Contributions to Smart Assistive Technologies

by

Eduardo Carrasco Alonso

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

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Abstract

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

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

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

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

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

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

Acknowledgements – Agradecimientos

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

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

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

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

Prefacio de Manuel Graña

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

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

Manuel Graña

San Sebastián, Noviembre 2014.

Contents

List of Figures

List of Tables

1 Chapter 1. Introduction and Overview

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

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

1.1 Thesis motivation

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

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

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

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

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

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

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

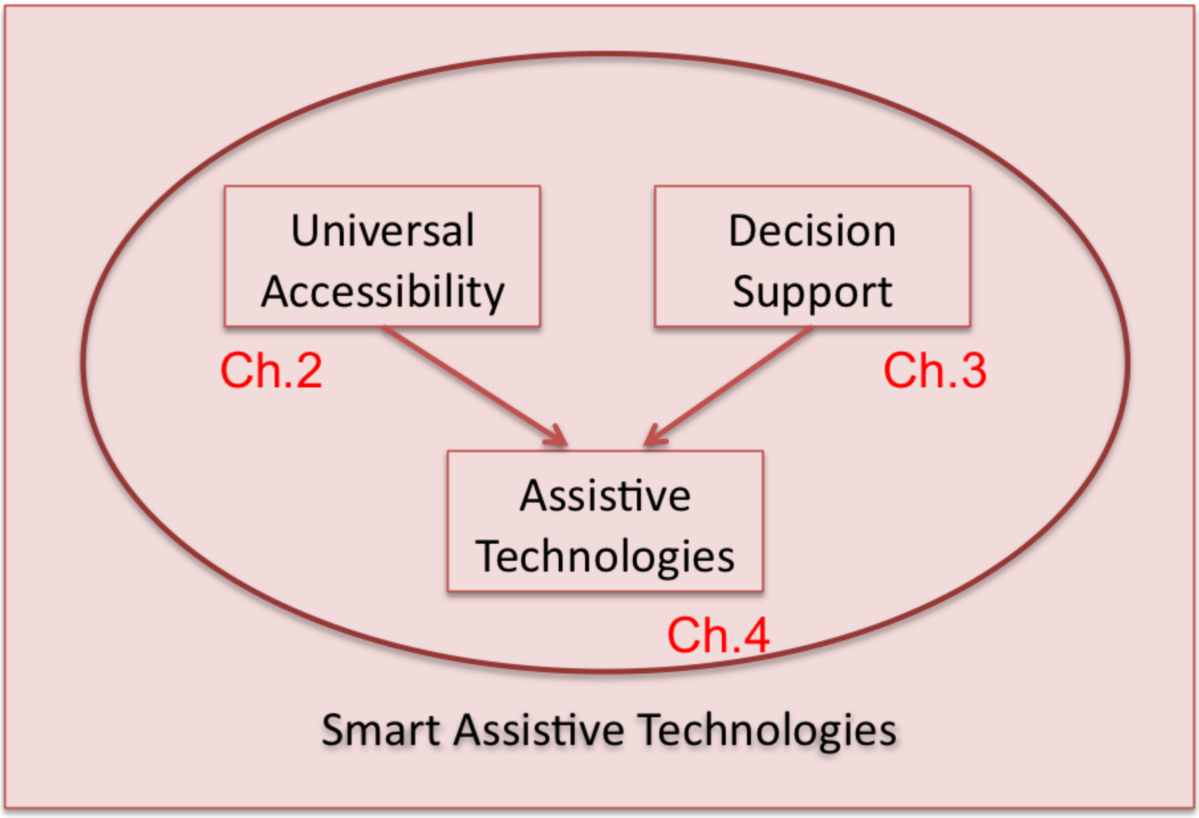

Figure 1.1. Smart Assistive Technologies as the general framework of the Thesis.

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

1.2 Publications

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

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

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

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

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

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

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

1.3 Structure of the Thesis

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

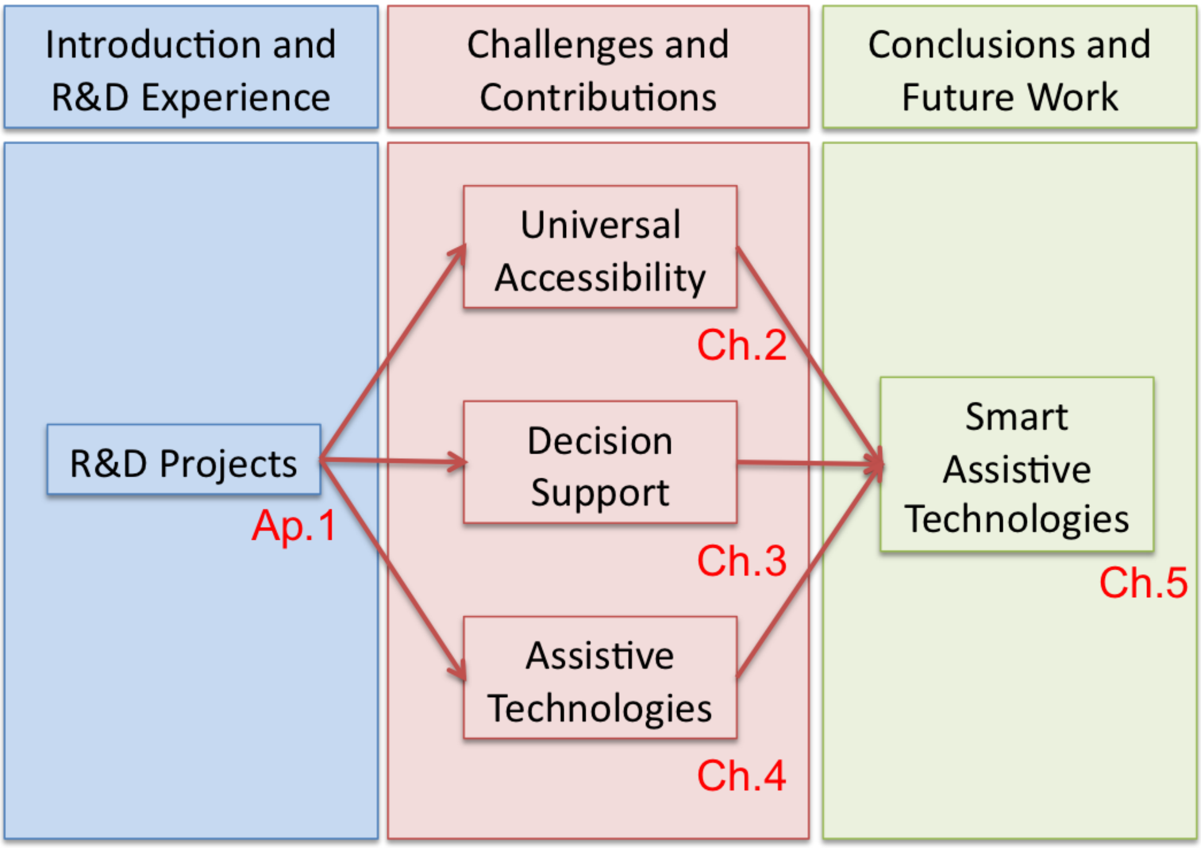

Figure 1.2. Structure of the Thesis.

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

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

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

- Chapter 4 describes the contributions obtained in the field of Assistive Technologies, covering several applications which are a sample of the field covering assisted living, rehabilitation, and assisted navigation for visually impaired people.

- Chapter 5 discusses the overall contributions in the context of Smart Assistive Technologies, assessing the impact of the conducted research and providing some lines for future work.

- Appendix 1 contains the summary description of the relevant projects that supported the works of this Thesis. As said in the introduction, the working environment is one of competitive applied research, so that achieving the completion of these research projects may be seen as an additional endorsement of the Thesis.
- Appendix 2 contains the summary descriptions of the papers selected to endorse the Thesis, as well as the actual copies of the published papers.

2 Chapter 2. Universal Accessibility

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

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

1. Firstly, we faced the provision of universally accessible remote controls for any given target device.
2. Secondly, we tackled the provision of universal access to interactive online services.
3. Finally, we worked on the provision of multicontext universal access to interactive online services.

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

2.1 Universal Accessibility

Universal Accessibility is a recent term in literature, which sets its foundations in two previous concepts: Design for All and User-Centered Design.

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

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

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

2.2 State of the art

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

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

2.2.1 openURC Alliance

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

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

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

2.2.2 UniversAAL

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

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

2.2.3 OSGi Alliance

The OSGi Alliance is a worldwide consortium of technology innovators that advances a proven and mature process to create open standards and specifications that enable the modular assembly of software built with Java technology. The OSGi technology facilitates the componentization of software modules and applications, assuring remote management and interoperability of applications and services over a broad variety of devices, services, and in diverse markets including enterprise, mobile, home, telematics and consumer. The alliance provides specifications, reference implementations, test suites and certification to foster a valuable cross-industry ecosystem [OSGi 2014].

The OSGI service platform is based on the AALuis middleware which follows a centralised approach. Services connected to the AALuis platform provide a description of the interaction steps following the Concurrent Task Tree (CTT) notation. Additionally, information on service method bindings has to be provided. These bindings are used by AALuis as instructions for service call-backs. Based on these documents, an AUI description is created. This root document is generated once after service registration. The result is a document that is described following the MariaXML notation. A modality and device specific (concrete) UI description is created based on the context information and the AUI description. Therefore, AALuis makes a sensible choice of output and input channels. This is done by applying a modality selection strategy utilising available context information. Depending on the adopted strategy, the user's capabilities and preferences can be respected [Epelde 2014b].

2.2.4 Raising the Floor

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

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

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

2.3 Framework

In order to provide universal access to local devices and online services of the Information Society for all possible end users, applications, and use cases, the architecture depicted at Figure 2.1 is proposed. In this architecture, the interface between system modules is always given by an URC.

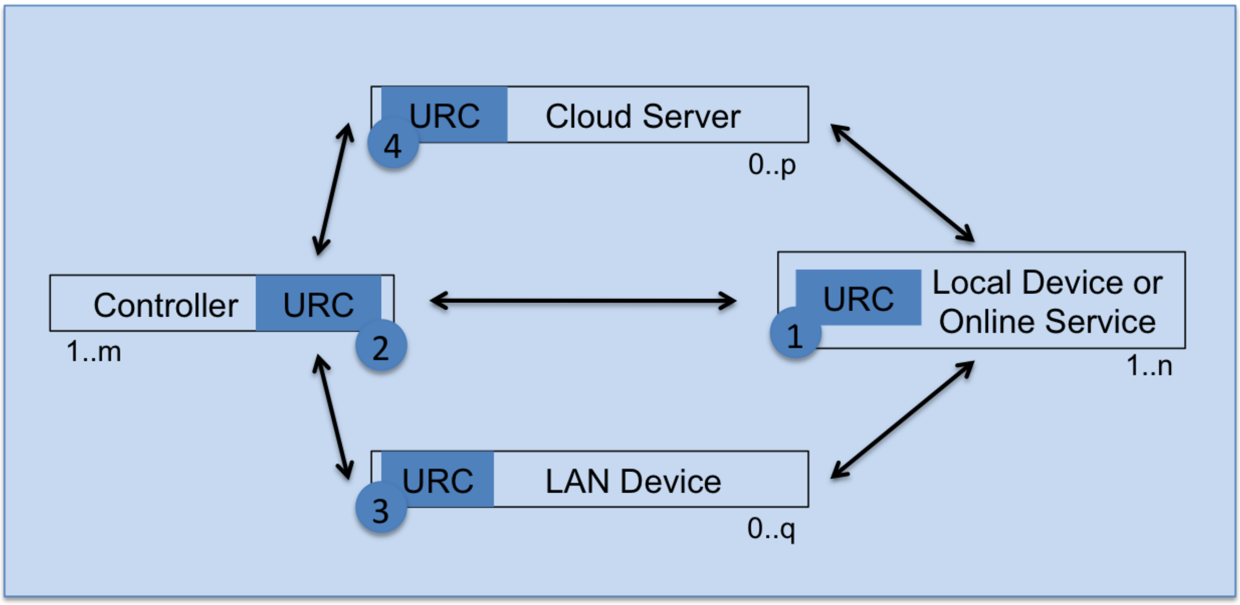

Figure 2.1. Architecture providing universal access to local devices and online services.

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

1. **Target Device/Service URC Implementation**. The URC is implemented in the target device or service and it advertises the UI sockets that can be used by remote clients, for example by using the URC-HTTP protocol to remotely control it.
2. **Client Device URC Implementation**. The URC can be implemented in the client device as well. Client device can be a smartphone, tablet or any other device the end user chooses to remotely control a single or a group of target devices or services. Different pluggable user interfaces can be run at the client device. Proprietary communication protocols to the target devices have to be included in the URC implementation, for example using Target Adaptors as it is done in the UCH.
3. **LAN Device URC Implementation**. Devices such as switches, gateways, routers, or servers present in the local area network can be used to host URC implementations such as the UCH. In this configuration, the UCH translates the communications among all specific protocols of clients and targets that are available in the local area network. Thus, the URC specifications act as a common control language.

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

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

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

Hence, an architecture that mixes universal access and activity management is needed. In this sense relevant research has been carried out in [I2HOME 2009b], [Murua 2010]. An architecture that integrates UCH and AMS is depicted in Figure 2.2.

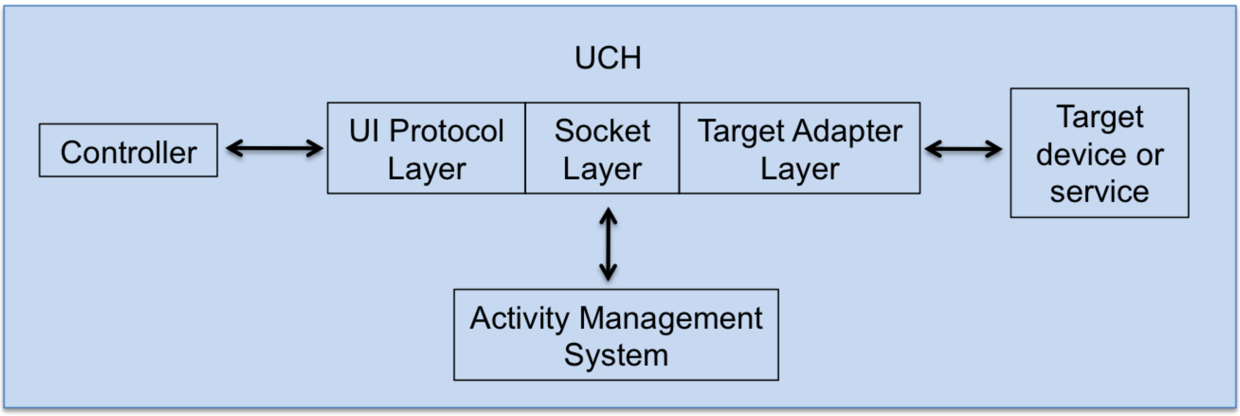

Figure 2.2. Activity Management System integrated in Universal Control Hub.

As it can be seen in Figure 2.2, all the interaction between targets, users and the Activity Management System can be made using UI sockets which are placed in the Socket Layer. The Activity Management System can be implemented using a task engine. There are several available open source engines [Rich 2009]. The modeling of tasks and the interaction between them can be represented by task models. The standard CEA-2018 which defines the semantics, and an XML notation for task models can be used for standardization purposes [ANSI/CEA 2008].

2.4 Challenges

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

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

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

2.4.1 Challenge 1. Universally Accessible Remote Controls

In this Challenge1, the provision on Universal Accessibility to daily life devices such as consumer electronics, domestic appliances and self-service terminals is analyzed. In particular, the case of the TV sets will be analyzed in detail, since TV sets are present in almost any home worldwide, and watching TV is one of the most frequent leisure activities [ITVE 2009]. Significant effort has been made in order to improve the user friendliness, appearance and usability of the TV remote controls. Anyway, the interaction paradigm based on infrared remote control technology has remained unchanged but a significant impact on accessibility has yet to be achieved [Weemote 2013].

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

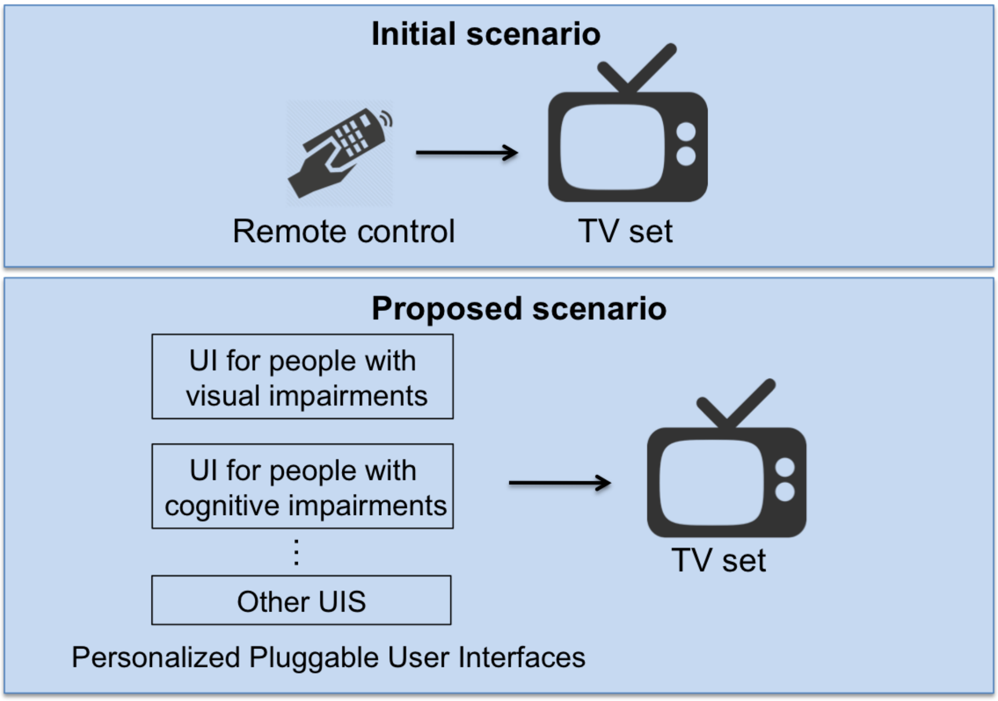

Figure 2.3. Universally Accessible TV Remote Control.

2.4.2 Challenge 2. Universally Accessible Online Services

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

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

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

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

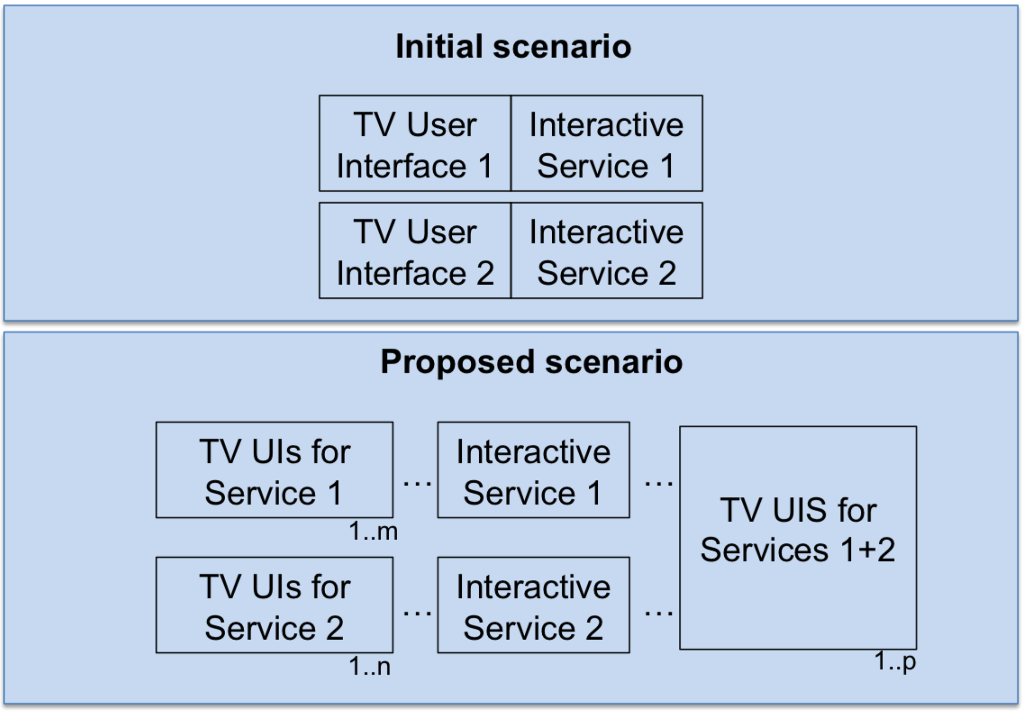

Figure 2.4. Universally Accessible TV Services.

2.4.3 Challenge 3. Multi-Context Universally Accessible Service Provision

Despite the achievements and advances in the user acceptance of technological products and services and their interaction, the shift toward multi-environment service consumption limits traditional systems' deployment [Burrell 2000]. From a design point of view, the main limitations of these services are (1) the limited consideration of the user's real-life context (e.g., not considering that user's needs and preferences changes from a home scenario to a work scenario or to an on-the-go scenario) and (2) the lack of an architecture support to provide the required flexibility in terms of location, client device, interaction means, and content [Hong 2001].

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

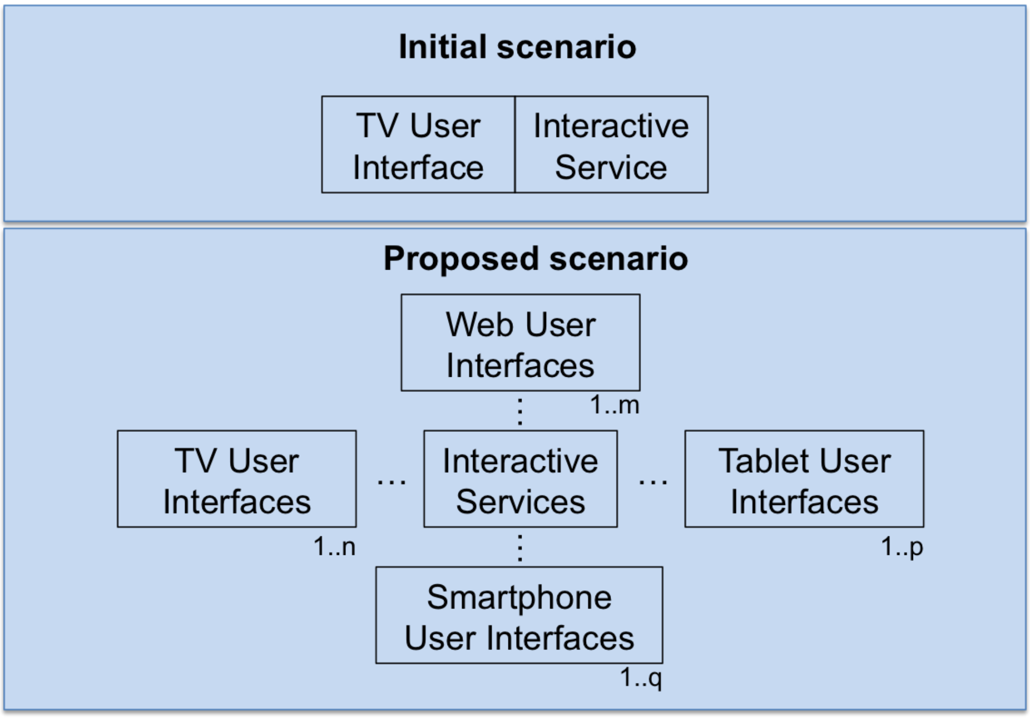

Figure 2.5. Multi-Context Universally Accessible Services Provision.

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

2.5 Contributions

In the following subsections, the corresponding contributions to the challenges presented in the previous section are described.

2.5.1 Contribution 1: Universally Accessible TV Remote Control Architecture

This section presents a solution that provides universal accessibility for remotely operating the TV set. The novelty here is the description of how, by using the Universal Control Hub (UCH) [openURC 2013a] architecture, it is possible to achieve this goal.

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

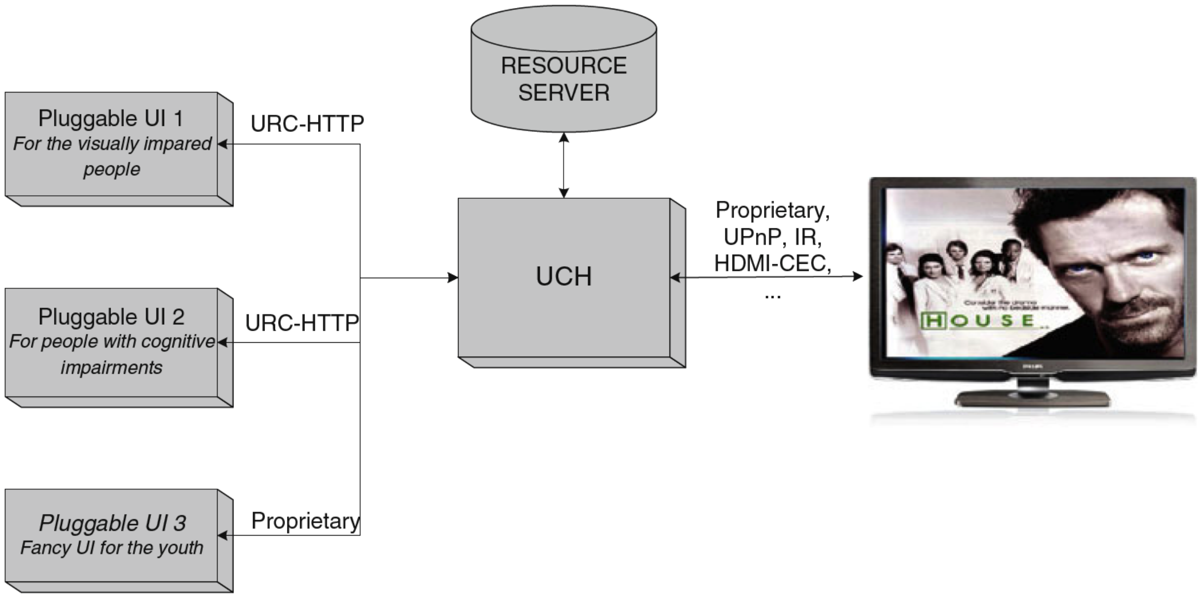

Figure 2.6. Universally Accessible TV Remote Control Architecture [Epelde 2013a].

The main features of the UCH are as follows:

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

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

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

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

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

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

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

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

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

These requirements would address the full integration of a TV set in the UCH. The TV set's remote control functionality integration into the UCH architecture is achieved by means of defining the required XML files (UI Socket, Target Description and Target Resource Sheets) and implementing the corresponding code for the target adapter layer requirements (Target Discovery Module and Target Adapter). For more information see [openURC 2013a].

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

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

Implementation and validation

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

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

Closing remarks

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

2.5.2 Contribution 2: Universally Accessible TV Services Architecture

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

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

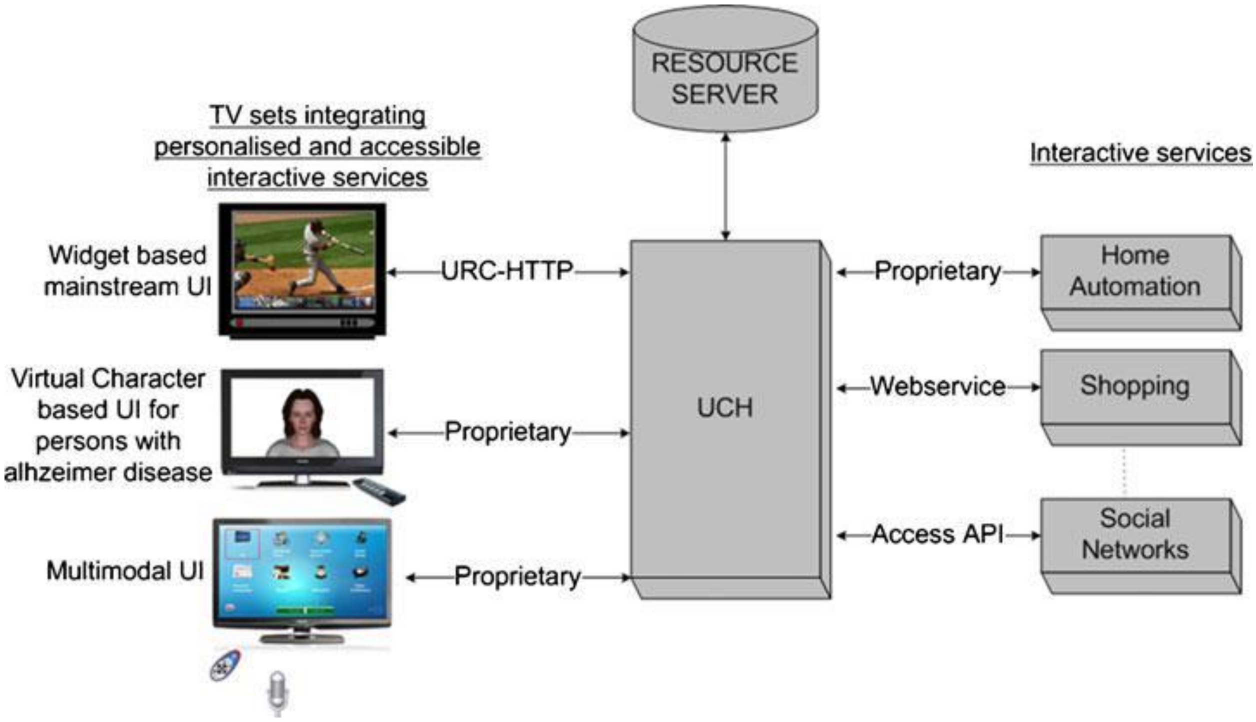

Figure 2.7. Universally Accessible TV Services Architecture [Epelde 2013b].

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

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

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

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

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

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

Implementation and validation

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

Closing remarks

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

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

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

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

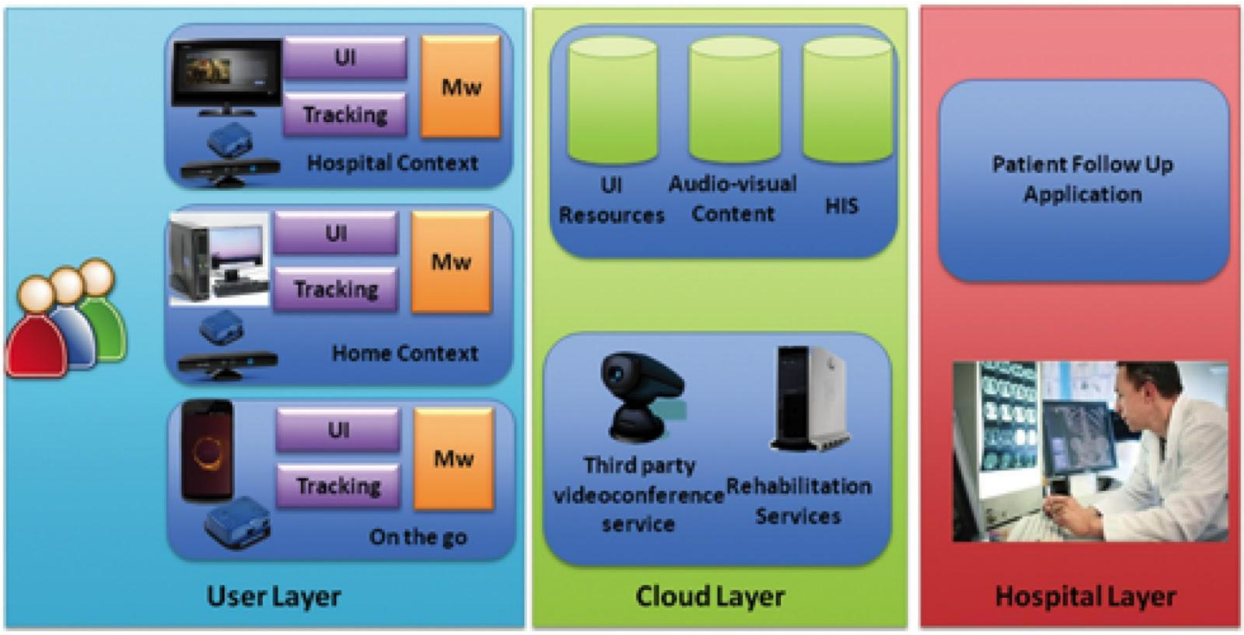

Figure 2.8. Multi-Context Universally Accessible Services Architecture [Epelde 2014a].

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

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

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

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

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

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

Implementation and validation

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

Closing remarks

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

Second, an Activity Management System (AMS) could be integrated and implemented into the UCH (see Figure 2.2). The AMS are those systems that provide support to the end user in order to accomplish complex tasks. In this way, the users of the aforementioned telerehabilitation system may benefit from assistance during the execution of the exercises prescribed. This requirement is particularly important because the system is intended for universal use, and users with special needs such as people with cognitive impairments may also use the system and may have to be assisted during the rehabilitation sessions.

2.6 Discussion on the results and future work

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

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

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

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

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

- The concept of applying the Universal Remote Console (URC) framework to Web services, in particular to those described by the Web Service Description Language (WSDL) needs to be continued. In this sense a new standardization effort is currently initiated under ISO/IEC JTC 1, Subcommittee SC 35, to extend the URC series of standards by a part on Web service integration. Both the User Interface Socket Description language and the Web Service Description Language (WSDL) define suitable extension mechanisms for such integration. It is expected that this approach will help adoption of the URC technology for Web services, and thus make personalized and pluggable user interfaces widely available for Web services.

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

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

- Progress has to be carried out in the development of user interface repositories, target and service adaptor repositories, user profiling techniques and user interface matchmaking algorithms in order to provide pervasive user interfaces for any context the users meet in their daily life.

- Finally, open source implementations of an UCH integrated with an Activity Management System and easy to use task modelling tools are needed. Furthermore, demonstration prototypes which show the full potential of activity management support and the URC technologies are needed in order to mainstream its benefits into society.

3 Chapter 3. Decision Support

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

1. Firstly, the design of an architecture for a Experience-based Decision Support System that can assist in the decision making of single defined tasks in concrete scenarios.
2. Secondly, we tackled the design of an architecture for a Generic Semantically-enhanced Decision Support system that can support multiple related decisional tasks in complex scenarios.
3. Finally, the third challenge considers the detailed specification of the process of experience acquisition, formalization, and reuse in Decision Support Systems. However, here we will not reproduce the details already reported in the annexed papers.

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

3.1 Decision Support Systems (DSS)

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

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

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

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

The third big issue is maintainability, extensibility, and scalability. Maintainability refers to the update of knowledge embodied in the CDSS according to the shifting state of the art and clinical practices. Extensibility is the ability of the system to add new aspects not previously taken into account, i.e. new clinical variables or treatments. Scalability is the property of maintaining similar performance and response time when the magnitude of the data increases greatly. Hence, CDSS architectures must be optimal in the sense of achieving an optimal balance between cost and performance to maintain the underlying knowledge model and the criteria for reasoning of the system. For that purpose, knowledge representations must be sufficiently transparent to be understood directly by domain experts. In the same manner, easy-to-use, and technology-transparent tools for domain experts need to be developed [Peleg 2006]. On top of that, mimicking the learning paradigm of clinicians, the knowledge and criteria embedded in an actual CDSS should evolve with daily experiences [Berner 2007], following a experience-based learning paradigm. Therefore, mechanisms for the quantitative and qualitative evaluation of the performance of the system, as well as of the quality of the knowledge stored in it, should be provided [Liu 2006]. Finally, there is a need of an architecture for CDSS allowing sharing and reusing CDS modules and services [Sittig 2008].

3.2 State of the art

The variety of techonologies that have been applied to CDSS construction is astounding, therefore in this section we will limit ourselves to the fields closely related to the Thesis contents, as given by the papers in Appendix 2 supporting it. For instance, Computational Intelligence tools, encompassing machine learning, bioinspired learning and optimization, fuzzy reasoning, will not be reviewed, because we have not dealt with them in the works of this Thesis, though we are aware of their big impact and extensive use. Moreover, state of the art reviews are already provided in the accompanying papers.

3.2.1 Knowledge Engineering

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

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

3.2.2 Set of Experience Knowledge Structure

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

The Set of Experience Knowledge Structure (SOEKS) [Sanin 2009a] was proposed to represent and reuse experience in an adequate knowledge representation. It is designed to store formal decision events explicitly, and it is built from four basic elements that are considered to be crucial in decision-making actions. These elements are variables (V), functions (F), constraints (C), and rules (R). Variables are used to represent knowledge in an attribute-value form, following the traditional approach for knowledge representation. The sets F, C, and R of SOEKS are different ways of relating knowledge variables in V.

Functions V describe associations between a dependent variable and a set of input variables; therefore, SOEKS uses functions as a way to establish links among variables and to construct multi-objective goals (i.e., multiple functions). Constraints C are equalities or inequalities restricting the set of possible solutions, which can be used to control the performance of the system with respect to its goals. Finally, rules R are used to model inferences, and map actions to the conditions under which they should be executed. Rules express the connection between a condition and a consequence in the form if–then–else.

3.2.3 Decisional DNA

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

3.2.4 Multi-agent technology

Multi-Agent Systems (MAS) are systems in which many autonomous software agents are combined to solve large problems that are beyond the individual capabilities or knowledge of each agent [Isern 2010]. MAS are defined by four main characteristics: (i) each agent has incomplete capabilities to solve a problem; (ii) there is no global system control; (iii) data is decentralized; and, (iv) computation is asynchronous [Sycara 1998]. Different MAS have been already proposed for medical applications in general, and for clinical decision support in particular [Isern 2010], [Shirabad 2012]. These systems are oriented to the reutilization of medical resources physically distributed in different health centers. Regarding the use of MAS during the different stages of the clinical workflow (i.e. diagnosis, prognosis, treatment, evolution and prevention) in a CDSS, the work presented in [Shirabad 2012] supports the entire clinical decision making process with the use of MAS. Nevertheless no knowledge reutilization is supported between the different stages, as separate decision systems are proposed for each stage. Additionally, no learning mechanisms based on user experience are provided.

3.3 Framework

In order to develop DSS that mimic the learning paradigm of human decision makers, experience-based approaches are needed in which the knowledge and criteria embedded in an actual DSS should evolve with the daily experiences. We have carried out a reflection on human learning model in order to identify the main elements and processes that produce the experience gain on human. We came out with three learning models that are somehow related to the SOEKS and DDNA framework. Each learning model has a corresponding computational architecture that may serve as a general templates for the DSS proposed in this Chapter.

3.3.1 Supervised decision learning model

First model refers to the process of learning decisions when there is some master (expert) that can provide the correct decision. Figure 3.1 depicts a time frame dynamics illustrating this process. At discrete instants in time, the decision maker is confronted with situations Si that require some decision. We call Di the decision actually taken, while Dei is the decision that the expert would recommend. The difference between them Eai is the decision error which provides the experience to correct future decisions, hence this experience is incorporated in the next time instant when some new decision is required. Ideally, the learner would converge to the expert, so that the error will go down to zero after a finite time.

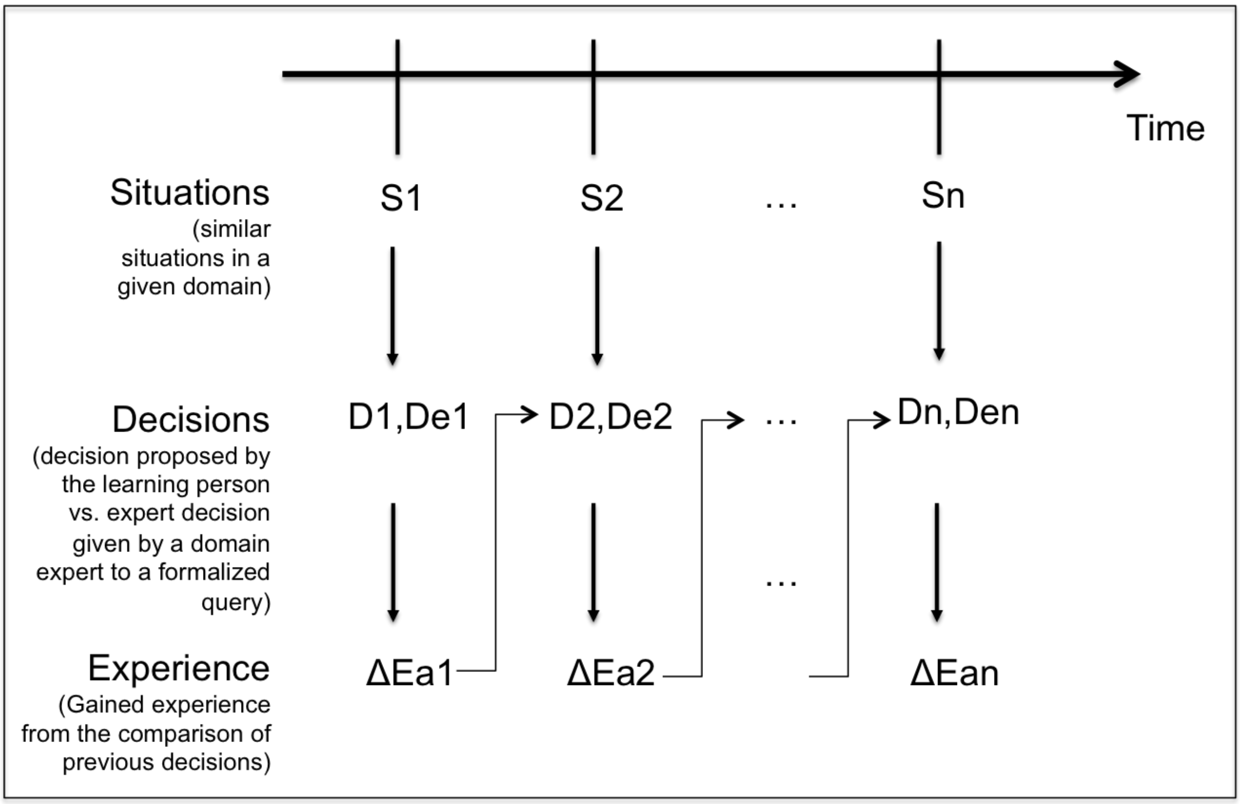

Figure 3.1. Supervised human experience acquisition model.

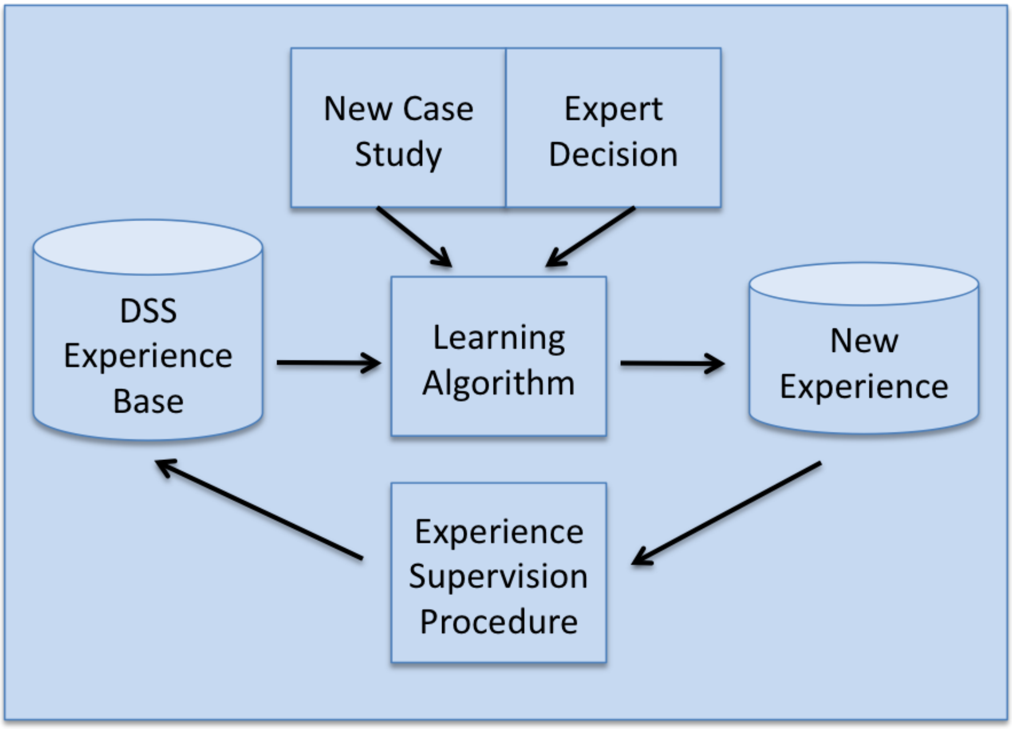

Figure 3.2. Computational architecture for the implementation of the supervised decision learning method in DSS.

The computational architecture shown in Figure 3.2 for a DSS performing the experience extraction and update process of figure 3.1 is composed of the following modules.

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

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

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

d. **Experience Supervision Procedure**. A procedure to check the validity of the new experience inferred is needed in order to ensure the correctness of the knowledge increments in the system. This procedure may involve domain experts in order to guarantee the validity of the new experience to insert in the DSS Experience Base. In fact, this mechanism ensures that the system is really learning the decision policies of the master. As it can be seen in Figure 3.2, the process is cyclic. Hence, the periodicity of the update of the DSS Experience Base has to be established by the managers of the DSS.

3.3.2 Learning from consequences model

The previous model is oriented to teach an agent (human or DSS) to mimic the decisions taken by an expert. This model does not take into account the observation of the actual consequences of the actions, the output of the real life system when we perform an action according to the decision taken. Next model, whose time process is illustrated in figure 3.3, learns at the level of the consequences. There is no master giving a correct decision, but there are expected (desired) consequences from decision Dei, denoted Cei in the figure. When the decision is carried out, the actual consequences are Cri, and the difference between the expectations and the actual results is the error Eai. This error is the experience that is incorporated by the learning agent for subsequent decision making situations. Ideally, the system will learn making the error converge to zero.

From a computational point of view, the modules in figure 3.2 have slightly different roles in this model, where the learning process must be able to perform the backwards translation of consequence error into variations of the decision making parameters. Most conventional learning algorithms have some kind of functional model of the decision generation that provides predictions of the consequences, i.e. an artificial neural network, so that the learning process is some kind of differential process which can be analytically derived. When the relation between decisions and consequences is not directly functional, i.e. when there is not a good quantification of the description of the system, then this learning paradigm does not apply.

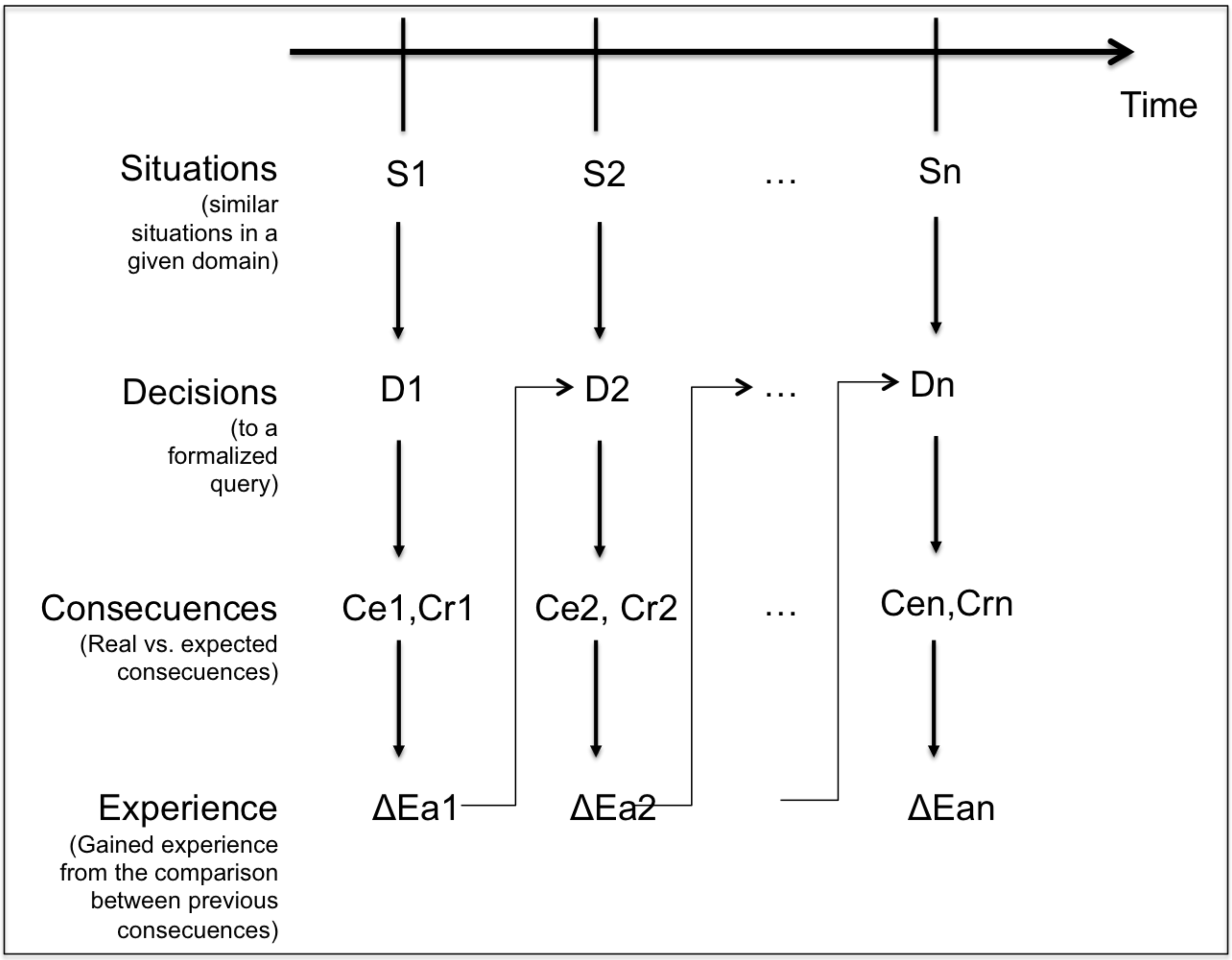

Figure 3.3. “Learning by doing” experience acquisition model.

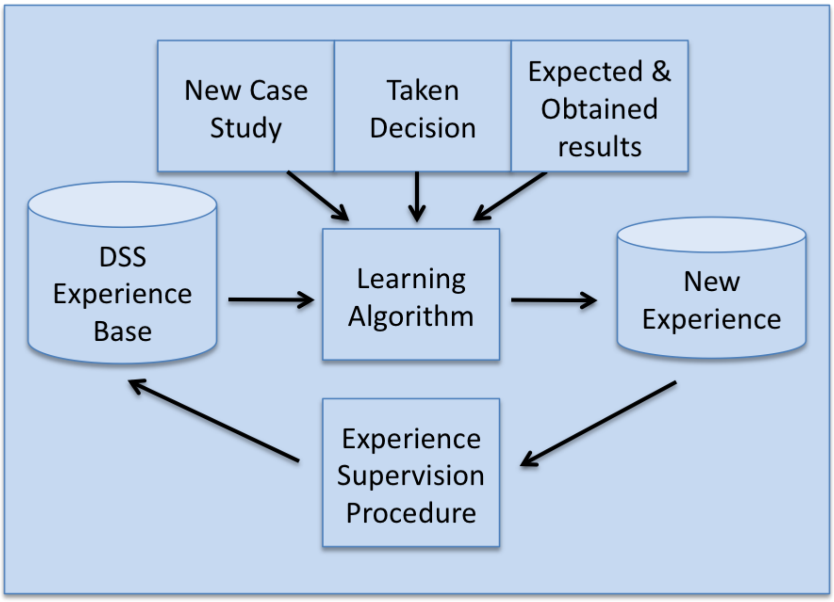

Figure 3.4. Architecture for the implementation of the “learning by doing” method in DSS.

3.3.3 3.3.3 Hybrid model

The hybrid model described by the process in figure 3.5 combines the two information sources that can teach the learning agent: the expert decisions and the expected consequences. Therefore, the system would be able to mimic the good expert decisions, those leading to desired consequences, while minimizing the error in the consequence domain. In the computational design of the DSS, the role of the learning algorithm is much more complicated, because it must combine two kinds of information which can not easily be managed by conventional learning algorithms. In fact, we do not know of any such system proposed in the literature.

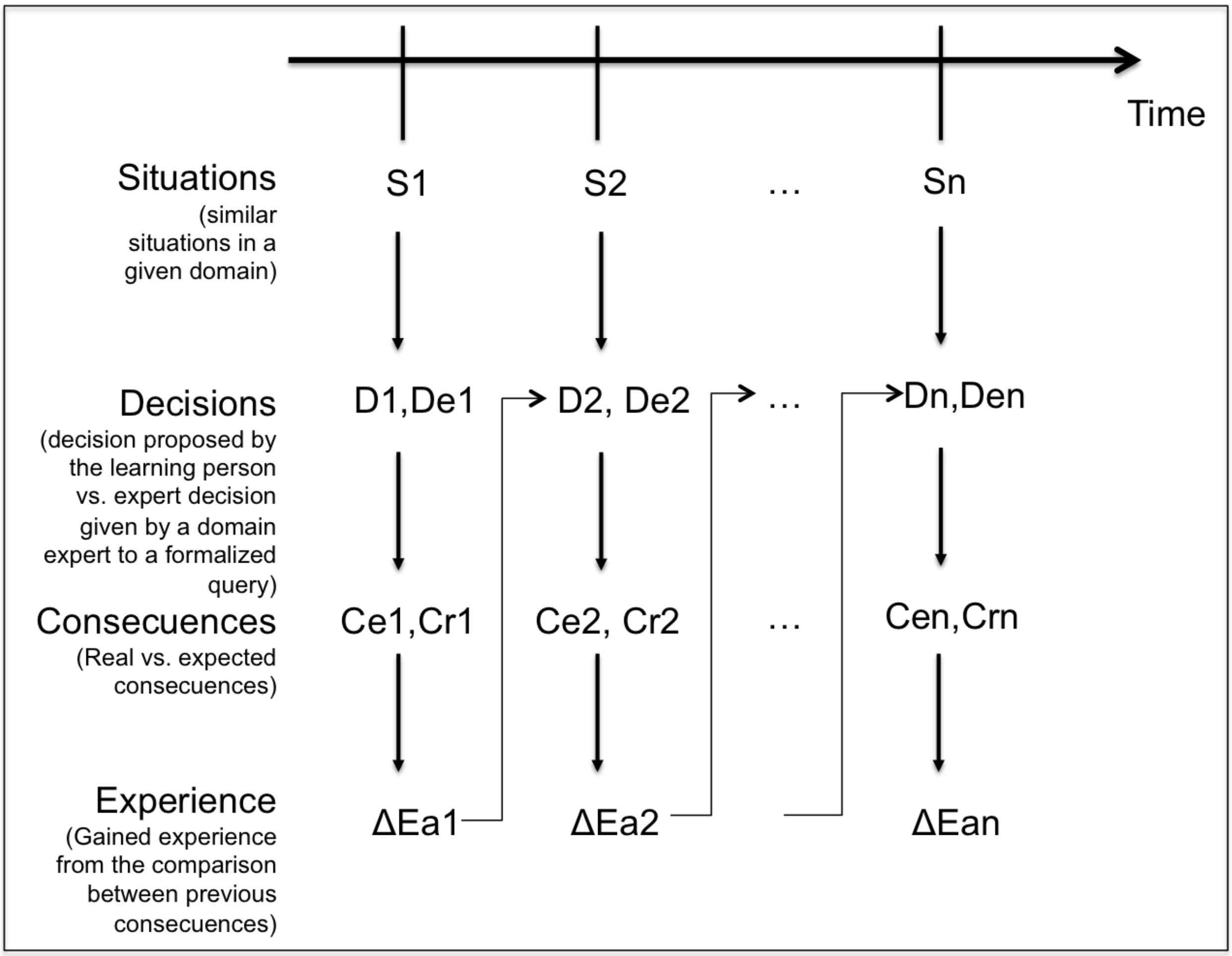

Figure 3.5. Hybrid experience acquisition model.

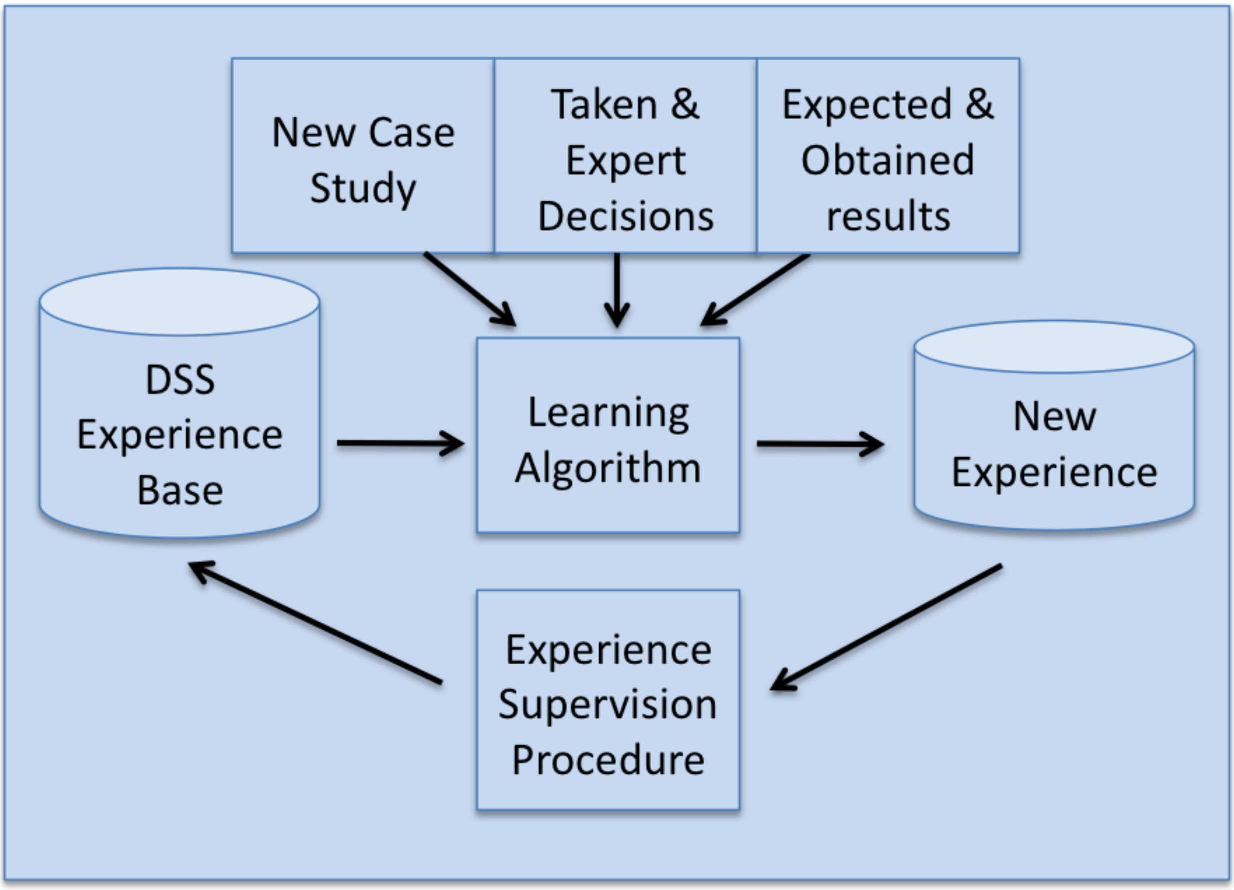

Figure 3.6. Architecture for the implementation of the hybrid learning method in DSS.

3.4 Challenges

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

3.4.1 Challenge 1: Experience-based Decision Support Systems

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

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

3.4.2 Challenge 2: Generic Semantically-enhanced Decision Support Systems

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

3.4.3 Challenge 3: Adaptive Decision Support Systems

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

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

3.5 Contributions

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

3.5.1 Contribution 1: Experience-based Clinical Decision Support System for the early diagnosis of Alzheimer’s Disease

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

The proposed system is the evolution of a previous work presented by [Sanchez 2011a] in which a knowledge-based CDSS for the diagnosis of AD was introduced. The system was based on ontologies for knowledge representation and a semantic reasoning process that inferred diagnoses for patients. The semantic reasoning was driven by a static set of production rules provided by AD experts. The previous system has been extended [Toro 2012] with the application of SOEKS and DDNA to provide it with the ability to evolve the rule set and discover new rules. The architecture of the ECDSS consists of five layers (Figure 3.7): a data layer, a translation layer, an ontology and reasoning layer, an experience layer, and an application layer. Each layer is described next.

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

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

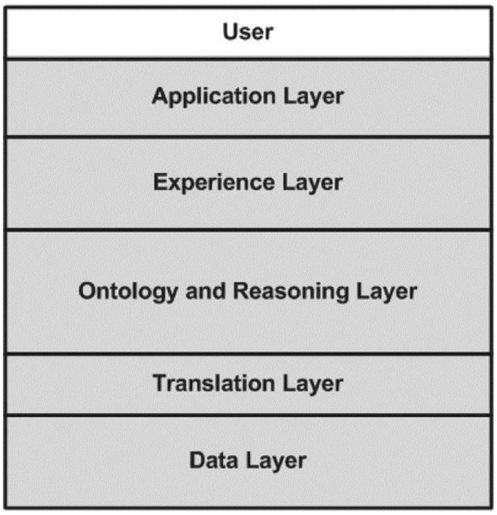

Figure 3.7. Experience-based Clinical Decision Support System architecture, from [Toro 2012].

The ontology and reasoning layer. It contains the knowledge of the system and performs reasoning processes for clinical decision support. Figure 3.2 shows the structure of the ontology and reasoning layer. Ontologies were chosen as the knowledge containers of the system. In particular, an ontology made of three different ontologies model this domain of diagnosis of AD: the Mind ontology (which contains the medical tests results on patients) [Sanchez 2011a] and the supporting ontologies SWAN (which links to accepted medical hypotheses and publications) [Ciccarese 2008] and SNOMED CT (for standardization purposes on terminology) [Nyström 2010]. The intrinsic semantics embedded in the ontologies can lead to the discovery of new knowledge, such as diagnoses from implicit knowledge or new connections in the model when queried and inferred using production rules and description logic (DL) reasoners. Additionally, domain experts have generated a set of production rules that drive the semantic reasoning process [Sanchez et al. 2011].

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

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

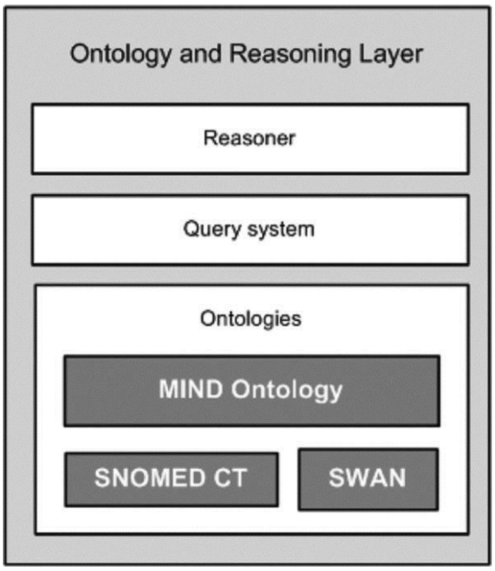

Figure 3.8. Proposed structure of the ontology and reasoning layer [Toro 2012].

Implementation

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

Closing remarks

As it can be seen in Figures 3.7 and 3.8, the generalization of the resulting architecture to other domains outside the health sector is straightforward, by exchanging the ontologies that apply to other domains. Though the proposed architecture is valid for a big number of domains and applications, it still faces several limitations such as the lack of modularity and scalability, and adaptability to complex scenarios that involve decision taking in several steps of the process. In order to solve these limitations new architectures have to be devised (see Section 3.4.2 Contribution 2: Generic Semantically-enhanced Clinical Decision Support System).

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

3.5.2 Contribution 2: Generic Semantically-enhanced Clinical Decision Support System

The use of the agents-based paradigm provides the system with the so-desired modularity, and in this way scalability is also intrinsically accomplished by the system. In order to achieve this scalability, our system supports the inclusion of new agents, which could be implemented in the future and then incorporated. Figure 3.9 depicts an overview of the MAS architecture proposed for the clinical domain. There are nine distinct agents: (i) information agent, (ii) data translation agent, (iii) knowledge and decision agent, (iv) standards and interoperability agent, (v) reasoning agent, (vi) experience acquisition agent, (vii) application agent, (viii) user profiling agent and (ix) majordomo agent.

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

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

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

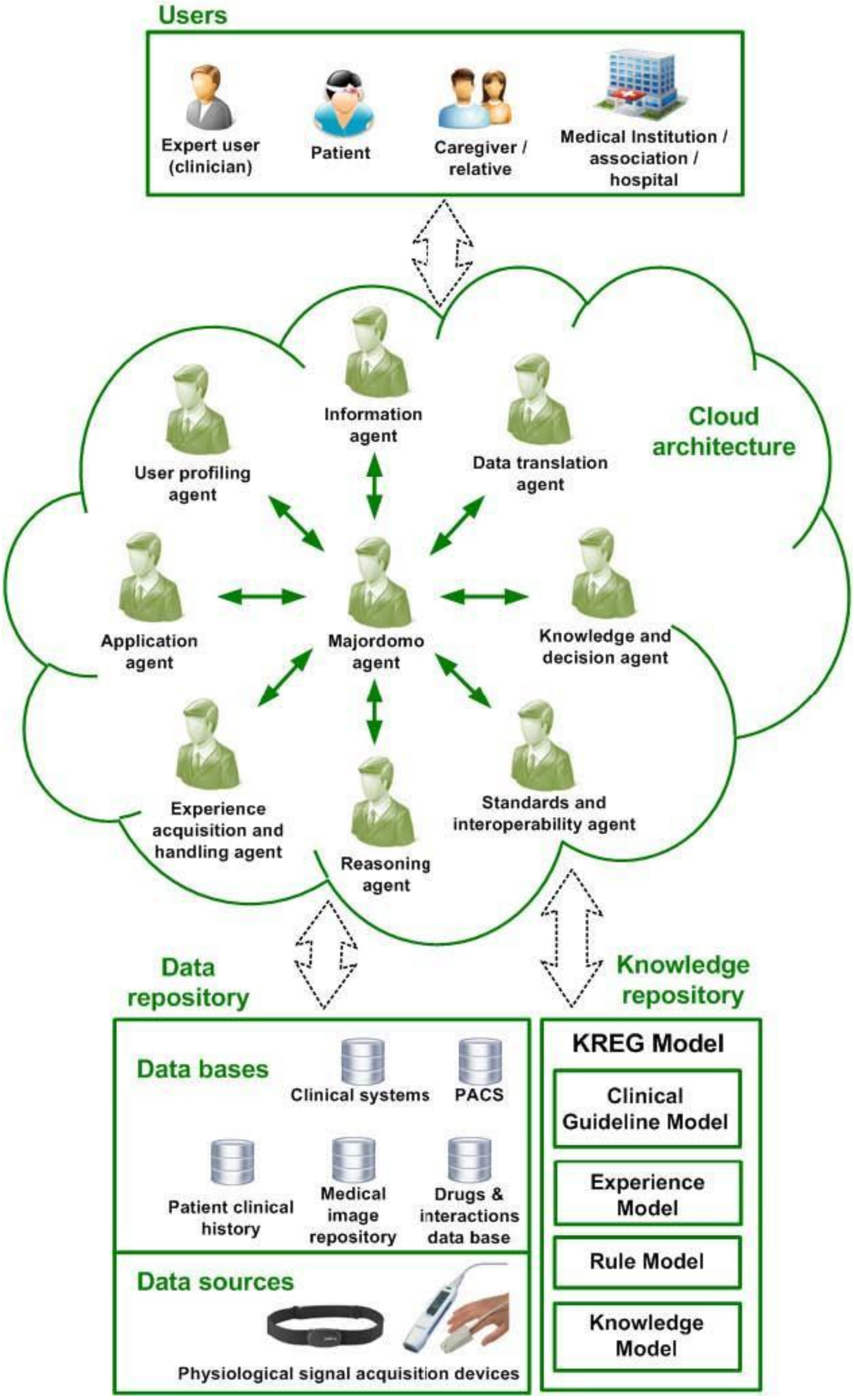

Figure 3.9. Generic Semantically-enhanced Clinical Decision Support System Architecture [Sanchez 2013].

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

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

Experience acquisition and handling agent. Clinicians learn new criteria for decision making during their daily experiences. Following this same paradigm, the experience acquisition and handling agent gathers and stores the experience of clinicians or other users in the system, for the evolution of the initial knowledge and rule models. In fact, the experience acquisition and handling agent provides automatic maintenance and updating of the KREG model. The use of the Set Of Experience Knowledge Structure (SOEKS) and Decisional DNA (DDNA) technologies to evolve the rule model of a CDSS with acquired experience is proposed [Toro 2012].

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

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

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

Implementation

The proposed generic Semantically-enhanced Clinical Decision System was designed and implemented in LIFE project as a case study for the Breast Cancer Functional Unit (BFU) of the Valencia University General Hospital. It is fully described in [Sanchez 2013]. Additionally, a methodological evaluation of the system which lasted 15 months was performed, including i) verification, ii) validation, iii) evaluation of the human factors, and

iv) evaluation of the clinical effects of the system. The results obtained were very promising and they will be published in a relevant journal in the next future.

3.5.3 Contribution 3: Adaptive Clinical Decision Support System

A Decisional Event represents a decision made on an individual, and on a decision category, for which a set of recommendations have been generated based on a given set of rules. The action of making the decision implies the selection of a final decision by the decision maker. Such final decision can be made according to the provided recommendations or not. Next, the Decisional Event is stored into a SOEKS as follows; data associated with the individuals is mapped into SOEKS variables. Variable values and constraints are also mapped into the SOEKS variables. Rules applying to decision domain of the decision category are stored in the SOEKS rules. Finally, applying functions are stored in the SOEKS functions.

The set of SOEKS stored into Decisional Chromosomes and Decisional DNA will follow a temporal succession. Once Decisional Events are acquired into a SOEKS structure, the information they contain can be used by algorithms evolving the rulesets. Some of those algorithms allow to (i) gradually and repeatedly correct rules as well as deprecate them relying on the existing experience, and (ii) generate new rules. Three particular rule managing algorithms are described in [Sanchez 2014a]. Suggested changes on rules resulting from those methods will result in a secondary rule set. Such secondary ruleset will then be analyzed by a committee of domain experts, that will discuss on which of those changes are to be included in the primary ruleset. Figure 3.10 illustrates the complete experience acquisition process, including the generation of SOEKS and the evolution of the ruleset.

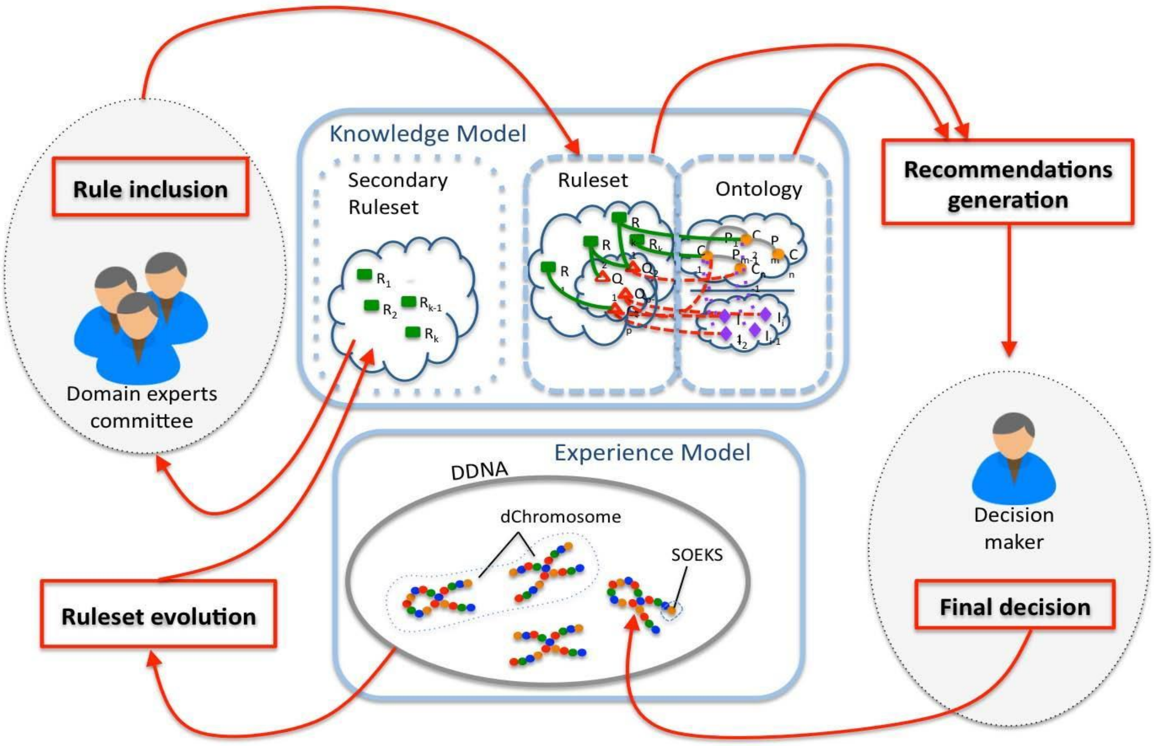

Figure 3.10. Experience acquisition process [Sanchez 2014a].

Implementation and validation

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

Closing remarks

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

3.6 Discussion and future work

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

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

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

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

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

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

Regarding the future work, the following research lines are proposed:

- To complete the full chain of the automatic computerization of decision support, by focusing on the acquisition of decision criteria and rules directly from current available knowledge sources, such as clinical guideline repositories and Evidence Based Medicine databases.
- Related to the latter, work on the application of decision support standards for the modeling of the knowledge and criteria in the system, in order to provide a universal clinical decision support service is also needed.
- Methodologies and tools for the evaluation of the quality and quantity of knowledge and experience in the system have to be explored.
- The traceability of the decisional events has to be further researched, in order to allow the analysis of the individual contribution of each decisional event in the whole decision chain results.
- The consequences of the decisions have to be formalized, added and reused in the experience model of the DSS, because the contain valuable information for the decision makers.
- The complete semantization of the Electronic Health Record (EHR) is needed, in order to allow the direct integration of S-CDSS in the clinical workflow. Remarkably,

this means the semantization of the information available in non-structured free-text fields of the clinical reports.

- Finally, the works presented in this doctoral dissertation can extended to cover relevant application sectors such as drug discovery, or cancer diagnosis in the medical sector, where the discovery of new knowledge plays a fundamental role.

4 Chapter 4. Assistive technologies

This Chapter describes the research conducted in the field of Assistive Technologies. The main contributions have been performed in different contexts such as ambient assisted living, telerehabilitation and autonomous navigation, in which the needs of different target users with special needs, such as elderly people, people with Alzheimer's Disease, stroke patients, and people with visual impairments, have been considered. The relevance of Human-Computer Interaction for each scenario will be highlighted, since research on ways to facilitate the interaction between people and computers is the key element for the success of each assistive solution. In this chapter, we focus in four challenges that have appear elsewhere during this thesis.

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

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

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

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

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

4.1 Assistive Technologies: motivation

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

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

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

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

- Language, interoperability, standardization and cost [Stack 2009].
- Provision of appropriate training to the disabled end-user [Stack 2009].

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

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

4.2 State of the Art

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

4.2.1 Abstract User Interface Description Languages

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

4.2.2 Automatic User Interface generation

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

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

4.2.3 Natural Human Computer Interaction

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

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

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

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

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

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

4.3 Framework

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

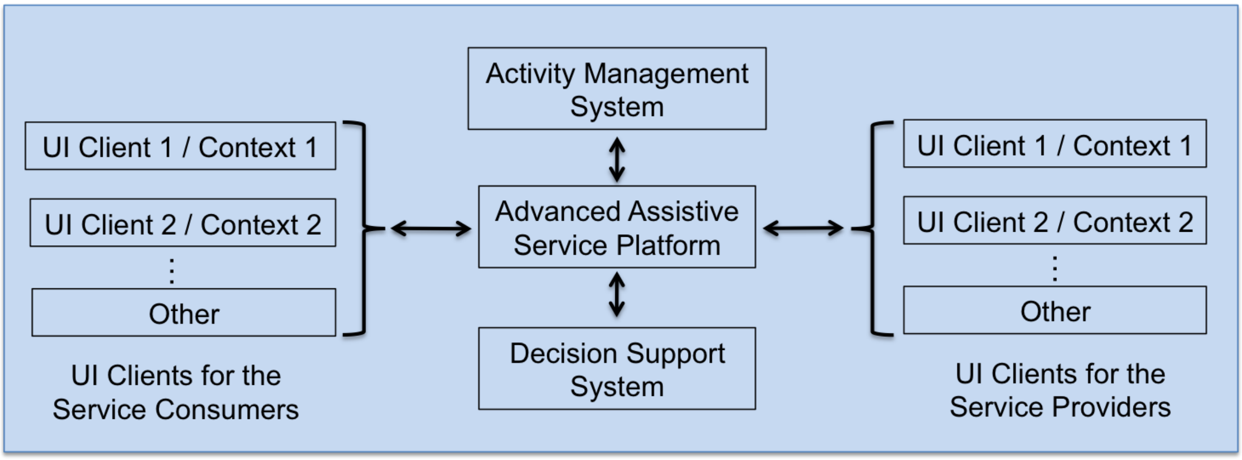

Figure 4.1. Advanced assistive services provision architecture. UI means User Interface.

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

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

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

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

a) **Activity Management System**. This system is intended to provide support to the service consumers in order to accomplish complex tasks, such as telerehabilitation sessions. The service sessions can be modeled using task models, which are run in a task engine, and the outputs are delivered to the user by means of the user interface. This module is particularly relevant for users with special needs, such as people with cognitive impairments, that may have to be assisted while using the system. More information on AMS in Chapter 2.

b) **Decision Support System.** This component supports healthcare professionals in the management of the healthcare data generated by the system, since the system as it is could overload the doctors with data coming from the patients. Hence, in order to increase the performance of the medical team, an intermediate component which analyses the data, detects anomalous situations, and triggers the corresponding alarms, would be needed. The technologies described at Chapter 3 "Decision Support" may be used to develop this component.

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

4.4 Challenges

The following three main challenges have been tackled with in the course of the Thesis works, and related research projects.

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

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

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

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

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

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

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

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

4.4.3 Challenge 3: Upper limb telerehabilitation for patients with stroke

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

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

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

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

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

4.4.4 Challenge 4: Autonomous navigation of people with visual impairments

The population of blind and visually impaired in Europe is estimated over 30 million. On average, 1 in 30 Europeans experience sight loss. Furthermore, sight loss is closely related to old age in Europe, where age-related eye conditions are its most common cause, resulting in 1 in 3 senior citizens over 65 experiencing it [EBU 2013]. Being able to navigate autonomously is one of the most relevant needs for blind people. Some navigation systems especially designed for blind people are entering in the market such as the Kapten Mobility from Kapsys. Nevertheless, its precision is very low for guiding blind people in normal settings such as sidewalks, and the interaction paradigm, which is based in oral natural language instructions, is not adapted to the needs of the blind people, leading to confusing and unsafe situations [Kapsys 2013].

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

Additionally, relevant progress is being carried out regarding satellite positioning technology. The European Geostationary Navigation Overlay Service (EGNOS), which is essentially Europe's precursor to the GALILEO system, is currently providing a terrestrial commercial data service named EDAS (EGNOS Data Access Service). It offers GPS data correction for providing increased positioning accuracy and integrity [5].

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

4.5 Contributions

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

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

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

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

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

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

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

Implementation and validation

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

Functional Layout

The work carried out in this section succeeded in demonstrating that even people with severe dementia can benefit from the technological progress, and interact with home appliances in ambient assisted living environments such as the digital home of the future. Results can be generalized, and it can be affirmed that most people can interact with local devices and online services at any context, if the appropriately tailored user interfaces are provided. This concept has been depicted at Figure 4.3.

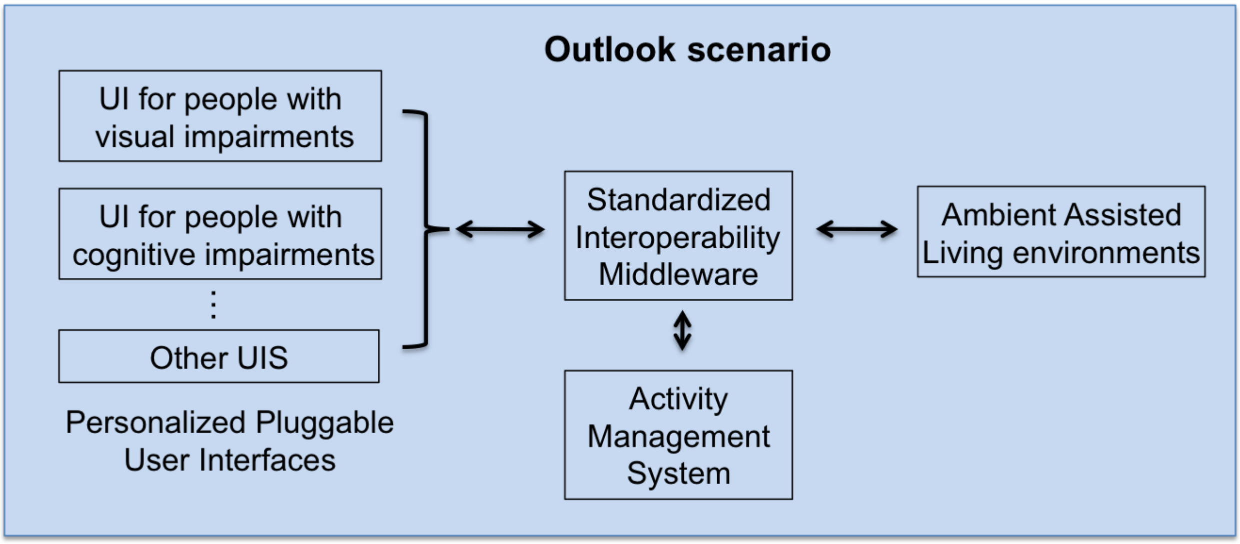

Figure 4.3. Functional layout on natural interaction on Ambient Assisted Living environments.

Figure 4.3 specifies the following modules to accomplish this new goal:

c) **Ambient Assisted Living Environment.** Typical AAL environments are those that combine local devices and online services in a given context such as the digital home. In these environments, all the devices and services are interconnected and several different protocols are used. Typically, communication protocols come from different manufactures and some of them are proprietary (f.e. CHAIN) while others are standardized (f.e. UPnP).

d) **Standardised Interoperability Middleware**. The Universal Control Hub (UCH) [openURC 2013a] described in Chapter 2, is a good middleware example because it allows the pluggable user interfaces and it is based in Universal Remote Console URC standard [ISO/IEC 2008]. Another remarkable benefit of the UCH is that is capable to include all the different communication protocols of the AAL environments.

e) **Activity Management System**. This system provides support to the end user in order to accomplish complex tasks, for example in AAL systems, either by scheduling and executing those tasks automatically or by providing ways to guide the users through such tasks. This module is particularly important because many users, such as people with cognitive impairments, may have to be assisted in the interaction with AAL environments. Typically, activity management systems implement a task engine [Rich 2009], and the modeling of tasks is represented by task models [ANSI/CEA 2008].

f) **Pluggable User Interfaces**. A set of pluggable user interfaces are needed in order to empower the different users to interact with the corresponding AAL environment. Different types of Pluggable User Interfaces can be envisaged, such as: i) personalised pluggable user interfaces for end users with special requirements, ii) generic pluggable user interfaces for wide audiences, and iii) automatically generated pluggable user interfaces in order to provide interaction means that can be adapted on the fly.

4.5.2 Contribution 2: Engaging and realistic telerehabilitation for elderly people

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

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

Figure 4.4. User interface design to provide telerehabilitation services to the elderly people [Epelde 2014a].

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

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

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

Implementation and validation

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

Functional layout

The work proposed succeeded in demonstrating that telerehabilitation services can be adapted to new use contexts such as telerehabilitation by elderly people at home. The results obtained can be generalized in order to include all possible tele-health or tele-care services, end users and use context. The new architecture proposed is depicted in Figure 4.5.

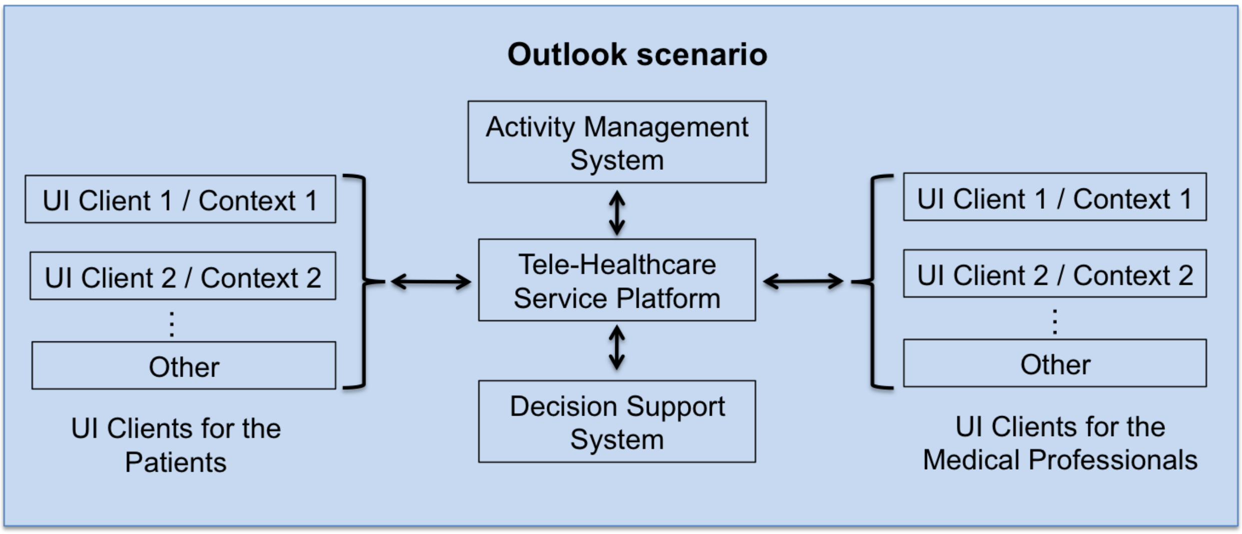

Figure 4.5. Functional layout of tele-health/care service architecture.

As illustrated in Figure 4.5, to accomplish this new goal the following modules are needed:

d) **Tele-Healthcare Service Platform**. The service platform, typically hosted in the cloud, stores all healthcare data including the therapies and exercises prescribed by the doctors and the monitored/feedback data of the different sessions conducted by the patients at the environment of their preference (home, on-the-go, on travel,...).

e) **Patient UI Clients**. These UI clients include software and hardware components. Hardware can be TV, smartphone, tablet or PC computers. The software includes therapy information, avatars (or other interaction modalities are also possible), and the communication modules to the tracking and health monitoring devices and to the service platform. The Universal Control Hub (UCH) could be used in the client to provide pluggable user interfaces concept based on the Universal Remote Console URC standard [ISO/IEC 2008].

f) **Medical UI Clients**. They can be developed analogously to the ones provided for the patients. In this way, doctors can benefit as well of the multicontext and personalized access to healthcare services. They can use different devices to access the system (laptop, tablet, ...) and use it from different environments (at the hospital, from home,...).

g) **Activity Management System**. This system is intended to provide support to the patients in order to accomplish the telerehabilitation sessions. The healthcare sessions are modeled using task models, and then the task models are run in the UIs. This module is particularly relevant for users with special needs, such as people with cognitive impairments, that may have to be assisted in their healthcare sessions.

h) **Decision Support System.** This component would support the healthcare professionals in the management of the healthcare data generated by the system, since the system could overload the doctors with data coming from the patients. Hence, in order to increase the performance of the medical team. an intermediate component which analyses the data, detects anomalous situations and triggers the corresponding alarms would be needed. The technologies described at Chapter 3 “Decision Support” could be used to develop this component.

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

A system called Rehabilitation Centre has been designed to meet the challenge described at section 4.4.3. The Rehabilitation Centre provides the user with the necessary virtual reality games to carry out the rehabilitation exercises. While the user is doing the exercises, the system monitors and records multimodal data. On the one hand, a webcam records the user for an offline analysis of the movement (see Figure 4.6). On the other hand, joint’s movement data is recorded for a more exhaustive study of the exercises carried out by the user. Joint’s movement data is later processed and presented graphically by visualisation tools.

Figure 4.6. Stroke patient using the Rehabilitation Centre [Epelde 2013d].

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

The Games Module is the responsible for capturing the movement data from the Armeo, for graphically representing the user movements and for implementing the games' logic. The data is processed translating it into the movements of the virtual arm. For the virtual arm movement generation, skeletal animation techniques have been used. These techniques mainly consist on dividing the model in two parts for animation development: the skin representation, and the hierarchical interconnection of bones. In order to develop a realistic arm model, skinning technique has been used. This technique consists of associating the bones with the vertices. In some cases, the vertices can be associated to more than one bone, therefore, weights are established so the vertices act as real as possible. Figure 4.7 shows the representation of the developed virtual arm. Arm's skeleton is represented in green, while the vertices are identified by the purple colour. The virtual arms' representation has six degrees of freedom (DOF): two in the shoulder, two in the elbow and two in the wrist, which allows representing arm's movements with high fidelity.

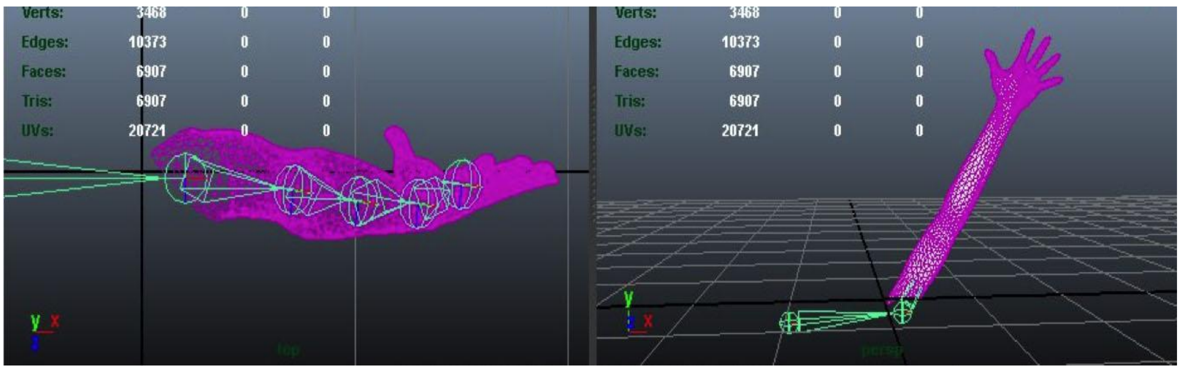

Figure 4.7. Virtual arm representation (skeleton in green and vertices in purple) [Epelde2013d].

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

With the aim of providing the user with a more entertaining rehabilitation process, several games have been developed. The games are based on object reaching and grasping tasks. These tasks have been selected because they are repeatedly used in users' daily living activities. Figure 4.8 shows a game in which the subject has to grasp a glass of water and to approach it to his mouth to simulate the process of drinking.

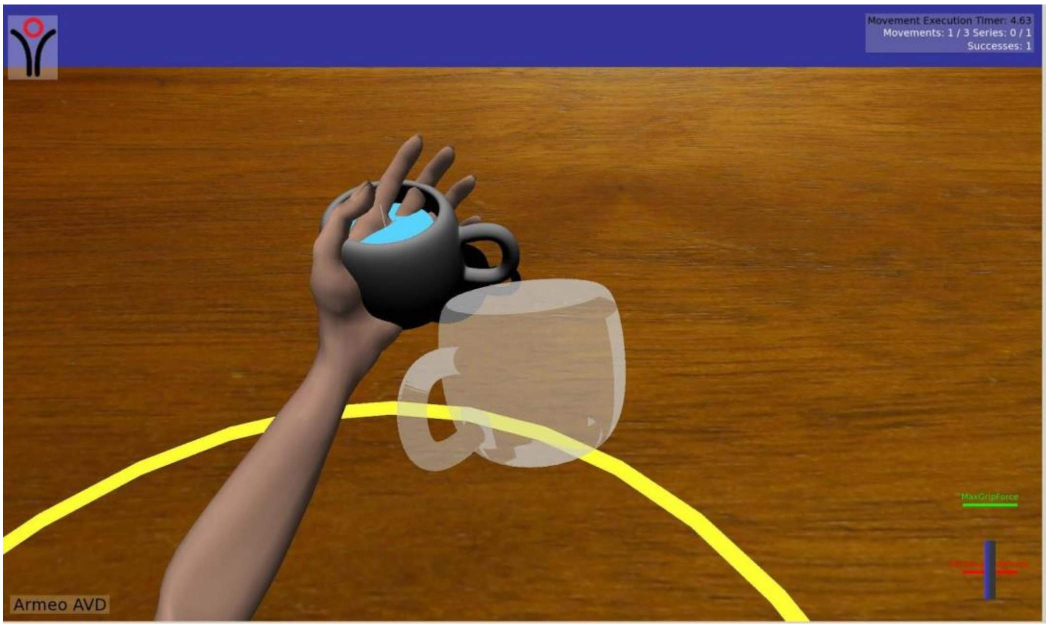

Figure 4.8. Example of the reaching and grasping rehabilitation game.

Implementation and validation

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

Functional layout

The work proposed in this section succeeded in demonstrating that immersive telerehabilitation services can be developed to new use contexts such as stroke telerehabilitation. In the same way as in previous sections, the results obtained can be generalized in order to adapt different health services, end users, exoskeletons and use context. The architecture proposed at Figure 4.5 is valid in the stroke telerehabilitation context as well. Particularly, in this case the clients for the patients will include: i) immersive virtual reality games, and ii) communication with the exoskeletons that track and assist the user. In this architecture, the Universal Control Hub can be installed in the clients to provide plug-and-play game connectivity (to the user interface) and to the robot.

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

An innovative system for the safe and autonomous navigation of blind and partially sighted people based on binaural audio guidance is proposed, which also covers pre-journey activities for journey planning and post-journey activities including sharing experiences and recommendations. The architecture of the ARGUS autonomous navigation concept is depicted in Figure 4.9.

Figure 4.9. Architecture of the ARGUS autonomous navigation system for blind people [Carrasco 2014a].

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

Implementation and validation

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

Functional layout

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

4.6 Discussion on the results and future work

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

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

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

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

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

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

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

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

5 Chapter 5. Conclusions and further work

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

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

5.1 Contributions vs. Application Sectors

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

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

Technologies\Applications	***Univer. Access.***	***Assistive Products***	***Decision Support***
URC/UCH	**C**	S	N
Pluggable User Interfaces	**C**	S	N
Avatars	N	**C**	N
Binaural sounds	N	**C**	N
Communication systems (videoconference, ...)	N	**C**	N
Dialog systems	S	**C**	S
Monitoring Systems	S	**C**	S

Home Automation	**C**	**C**	S
Adaptive User Interfaces	**C**	S	S
Ubiquitous User Interfaces	**C**	S	S
User Profiling Techniques and Standards	**C**	**C**	S
Knowledge Representation Techniques (ontologies,...)	S	S	**C**
Experience Representation Techniques (SOEKS, DDNA, ...)	S	S	**C**
Reasoning and Continuous Learning Techniques	S	S	**C**

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

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

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

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

5.2 Contributions vs. Users' Needs

As it was highlighted in Section 1.1 "Thesis motivation", there are a number of needs that current assistive products in the market do not meet in many cases, such as, for example, minimum training, or adaptation to context of use. Table 5.2 presents an analysis carried out to identify the mapping between the main needs of the users and the technologies presented in this Thesis that could be used to solve them.

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

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

5.3 Closing remarks

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

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

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

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

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

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

5.4 Future work

In order to make the Smart Assistive Systems come true, research has to continue in a number of lines. Next, the most relevant future research efforts are described.

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

application development frameworks, and iii) user interface and target adaptor repositories for public download.

2. **Standardized Universally Accessible Online Services Specification**. The concept of applying the Universal Remote Console (URC) framework to online services, such as the Web services and in particular to those described by the Web Service Description Language (WSDL) needs to be continued. This approach will help in the adoption of the URC technology for online services, and thus make personalized and pluggable user interfaces widely available for Web services.

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

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

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

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

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7 Appendix 1 Relevant projects

PROJECT: **I2HOME – Intuitive Interaction for Everyone with Home Appliances based on Industry Standards** FP6 – 033502 (http://www.i2home.org/)

FUNDING ENTITY: European Commission – FP6 IST – 2005-2.5.11 eInclusion

DURATION From: September 2006 To: December 2009

COORDINATOR: Dr. Jan Alexandersson, DFKI

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

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

PROJECT: **VITAL – Vital Assistance For The Elderly** FP6 – 030600 (http://www.ist-vital.org/)

FUNDING ENTITY: European Commission – FP6 IST – 2005-2.5.11 eInclusion

DURATION From: September 2006 To: December 2009

COORDINATOR: Dr. Jan Alexandersson, DFKI

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

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

PROJECT: **HYPER – Hybrid Neuroprosthetic and Neurorobotic Devices for Functional Compensation and Rehabilitation of Motor Disorders** (http://www.car.upm-csic.es/bioingenieria/hyper/)

FUNDING ENTITY: Ministerio de Ciencia e Innovación, CONSOLIDER-INGENIO 2010

DURATION From: January 2010 To: December 2015

COORDINATOR: Dr. José Luis Pons, CSIC

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

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

PROJECT: **EREHAB Plataforma Ubicua Multidispositivo de Telerehabilitación Personalizada** ETORGAI 2011, ER-2011/00036

FUNDING ENTITIES: Bilbomática, S.A., Baleuko, Ikusi-Angel Iglesias, STT Ingeniería y Sistemas, Teccon Ingenieros S.L., & Vilau Media.

DURATION From: January 2011 To: December 2011

COORDINATOR: Eduardo Carrasco, Vicomtech-IK4

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

The author had a double role in the project as the Coordinator of the Project and Researcher on Human-Computer Interaction. The most relevant publications achieved from project results are: [Epelde 2014a], [Epelde 2013b], & [Epelde 2012a]

PROJECT: **ARGUS – Assisting personal guidance system for people with visual impairment** FP7-288841 (http://www.projectargus.eu/)

FUNDING ENTITY: European Commission – FP7 – ICT – 2011 - 7

DURATION From: October 2011 To: July 2014

COORDINATOR: Dr. Oihana Otaegui, Vicomtech-IK4

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

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

PROJEC: **MIND – Abordaje Integral de la Enfermedad del Alzheimer** (CENIT-20081013) (http://www.portalmind.es/)

FUNDING ENTITY: Bilbomática y eMedica.

DURATION From: December 2008 To: December 2011

COORDINATOR: Dr. Vicente Belloch, ERESA

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

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

PROJECT: **LIFE – Desafío integral al cáncer de mama** (INNPRONTA IPT-20111027) (http://www.proyectolife.es/)

FUNDING ENTITY: Bilbomática.

DURATION From: December 2011 To: December 2014

COORDINATOR: Dr. Vicente Belloch, ERESA

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

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

8 Appendix 2 Thesis most relevant publications

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

8.1 Publications on Universal Accessibility

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

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

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

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

8.2 Publications on Clinical Decision Support

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

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

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

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

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

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

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

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

8.3 Publications on Assistive Technologies

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

The works described in this paper were carried out along the I2HOME (FP6-33502) project. In this paper, the study was focused on the adaptation and tailoring of Avatars to people with mild to high cognitive impairment. More in detail, the experiment was conducted using the Avatar on TV prototype developed in I2HOME, in order to engage in short dialogs and deliver short messages to elderly people with mild to severe Alzheimer's Disease (AD). The goal was to simulate a personal home assistant (the Avatar) who would deliver short and simple instructions or housekeeping messages, such as, "the entry door is open", "the oven is on", "the washing machine has finished the programme". The validation was carried out by INGEMA on a sample of 20 participants with astonishing results. Most subjects were able to understand correctly and follow the instructions given by the Avatar, even in cases of severe dementia. Further analysis of the data by INGEMA showed that participants with better cognitive and functional state, measured by a specific set of neuropsychological and functional tests, significantly performed better fulfilling the TV tasks. Hence, it was concluded that neuropsychological assessment may be used as a useful complementary tool for the assistive technologies adaption for the elderly with different cognitive and functional profiles. Finally, it was considered proven that even people with severe cognitive impairment can successfully interact with IT whenever tailored user interfaces are provided to them. Related relevant research was carried out in [Carrasco 2009], [Carrasco 2008] & [Carrasco 2007], [Murua 2010] & [Zimmermann 2010].

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

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