systems, health care services, and alarm technologies. One of their systems is a wireless domestic "carephone" that uses the telephone network to make contact with neighbors, friends, relatives or an emergency call center at the touch of a button in the event of accident, illness, or a panic attack [198]. In the U.K. there are more than 260 community alarm centers serving 1,160,000 customers, which make use of similar one-touch wearable devices. It is likely that up to 5 million people worldwide use a community alarm service. A monthly or annual subscription fee is charged by these assistance service [199].

The major power and communication utilities of France are becoming increasingly aware of their role in structuring smart home services. The French power company EDF has launched a range of services related to communication. Up to now, these applications have been limited to safety issues and energy savings. Soon EDF will start to provide other services via its subsidiary company Edev Teleservices, which operates a communication gateway under the Edelia brand. This approach relies on a house's existing equipment to deliver healthcare-related or entertainment services to support elderly independent living [200].

The French operator France Telecom launched *MaLigne Visio* in November 2004. This videophone service can provide home assistance to elderly, disabled or otherwise dependent persons [201]. A GSM/GPRS telephone bracelet named Colomba, developed by *Médical Mobile* in partnership with Orange (France Telecom Group), allows one to find patients suffering from Alzheimer's disease in case of flight or disorientation without constraining their liberty. It includes intelligent alert and detection software, a geopositioning system, a GSM/SPRS transceiver, and a SIM card. Telephony and data transmission rely on the Orange mobile network and AXA Assistance services. After being tested in a family environment between October 2005 and February 2006, the system is now sold in 22,400 pharmacies and 700 France Telecom stores across the country. When the product was launched, its price was €199 (tax included). After the introductory offer expired, this increased to €259. The system also requires a monthly subscription fee to *Médical Mobile*, which amounts to €59 (tax included). The subscription includes 24/7 assistance, geopositioning, and emergency communications [202,203].

In France security offerings have been developed as independent systems, which can be integrated into a house after the design and construction phases. They are installed by local operators, or by the resident himself. For example, the French company *Comod'Alarm* protects the elderly by allowing them to call the remote assistance center with a single button. For the protection of property, security systems typically rely on an easy-to-install system of infrared (IR) motion sensors. To detect smoke or gas, various substance detection devices are available. A distinction must be made here between anti-theft systems and those aiming to protect the person physically [204]. Few medical surveillance products are available on the market. The company *Tam Télésanté* is marketing only two: *BBA bootee* (a breathing monitor for newborns) and *Pressolink SMS* (a blood pressure monitoring service) [205,206].

5. Conclusion

Smart homes are a natural extension of current electronic, information and communication technologies. The concept refers mainly to comfort, leisure and healthcare. However, the last 20 years of development have failed to achieve anticipated results. Demand has been slack, and the supply of smart home technologies is too low. The main objective of this paper has been to identify those areas where progress has been recorded. We have taken stock of current research, and determined the main challenges for the future. All possible issues and technical solutions have been exposed and investigated. Most of the projects discussed here are currently being validated on protected sites. Some obstacles and restrictions hindering further progress are summarized by the papers of Koch [158] and Demiris [7]. In 2004, Demiris studied some of the key challenges faced by electronic home health care: privacy and confidentiality, accessible design, and reimbursement. He also defined criteria useful for evaluating telehomecare applications, such as clinical outcomes, clinical processes, cost of care, access to care, and acceptance by the patient and their family. He concluded that telehomecare has the potential to be a cost-effective alternative, capable of providing quality care to rural and poorly served urban households [7].

All the smart homes we have reviewed here, along with their intelligent technological or medical devices, have been designed to allow older subjects to live autonomously in a comfortable and secure environment. The main design difficulty is validating the alarms triggered by an older person living alone. Considering the safety objectives of these projects, this means that specific functions need to be added to manage and confirm emergency response procedures. For one thing, the alerted party may depend on the severity of the perceived problem:

- A family member, friend, or neighbor (informal help) who responds by going to see the person being monitored.
- A specialized assistance center (formal help), which organizes more extensive aid in case of a problem.

The second type of intervention labors under extremely demanding constraints:

- Intervention response time is paramount, since it is well known that time is of the essence in treating falls or heart attacks. This is true not just to avoid fatalities, but to minimize the secondary damage that might be difficult to treat.
- It is also important to learn the nature of the incident as soon as possible: whether the person is conscious, their exact location, etc.

In this respect, corporate robots are well-placed to take over so-called "passive" monitoring systems. Indeed, numerous successful prototypes of "smart homes" have been built. The main challenges of this field for the future can be summarized as follows:

- Smart homes need to more fully integrate their construction, computing infrastructure, and service delivery aspects.
- The proposed solution must match or exceed the patient's standard of living.
- User habits and intentions should be studied in more detail and respected whenever possible.
- Further research is needed into legal and ethical problems, user and provider acceptance, and user and provider requirements and satisfaction.

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