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Architecting Smart Home Environments for Healthcare: A Database-Centric Approach

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Abstract

The development of system architectures and applications for smart homes and ambient assisted living has been the main activity of a number of academic and industrial research projects around the world. Existing system architectures for smart environments usually employ different architectural styles in a multi-layer logical architecture to support the integration and interoperation of heterogeneous hardware and software technologies, which are subsequently used to provide two major functionalities: monitoring and assistance. It is also usual among existing architectures that the database management system is the most common but the least exploited architectural component, existing in the periphery of the system and devoted exclusively for data storage and retrieval. However, database technology has advanced and matured considerably over the years, and, as a result, current database management systems can be and do more.

This thesis considers the hypothesis of several features of modern database management systems being employed to address functional (e.g. well-being and security monitoring, automated control, data processing) and non-functional (e.g. interoperability, extensibility, data security and privacy) requirements of smart environments, i.e. the database management system serves as a platform for smart environments. The scope of this thesis is therefore to investigate the possibility of using different features supported by database management systems to create a database-centric system architecture for the development of smart home environments and ambient assisted living. The thesis also investigates the development of applications for health monitoring and assistance: 1) a serious game for fall prevention that assists people in practicing Tai Chi at home, and 2) a non-intrusive home-based method for sleep assessment.

The event-driven architecture of active databases, extensions for in-database processing, and built-in mechanisms for inter-process communication are technical features of some modern database management systems. These features are explored in this thesis to address general functional aspects of smart environments, such as monitoring, processing, coordination and control of various types of events in a given environment. Extensibility and security features and cross-platform capabilities of database management systems are employed to accommodate non-functional, but still technical, properties of smart environ-

ments, including interoperability, extensibility, portability, scalability, security and privacy. Heterogeneous technologies are integrated into the system using programming language and platform independent software resource adapters. Interoperation among integrated technologies is mediated in an active database.

The feasibility of the proposed database-centric system architecture was pragmatically investigated with the development of a "smart bedroom" demonstrator and with the implementation of a number of short-term and long-term types of services to support active aging, aging in place and ambient assisted living. In the proposed architecture, active in-database processing maintains sensitive data within the database. This increases data security and independence from external software applications for data analysis. Changes in the system are managed during runtime, which improves flexibility and avoids system downtime. The proposed system architecture was evaluated taking into account different application scenarios and heterogeneous computing platforms.

As a conclusion, modern database management systems support features that can be successfully employed in a database-centric system architecture to effectively and efficiently address functional and non-functional requirements of smart environments.

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List of Publications

This thesis consists of a collection of five papers. Throughout the thesis, the papers are referred to as Papers I, II, III, IV and V.

Appended Publications

Paper I

W. O. de Morais and N. Wickström. A Serious Computer Game to Assist Tai Chi Training for the Elderly. In *Proceedings of the 2011 IEEE 1st International Conference on Serious Games and Applications for Health (SeGAH)*, pages 1-8, 2011.

Paper II

W. O. de Morais and N. Wickström. A lightweight method for detecting sleep-related activities based on load sensing. In *Proceedings of the 2014 IEEE 3rd International Conference on Serious Games and Applications for Health (SeGAH)*, pages 1-7, 2014.

Paper III

W. O. de Morais and N. Wickström. A "Smart Bedroom" as an Active Database System. In *Proceedings of the 2013 IEEE 9th International Conference on Intelligent Environments (IE)*, pages 250-253, 2013.

Paper IV

W. O. de Morais, J. Lundström, and N. Wickström. Active In-Database Processing to Support Ambient Assisted Living Systems. *Sensors*, 14(8): 14765-14785, 2014.

Paper V

W. O. de Morais and N. Wickström. Evaluation of Extensibility, Portability and Scalability in a Database-centric System Architecture for Smart Home Environments. Technical Report, Halmstad University, 2015. Available at `http://urn.kb.se/resolve?urn=urn:nbn:se:hh:diva-29141`.

Related publications

- J. Lundström, W. O. de Morais, and M. Cooney. A Holistic Smart Home Demonstrator for Anomaly Detection and Response. In *Proceedings of the 2015 2nd IEEE PerCom Workshop on Smart Environments: Closing the Loop*, pages 330-335, 2015.
- W. O. de Morais, M. Mayr, N. Wickström, and R. Philippsen. Ambient Intelligence and Robotics: complementing one another to support Ambient Assisted Living. In *Proceedings of Workshop and Tutorials of the 2014 13th Intl. Conf. on Intelligent Autonomous Systems (IAS13) and 2014 1st Intl. Workshop on Intelligent Robot Assistants (IRAS)*, pages 197-199, 2014.
- W. O. de Morais, J. Lundström, and N. Wickström. A Database-Centric Architecture for Home-Based Health Monitoring. In *Ambient Assisted Living and Active Aging*, Springer, pages 26-34, 2013.
- W. O. de Morais and N. Wickström. Sleep and night activities of care beneficiaries at the "Trygg om Natten" (Safe at Night) Project. Technical Report, Diva, Halmstad University, 2013. Available at `http://urn.kb.se/resolve?urn=urn:nbn:se:hh:diva-24030`
- W. O. de Morais, A. Sant'Anna, and N. Wickström. A wearable accelerometer based platform to encourage physical activity for the elderly. *Gerontechnology*, 7(2):181, 2008.

Awards related to this thesis

- **Winner of the Doctoral Colloquium Award**
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Chapter 1

Introduction

Smart homes aim at interconnecting heterogeneous home-based digital technologies to offer functionalities that enhance the comfort, entertainment, safety and security of the residents. Ideally, a smart home is an integrated system that monitors the function of the household and learns the habits and preferences of the residents in order to anticipate their needs or help them in making informed decisions [Wilson et al., 2014].

There have been an increasing number of academic and industrial research projects in recent decades towards the development of smart home technologies for healthcare purposes, in particular to assist older and disabled people living alone. Important application areas of smart homes in the healthcare domain include rehabilitation, assisted living, and continuous health and activity monitoring [Acampora et al., 2013].

Considering current demographic changes, the financial and human resources that are available and future demands for healthcare, smart homes provide a domestic technical infrastructure that has the potential to enable and support active aging [WHO, 2002], aging in place [Marek and Rantz, 2000] and the recent concept of ambient assisted living (AAL) [van den Broek et al., 2010]. These initiatives focus on strategies that:

- Promote healthy and preventive lifestyles;
- Help older and disabled individuals to live longer, more safely and independently in a residence and community of their choice;
- Support formal and informal caregiving;
- Move healthcare from traditional healthcare environments (e.g. hospitals) to the home;
- Reduce costs in healthcare.

Despite the potential benefits, the cost, fitness for purpose, user friendliness and trustworthiness are still not evident for homeowners and are well documented barriers for the adoption of smart home technologies [Dewsbury et al., 2003; Balta-Ozkan et al., 2013]. Moreover, the evolving diversity of people's needs and preferences, as well as the heterogeneity and dynamicity of home environments and involved technologies, lead to a number of technical challenges that hinder the development of smart homes and AAL systems in real life. For example, the task of incrementally integrating and extending heterogeneous smart home technologies that must interoperate in a reliable and secure way is challenging. Several authors remark [Edwards and Grinter, 2001; Nehmer et al., 2006; Eckl and MacWilliams, 2009; Brush et al., 2011; Wilson et al., 2014; Mennicken et al., 2014] the following technical challenges for smart homes:

- **Integratability and Interoperability:** due to the lack of standards;
- **Extensibility and Scalability:** due to the evolving diversity of individual needs, technologies and environments;
- **Security and Privacy:** due to the different actors and technologies involved and sensitivity of data;
- **Dependability:** due to life-threatening consequences;
- **Usability:** due to individual needs, capabilities and preferences.

Besides the above mentioned aspects and challenges, another critical issue associated with the development of complex distributed systems, such as smart environments, is the system architecture [Oussalah, 2014]. Therefore, and for the most part, this thesis proposes and investigates the feasibility of a database-centric architecture for smart home environments and AAL. The main hypothesis is that database management systems incorporate features that enable these types of systems to function as a platform for smart home and AAL applications. It also concerns the development of assistive and monitoring applications for smart environments in healthcare.

Following this introduction, Section 1.1 presents the main research problems investigated. Section 1.2 introduces the research approach and Section 1.3 the main contributions. A summary of each of the appended publications is given in Section 1.4. The structure of the remainder of the thesis is outlined in Section 1.5.

1.1 Problem and Research Questions

1.1.1 System Architecture for Smart Home Environments

Platforms for smart homes and AAL typically follow different architectural paradigms in a multi-layer logical architecture to support the integration and interoperation of heterogeneous technologies and the development of a variety of monitoring and assistive application scenarios [Becker, 2008; Fagerberg et al., 2010; Brink et al., 2013]. Moreover, storage and processing of short- and long-term data are important requirements in these applications. Among existing system architectures, the database management system is the most common architectural component. However, despite the advancements in database technology, modern database management systems are devoted exclusively to data storage and retrieval.

Hence, *it is the hypothesis of this thesis that modern relational database management systems can i) serve as a platform for the implementation, deployment and management of smart homes and AAL applications, and ii) address functional (e.g. monitoring, data processing, control) and non-functional (e.g. interoperability, extensibility, security and privacy) requirements of such smart environments.* This thesis therefore poses and attempts to answer the following questions:

- *How should a database-centric system architecture be designed to support smart home environments and AAL applications?*
- *How should the functional and non-functional requirements of smart environments in a database management system be accommodated?*

1.1.2 Smart Home Technologies in Healthcare

This thesis is also interested in approaches to the development of smart home technologies for unobtrusive and continuous monitoring of the residents' health and for assistance for overall well-being. These are among the main applications of smart homes in healthcare [Demiris and Hensel, 2008]. For example, beds equipped with sensors can provide contactless and semi-constant home-based assessment of sleep patterns and fall risks, and monitoring of other health-related parameters [McGrath and Scanaill, 2013]. Moreover, digital gaming technology is being increasingly integrated into the AAL domain [AAL JP, 2013]. These digital games are commonly referred to as serious games and are games that have, besides the entertainment aspect, real-life purposes (e.g. education, training) [Zyda, 2005].

This thesis implements different smart home technologies to improve comfort, enhance independence and support continuous care, in particular home-based sleep monitoring and assessment. The thesis also introduces a serious *game for home-based fall prevention*. Therefore, the following questions are investigated:

- *How to incorporate knowledge about normal sleep and load sensing into a method to detect sleep-related activities and patterns?*
- *How to accommodate the requirements for home-based rehabilitation games (e.g. customization, on-line feedback, follow-ups, easy set-up) in the proposed serious game for home-based fall prevention?*

1.2 Research Approach

To address the questions posed in Section 1.1, literature studies were combined with a pragmatic and exploratory approach concerning the design, implementation and evaluation of proof of concept prototypes for smart home and AAL systems. Such an approach is a common research methodology in ubiquitous computing [Bardram, 2008] and is based on the construction of working prototypes to ensure functional and non-functional properties in the face of the details of the real world [Weiser, 1993].

Much of the exploratory work originated from the collaboration with the Centre for Health Technology Halland at Halmstad University (HCH)[1]. The collaboration resulted in technology demonstrators, such as the "Smart Bedroom", that are hosted at HCH for permanent exhibition and demonstration[2]. Evaluations with data involving real-life situations have been made for most of the methods and contributions presented. However, no usability studies involving end-users (e.g. residents, caregivers) and developers have been conducted to evaluate developed applications that have been developed and the proposed system architecture.

1.3 Contributions

This thesis focuses on and contributes to the research in Computer Science and Engineering with approaches for their application in the healthcare domain. A summary of the main contributions follows.

In the computer science and engineering domain:

- Design and development of a novel database-centric system architecture that employs a database management system as a platform for smart home environments and AAL applications. The feasibility of the proposed approach was evaluated with the implementation of demonstrators.

[1] http://hch.hh.se
[2] http://hch.hh.se/6/259.html

- Design of a model for abstracting and integrating heterogeneous hardware and software technologies into the proposed architecture. The model was implemented in different programming languages and tested in different operating systems.

- Design of a serious game to measure the similarity between gestures presented by a virtual instructor and the imitated gestures performed by the player. The feasibility of the proposed approach was tested with the implementation of a computer game demonstrator.

- Design of a finite-state machine to detect sleep-related activities by combining characteristics of normal sleep and features of load sensing signals. The approach was implemented and tested with a dataset containing load cell data collected in real homes.

Considering applications of information and communication technologies in the healthcare domain:

- Development of different smart home and AAL technology demonstrators. For example, a “Smart Bedroom” was implemented and provides services to improve comfort, enhance independence and support continuous care. AAL-related services support short- and long-term monitoring, such as bed entrance and exit detection and nighttime behavior monitoring.

- Development of a computer game for fall prevention that assists individuals in practicing Tai Chi.

- Development of a home-based measurement system for unobtrusive and continuous monitoring and assessment of sleep-related activities.

1.4 Publications

This thesis consists of a collection of five papers, Papers I, II, III, IV and V. This section presents a high-level overview of the main contributions of each paper.

- **Paper I:** introduces a method for developing serious games for home-based computer-assisted fall prevention.

  The objective was to reduce the requirements for complex equipment, processes and settings during the development and use of serious games in healthcare. The approach was demonstrated by the implementation of a serious game for home-based fall prevention: a virtual Tai Chi instructor assists older people in practicing Tai Chi at home on their own.

During the development of the game, a camera and wearable wireless inertial measurement units (WIMUs) are employed to record and measure body movements, such as of an instructor training Tai Chi. In a subsequent off-line process, images and signals that are collected are segmented in time and used to create gesture templates and a virtual instructor. The sum of the absolute difference between adjacent recorded images is used in the segmentation process to detect and discriminate in time segments corresponding to postures and gestures.

During the gameplay, the player is challenged to mimic the virtual instructor. The player's body movements are also measured with WIMUs in the gameplay, and a flexible distance measure technique, known as longest common subsequence (LCSS), is used to compute on-line the similarity between the ongoing gestures with a known pre-recorded gesture template of the virtual instructor. The computed similarity is presented to the player as a score, indicating how well the player reproduced the movements. The LCSS technique allows matching two sequences by tolerating some elements to be unmatched in time (sequence length), space (sequence amplitude) or both. Such tolerance can be used to overcome small sensor displacements and time lags while measuring gestures. The time and space parameters can be adjusted and are used to control the difficulty of the game. The lower the tolerance in time and space, the more difficult the game.

Alternative approaches commonly employ WIMUs and vision-based motion capture systems and techniques to classify or recognize Tai Chi gestures. These require complex equipment and settings that are not convenient in a home environment. Moreover, considerable amounts of data might be needed to train the system.

- **Paper II:** introduces a finite-state machine to detect sleep-related activities and patterns.

  As an alternative to labor-intensive clinical-based procedures, such as polysomnography, the purpose of **Paper II** was to develop a home-based tool for non-intrusive detection of sleep-related activities.

  The proposed finite-state machine combines known characteristics of normal sleep (e.g. changes in muscle tone) with signal processing of a strain gauge load cell. Normal sleep is a cyclic process that alternates between phases of low and non-existent muscle activity. Given a bed instrumented with load cells, voluntary and involuntary sleep-related body movements generate distinct disturbances in the load cell signal. Features extracted from the signal are combined with a priori knowledge about normal sleep and then employed to define the conditions for the FSM transitions or state changes. The states indicate whether the person is in bed or not and, if in bed, whether the person is awake or cycling between sleep phases.

The approach was tested with a dataset collected in real homes of older people receiving nighttime home care services. Sleep-related activities and patterns of 7 individuals were identified. Because no formal validation of sleep parameters was conducted in **Paper II**, it is best described as a proof of concept.

- **Paper III:** introduces the approach of employing a database management system as a platform for smart homes and AAL applications. The paper also presents the development of smart environments as active database systems.

  The aim was to explore database technologies not only for data storage purposes but to create a database-centric architecture for smart environments. In the proposed architecture, the logic for governing the smart environment (e.g. monitoring, processing and control) is contained in the database management system.

  The integration of different technologies is achieved with resource adapters, which are simple software applications abstracting hardware and software technologies present in the system. Resource adapters serve as gateways between the environment and the active database system.

  The extensibility capabilities of database management systems and the event-driven architecture of active databases are employed to support the on-line reactive behavior of smart environments. The aforementioned features of database management systems also provide the means to create a database interface that protects stored data by exposing a high level interface for data access and manipulation (select, insert, update and delete).

  The interoperability among heterogeneous technologies is handled inside the active database.

  On the whole, the integration and interoperation of heterogeneous technologies are facilitated and the feasibility of the proposed approach was evaluated with a real implementation of a "Smart Bedroom" demonstrator, which provide services to improve comfort (e.g. automatic lighting), enhance independence (e.g. functional monitoring and assistance) and support continuous care (e.g. physiological monitoring) .

- **Paper IV:** extends **Paper III** and explores the extensibility capabilities of database management systems to address other requirements of smart environments, such as data processing and analysis, data security and privacy, and system maintenance.

The objective was to process events that indicate personal activity changes in the active database rather than exporting and loading data into an external software application for analysis.

Smart home environments developed as active database systems can detect and respond to events taking place in the home environment. Modern database management systems can be extended with user-defined data types and functions that operate just as built-in database objects. These enable the semantics of domain-specific applications to be integrated and executed in the database management system and allow adding in-database analytical capabilities to database engines. Built-in database mechanisms for authentication and authorization can reinforce data security and privacy.

The above mentioned database mechanisms were experimentally evaluated with the development of three distinct AAL services to enhance nighttime caregiving and tested with a dataset collected in real homes. Implemented in-database services include: i) detecting bed entrances and exits, ii) discovering transition probabilities of events happening during the night and iii) modeling of early night behavior using decision trees.

Together, active databases and in-database processing avoid transferring sensitive data outside the database for analysis. Because the domain logic is centralized in the database management system, code maintenance is facilitated and, as changes are managed on the fly, the approach can reduce system downtime.

- **Paper V:** evaluates non-functional properties, such as the extensibility, portability and scalability of the proposed database-centric architecture.

  Although **Papers III** and **IV** report on the practical feasibility of the proposed approach, little was known about extending, porting and scaling the whole system architecture to different computing platforms. In an attempt to evaluate these system properties, **Paper V** employs a method that encompasses: i) extending the system with three different test scenarios (data storage, reactive behavior, and advanced data processing), ii) porting the system architecture and applications to different computing platforms and iii) evaluating scalability by incrementally adding more processes corresponding to a given test scenario. Evaluation results allowed identifying which components in the database-centric architecture become performance bottlenecks when extending, porting and scaling the system.

1.5 Outline

The remainder of the thesis contains four chapters organized as follows:

Chapter 2: presents an overview and the potential of the main features of modern database management systems.

Chapter 3: presents an overview of smart home environments and the main associated challenges. The different architectural styles employed in existing system architectures, middleware and platforms supporting current smart home environments and AAL systems are also presented. Given the background and related work, Chapter 3 introduces the database-centric system architecture by describing how different mechanisms provided by modern database management systems are put together to address functional and non-functional requirements of smart environments. Chapter 3 also presents how the feasibility of the proposed architecture was evaluated with the development of different smart home and AAL applications.

Chapter 4: exposes future healthcare challenges related to the ongoing demographic change towards a growing aging population. Given the importance of smart home technologies in health monitoring and assistance, Chapter 4 highlights the purpose, method, results and technical contributions associated through the development of home-based applications, such as for sleep assessment and fall prevention.

Chapter 5: covers concluding remarks highlighting the main benefits and limitations of the contributions as well as potential directions for future research.

Chapter 2

Database Technology: Features and Possibilities

"[...] there is not one aspect of modern business that has avoided the need to collect, collate, organize and report upon data" [Hill, 2013].

2.1 Overview

An organized and indexed collection of data is called a database. To make data storage and retrieval more efficient and reliable, database management systems (DBMS) provide features to create, manage and administer databases, as well as mechanisms for concurrency control, access authorization and recovery. Due to their maturity and robustness, database management systems are commonplace.

In particular for relational DBMS, a standardized declarative language called Structured Query Language (SQL) is used to generate statements or queries, which contain operations to define and manipulate database objects (e.g. tables) and stored data. SQL statements for data definition operations contain commands to create, alter and drop database objects. SQL statements for data manipulation operations include commands for creating, reading, updating and deleting (CRUD operations) data in the database. When a SQL statement is sent to the DBMS, the DBMS parses and syntactically checks the validity of the SQL statement. The DBMS also manages data access permissions and ensures that the client issuing the SQL statement has the right privileges for accessing the objects associated with the request. The DBMS query processor will execute the SQL statement only if all these requirements are satisfied.

Database Extensibility

Database management systems may not completely follow or implement the SQL standard. However, DBMS commonly implement SQL extensions, known as SQL dialects, that contain features for more procedural control (e.g. conditional and loops structures) and complex processing (e.g. math and string operations) than standard SQL. Database management systems may also let developers create their own SQL extensions, such as user-defined types, user-defined aggregates, user-defined functions and stored procedures. These allow the semantic or logic of a domain-specific application to be implemented, stored, executed and managed in the DBMS. This means that, besides data storage and retrieval, DBMS can incorporate facilities for in-database data processing, including advanced algorithms, such as methods for statistical analysis and machine learning.

SQL extensions are managed on the fly without requiring system restarts and can subsequently be included and executed within SQL statements and vice versa. User defined SQL extensions might be created using standard SQL, SQL dialects and other programming languages, such as C, Java and Python.

Active Databases

The SQL standard also defines constructs, known as database triggers or active rules, that provide an in-database event-driven architecture to detect and respond to data definition and manipulation operations. These operations represent events that are happening either inside or outside the DBMS itself. Database systems exploiting active rules are called active databases [Paton and Díaz, 1999]. Database triggers are event-condition-action (ECA) structures, meaning that when an event occurs, the condition is evaluated and, if it holds, an action is executed. The action can be executed before or after a data definition and manipulation operation (e.g. after a table insertion and/or update). The action invoked by a database trigger is commonly implemented as user-defined functions or stored procedures. Active rules allow developers to transfer the reactive behavior from the application to the DBMS. As a result, the reactive semantics is both centralized and handled by the DBMS in a timely manner. Active databases can also reduce the need of client applications to periodically query the database for data changes.

Security and Privacy

Database management systems support different features for protecting the database against unauthorized access and manipulation. Client applications connecting with a DBMS must inform the login credentials (e.g. user name and password) of an existing database user. Database management systems use authentication mechanisms to check and confirm the identity of the informed user attempting to connect and access a database. The connection itself can be secured by encrypting the communication between the client and the DBMS. Besides password-based authentication, modern DBMS enable stronger types of authentication, such as network and certificate-based authentication services. Modern DBMS also provide authorization mechanisms to control the users' access privileges or permissions. These authorization mechanisms enable database administrators to grant or revoke access privileges to a user or to a group of users using different granularities. For example, a database user might be granted access privileges to only one database managed by the DBMS. Another example is to grant access privileges for individual database objects (e.g. tables, functions, stored procedures) in a particular database. Granted privileges might enable the user to read data but not to modify them.

2.2 PostgreSQL

As an example of an DBMS that supports the aforementioned features, PostgreSQL [The PostgreSQL Global Development Group, 2015] is a cross-platform, free and open source object relational DBMS that complies with the SQL standard and implements its own SQL dialect, PL/pgSQL (Procedural Language/PostgreSQL).

As an example of an SQL extension, PostgreSQL provides a built-in asynchronous publish-subscribe mechanism for inter-process communication. These mechanisms are the NOTIFY (publish), LISTEN (subscribe) and UNLISTEN (unsubscribe) commands. In conjunction with database triggers, inter-process communication mechanisms can be employed to notify client applications of particular data changes in the database. This event-driven notification approach relieves client applications of periodically querying the database for data changes, i.e. avoids database polling. Finding an optimal polling interval is difficult and periodic database polling mechanisms can be inefficient (e.g. too many intermittent connections and queries due to a short polling interval) and inaccurate (e.g. delayed detection and response due to a long polling interval). Such an asynchronous communication method, i.e. publish-subscribe, requires client applications to maintain an open connection with the DBMS and to subscribe to a particular notification channel.

In PostgreSQL, SQL extensions can be implemented in SQL, PL/pgSQL, Python variants and C. Moreover, SQL extensions are incorporated into PostgreSQL through dynamic loading, i.e. loaded on demand and on the fly [The PostgreSQL Global Development Group, 2015]. SQL extensions adding in-database analytical capabilities for PostgreSQL are also available. For example, MADlib [Hellerstein et al., 2012] is an open-source library package that implements established methods for supervised learning (linear and logistic regression, decision trees and support vector machines), unsupervised learning (k-means clustering and association rules) and descriptive statistics.

2.3 Beyond Data Storage and Retrieval

Several authors investigated the feasibility of implementing different statistical models and machine learning techniques such as SQL extensions. The authors reported that in-database data processing is more efficient than exporting data sets to external software application for data analysis and data mining, leading to significant gains in performance and improved data security [Sarawagi et al., 2000; Cohen et al., 2009; Ordonez, 2010].

The concept of active databases, in particular the concept of ECA rules, was combined with temporal-reasoning and explored to detect events happening in a smart home, as well as to distinguish and anticipate potentially unusual or hazardous situations [Augusto and Nugent, 2004].

In an alternative to a continuous query model, i.e. database polling, Vargas et al. [2005] described the integration of active databases with the publish-subscribe communication paradigm so that database clients can subscribe to events of interest.

Although SQL extensions offer flexibility for data manipulation, SQL statements containing SQL extensions are typically incompatible between different DBMS. Moreover, despite the benefits of active in-database processing, user-defined functions and database triggers can be hard to debug and test [Ceri et al., 2000; Sarawagi et al., 2000].

Chapter 3

Smart Home Environments

3.1 Overview

Advances in electronics, wireless communication and sensor and actuator technologies are enabling researchers and engineers to bring the concept of ubiquitous computing into reality. Introduced by Mark Weiser in the early 1990's, ubiquitous computing, which later has also become known as pervasive computing, is a computing paradigm in which ubiquitously deployed networked smart objects continuously, and unobtrusively, support people in different kinds of activities and needs [Weiser, 1991].

In ubiquitous computing, miniaturized information and communications technologies (ICT) are integrated into physical environments and objects. As a result, things become smart and unnoticeably capture, communicate or react to events happening in their surroundings. Ubiquitous and pervasive computing involves many areas of computer science, including distributed systems, artificial intelligence, human-computer interaction and sensor networks, and leverages paradigms such as mobile and wearable computing [Satyanarayanan, 2001]. As a result of further advancements in ICT and ubiquitous computing, several related concepts have emerged, such as the concepts of smart environments and ambient intelligence (AmI).

Smart environments are physical spaces that integrate a diverse range of sensors and actuators, along with other types of network-enabled devices, to acquire and apply knowledge about the environment and its occupants, so that their experience in that environment is enhanced [Cook and Das, 2007].

Similarly, the concept of AmI refers to a multidisciplinary approach that combines ubiquitous computing, ubiquitous networks and intelligent user interfaces to offer a digital environment that is sensitive and responsive to the presence of people [Ducatel et al., 2001]. More specifically, AmI comprises the mechanisms that intelligently orchestrate the pervasive infrastructure of smart environments, providing an intelligent environment that sensibly supports and assists people [Augusto et al., 2013].

The concept of smart home is the most typical example of smart environments and applications of AmI in a domestic environment. As an extension of home automation, smart homes attempt to integrate different home-based smart objects (e.g. consumer electronics, appliances, furniture) to offer new or advanced functionalities to residents, such as enhanced safety and security, care and comfort, as well as the opportunity to reduce energy use [van Berlo, 2002].

Home automation can be described as home-based systems that can be remotely controlled by the resident or pre-programmed with fixed rules to function without human intervention. Home automation is characterized by islands of functionalities [Bierhoff et al., 2007], i.e. separate systems from different vendors control only one aspect of the home, such as safety (e.g. smoke detectors), security (e.g. motion activated alarms) and comfort (e.g. timer activated heating systems, motion activated lighting systems, multimedia entertainment systems). Moreover, there is no single interface to control these systems and no overall view of their operational state.

Smart homes deal with more than the automation of domestic tasks [Gann et al., 1999]. Smart homes are ideally controlled by an artificial type of reasoning mechanism that takes into account the current and past states of the environment and its occupants to learn and anticipate needs, and perform actions in the environment that are in accordance with the residents' preferences. Such an artificial reasoning mechanism acting on behalf of people is not present in home automation.

Aldrich [2003] suggests a five-level hierarchical classification for smart homes. According to the author, the simplest type of smart home includes single and stand-alone intelligent objects. In the second class, intelligent objects communicate and are able to exchange information to increase their functionality. In the third class in the hierarchy, objects and services in a connected home can be remotely accessed and controlled. The next class comprises smart homes that are able to learn the activity patterns of its residents and anticipate their needs. In the last class, the home system constantly monitors the residents, the objects and their interaction to control technology on behalf of the occupants.

Eventually, and therefore different from home automation, smart home technologies will not need to be directly programmed or controlled by the residents. The Adaptive Home project [Mozer, 1998] is a pioneer in implementing the vision of smart home systems that can learn and self-program. To reduce the burden of programming home automation, the adaptive control of home environments (ACHE) system programmed and controlled itself by monitoring the habits of the resident and predicting daily routines in order to increase comfort and manage energy use.

Learning about the residents' behavior and intentions to automatically control and adapt the environment was also investigated in other smart home projects, such as intelligent Dormitory (iDorm) [Hagras et al., 2004] and Managing an Adaptive Versatile Home (MavHome) [Das et al., 2002].

The Aware Home is a smart home that is continuously aware of its state and the activity and location of the people in the home, i.e. context-aware [Kidd et al., 1999]. Context is described as “any information that characterizes a situation related to the interaction between users, applications, and the surrounding environment” [Dey et al., 2001].

In recent decades, smart homes have continuously been suggested as a platform to support the concept of ambient assisted living (AAL), which aims at fostering intelligent and transparent forms of monitoring and assistance to older and disabled individuals [van den Broek et al., 2010].

3.2 Challenges

Despite the number of initiatives and proofs of concepts in the areas of smart homes and AAL in the last decades, there are still several challenges that hinder the opportunity for providing smart home environments.

People have unique needs and preferences that vary over time. Furthermore, adverse health conditions may cause sudden changes in a person’s habits and functioning. The onset, cause and extent of these changes vary considerably from person to person [Berleen and Watson, 2004]. As a consequence, **extensibility** and **scalability** problems may arise when adapting applications for a new scenario.

Heterogeneous hardware and software technologies are employed to cater to or accommodate people’s needs. These technologies come from different manufacturers, have distinctive characteristics and capabilities, and operate and communicate using different, often competing, standards and protocols. Different wired and wireless communication standards exist only for home automation [Withanage et al., 2014]. Homes also differ, and thus no universal selection, arrangement of devices and system configuration will fit every home environment or household.

Integratability and **interoperability** issues come as a result of these, as well as data heterogeneity, which prevent data and information exchange between different systems, hindering the cooperation between existing technical resources in the environment. Although the use of standards is the common approach to achieve interoperability, manufacturers might not be interested in a uniform approach because it can lead to a loss of control of the provided device or system [Wartena et al., 2009].

Privacy and **security** are other issues associated with the use of technology [Nixon et al., 2004]. People care about their privacy and are very concerned about technologies that can monitor or take control of different aspects of their lives. Ideally, smart objects disappear in the environment [Weiser, 1993] and may silently collect, process and communicate information without people's awareness and consent [Kang et al., 2010]. People are also concerned about who will have access to data that are collected and technologies in the home [Cook, 2012].

Usability is also an issue. Certain technologies are perceived as invasive and obtrusive, while others are hard to use or to maintain (textiti.e. require technical skills) and, as a consequence, are not accepted or adopted [Brush et al., 2011]. People are also afraid of technology replacing human care.

A far more important fact is that individuals might be dependent on the technology to cope with different kinds of impairments and limitations. Thus technology's **dependability** or **trustworthiness** is imperative, in particular where technical support is not immediately available [Dewsbury et al., 2003; Balta-Ozkan et al., 2013].

3.3 Related work

Inside automated homes, smart homes and AAL systems, devices (e.g. appliances, sensors, actuators) communicate and are controlled via a diverse range of communication standards, including X10[1], Z-Wave[2] and ZigBee[3]. Although these are among the most common standards to integrate devices into the home network, they are not cross-compatible. Integration platforms like openHAB[4] and openRemote[5] implement software gateways to translate one protocol to another.

Several platforms have been created to facilitate the development, use and maintenance of smart homes and AAL systems [Fagerberg et al., 2010]. Moreover, various underlying software architectures have been proposed to handle issues associated with the integration and interoperation of devices and systems, usability of tools and applications, privacy and security of resources, and extensibility, scalability and dependability of platforms and systems [Becker, 2008]. A recent review focusing on existing AAL frameworks, platforms, standards and quality attributes is presented in [Memon et al., 2014].

Software platforms for smart environments are typically designed following a multi-layer architecture combined with other types of basic architectures, such as service-oriented architecture (SOA), peer-to-peer architecture (P2P), event-driven architecture (EDA) or publish-subscribe (PubSub) architecture, component-connector (C2) architecture and multi-agent system (MAS) architecture, among others [Becker, 2008]. An important component in smart homes and AAL platforms is the middleware, which is a software layer that makes

[1] www.x10.com. Accessed on April 2015.
[2] www.z-wavealliance.org. Accessed on April 2015.
[3] www.zigbee.org. Accessed on April 2015.
[4] www.openhab.org. Accessed on April 2015.
[5] www.openremote.org. Accessed on April 2015.

the heterogeneity, distribution and complexity of hardware and software components in the system as transparent as possible [Zhang et al., 2008].

The MavHome [Youngblood et al., 2005], CASAS [Cook et al., 2013] and iDorm [Hagras et al., 2004] projects are examples of adoption of a multi-layer agent-based system architecture. Both the MavHome and CASAS projects integrate devices using proxies or bridges that encapsulate device drivers and libraries. These projects also simplify the interoperation of devices and services by relying on a homogenous networking infrastructure and on a publish-subscribe communication middleware.

A more common design approach is to architect systems around a service-oriented middleware that abstracts devices and functional system capabilities as software components that provide services to other components. Interoperability, platform independence, loose coupling between service providers and consumers, and composition and reuse functionalities are benefits of using SOA [Lewis et al., 2011].

Service-oriented technologies include web services, service protocols like UPnP[6](Universal Plug and Play) and service frameworks like OSGi[7] (Open Services Gateway initiative), and are typically used to implement middleware systems for smart homes and AAL.

For example, the Gator Tech Smart House [Helal et al., 2005] built a service-oriented multi-layer middleware using OSGi to facilitate the programming of smart home systems.

AmI infrastructures such as Amigo [Vallée et al., 2005] incorporated service frameworks, web services, web semantics and agent-technology into a SOA middleware to provide dynamic integration and interoperation of heterogeneous devices and services.

The OASIS (Open architecture for Accessible Services) [Bateman et al., 2009] project provides an ontology framework to simplify the integration and interoperation of services.

A service-oriented multi-layer approach was adopted in the MPOWER (Middleware platform for eMPOWERing cognitive disabled and elderly) [Stav et al., 2013] project as well, which also implemented security mechanisms, such as access control, and standards in the health domain to provide secure interoperation between services from different healthcare providers.

To ensure the interoperability of devices, components and services in the platform, the PERSONA (PERceptive Spaces prOmoting iNdependent Aging) [Fides-Valero et al., 2008] project proposed an OSGi-based middleware that supports message brokering using communication buses.

The universAAL (UNIVERsal open platform and reference Specification for Ambient Assisted Living) [Tazari et al., 2012] is OSGi-based SOA platform

[6]www.osgi.org. Accessed on April 2015.
[7]www.upnp.org. Accessed on April 2015.

proposed to consolidate the results of previously developed platforms, such as MPOWER, PERSONA, and SOPRANO, among others.

The aforementioned projects are only a few examples of platforms, and many others exist. As a consequence, selecting one or more platforms for the development of smart homes and AAL is difficult.

Antonino et al. [2011] evaluated six well-known AAL platforms, including PERSONA and universAAL, according to quality attributes, such as reliability, security, maintainability, efficiency and safety, which are treated as equally important. Authors identified that all the selected platforms are based on the OSGi framework and rely on its mechanisms to handle reliability and maintainability (changeability and installability) issues. Due to the use of the OSGi framework, all six platforms require the Java Virtual Machine (JVM) and use a database management system. Resource consumption and communication overhead tend to be slightly high. Security is typically addressed using encryption, while access control is managed with the concept of roles.

Safety is the least addressed quality attribute. Platforms typically do not include mechanisms, such as redundancy, to support safe execution and increased availability. With the exception of universAAL, all the other platforms contain a single point of failure.

Fabbricatore et al. [2011] compared AAL platforms such as Amigo and PERSONA with a platform developed by the authors, and noted that security is the major issue that is not addressed.

3.4 Database-Centric System Architecture

A novel method to approach the challenges associated with the development of smart home environments and AAL systems is to design such systems following a database-centric architecture. To implement an approach of this kind, a modern DBMS, such as PostgreSQL, was employed as a platform for the development, deployment and management of smart environments, and to address functional and non-functional requirements. A high-level overview of the architecture is shown in Figure 3.1.

The aforementioned database-centric architecture is introduced in **Paper III**. The feasibility of the proposed approach is also investigated in **Paper III** with the implementation of a "Smart Bedroom" demonstrator. In **Paper IV**, mechanisms for in-database processing are explored in order to implement distinct AAL services. **Paper V** evaluates non-functional properties of the architecture, including extensibility, portability and scalability.

The proposed database-centric system architecture is composed of a set of independent software components, called resource adapters, which communicate with a central DBMS, referred to in the architecture as an active database. The main architectural components are described in the next sections, as are

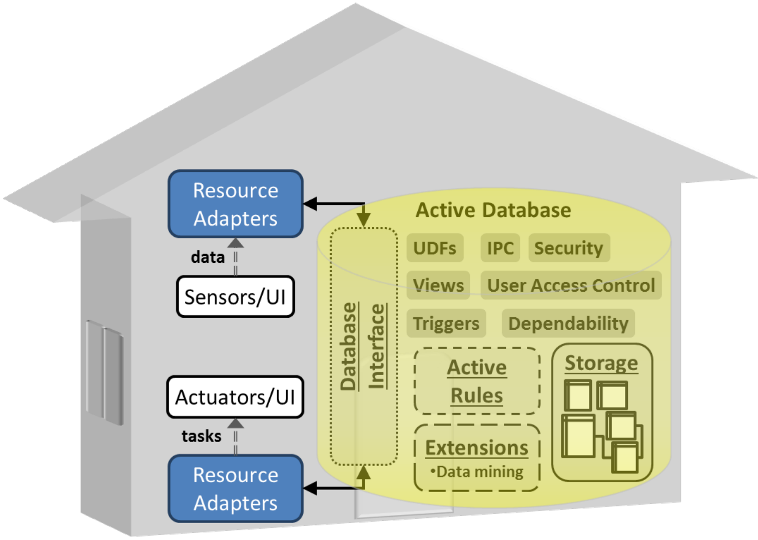

Figure 3.1: An overview of the integrated database-centric architecture. Resource adapters and the active database are the two main architectural components.

approaches to investigating the feasibility of the approach introduced to support smart environments.

3.4.1 Main Architectural Components

Resource adapters

Paper III introduced the concept of resource adapter and described it as software components used to encapsulate the communication logic of heterogeneous hardware (e.g. sensors, actuators, appliances) and software (e.g. user interfaces, software libraries, script and speech engines, services from other platforms) technologies, providing a software interface to *integrate* these into the system. Hence, any resource in the environment (e.g. device, application, service) is abstracted as a resource adapter, which can also be employed to create virtual devices for simulation purposes.

The functionalities of a resource adapter are limited to:

(a) streaming to the active database data that have been acquired by sensors, entered by the user, or generated by external applications, and

(b) receiving notifications from the active database to control actuators, update user interfaces, or inform external applications about the occurrence of an event of interest.

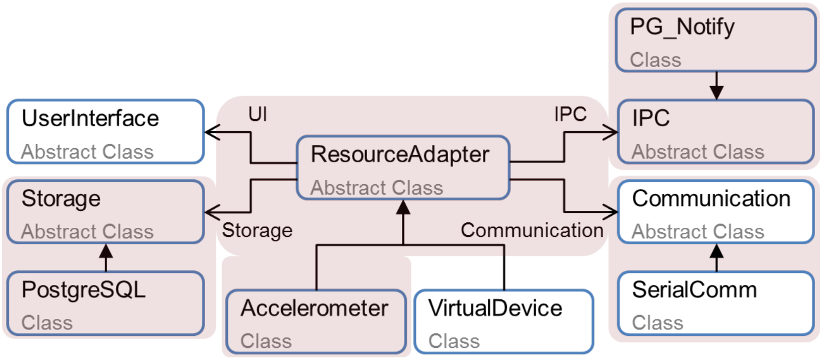

Figure 3.2: The class diagram describes the structure of a resource adapter. As an example, the highlighted area delimits the associated classes and subclasses of a resource adapter for a Bluetooth-enabled accelerometer device.

Therefore, a resource adapter acts as a lightweight (small consumption of computational resources and not complex) gateway between the environment and the active database.

The class diagram in Figure 3.2 gives a static view of a resource adapter and the main classes that compose such an architectural component. In the same diagram, the Storage class encapsulates methods for accessing the Database Interface in the active database. The UserInterface class provides a component for the design of user interfaces. The IPC class abstracts interprocess communication mechanisms used by the active database to notify resource adapters. The Communication class encapsulates the underlying communication standard (e.g. Bluetooth) of a resource.

Resource adapters do not intercommunicate and are not aware of the existence of other resource adapters. The *interoperation* between resource adapters is therefore managed by the active database. Moreover, resource adapters do not interact directly with the tables in the active database but by invoking methods in the database interface provided by the active database.

A hybrid communication model (client-server and publish-subscribe) is used in the interaction between resource adapters and the active database. To invoke methods for inserting or querying data from the active database, resource adapters employ a client-server computing model. To avoid connection overhead in the client-server model, resource adapters abstracting resources generating data at high sampling rates maintain a continuous connection with the active database. Otherwise, intermittent connections are used. To receive notifications from the active database, the resource adapter uses a publish-subscribe pattern and a continuous connection with the active database is required. To improve *security*, communication between resource adapters and the DBMS can be encrypted.

A universally unique identifier (UUID) is assigned to each individual resource adapter in the system. The UUID given also identifies the communication channel used by the active database to publish notifications specific to a resource adapter, i.e. one-to-one notification. The active database also has its own UUID and corresponds to a global channel to which all resource adapters must subscribe, so the active database can notify all resource adapters more efficiently, i.e. a one-to-many notification.

The model for implementing resource adapters, illustrated in Figure 3.2, is programming language independent but the Storage class depends on a data provider to connect to the underlying DBMS supporting the active database. As a consequence, resource adapters are hosted in computer platforms supporting the data provider (e.g. Npgsql[8], Psycopg[9]) for the selected DBMS. Currently, resource adapters have been implemented in C# and Python. Listings 3.1 and 3.2 present the code for instantiating the Bluetooth-enabled accelerometer resource adapter previously exemplified in Figure 3.2.

Code Listing 3.1: Instantiation of a resource adapter in C#.

```
ResourceAdapter resource = new AccSCA3000();
resource.ResourceID = args[0];
resource.Communication = new communication.SerialComm();
resource.IPC = new ipc.PostgreSQLIPC();
resource.Storage = new storage.PostgreSQL();
resource.Initialize();
```

Code Listing 3.2: Instantiation of a resource adapter in Python.

```
resource = base.SCA3000Acc()
resource.uuid = argv[0]
resource.comm_module = communication.SerialComm()
resource.ipc_module = ipc.PG_Notify()
resource.storage_module = storage.PostgreSQL()
resource.initialize()
```

Active Database

The active database is the most important component in the architecture. In the active database, database objects such as tables, views, triggers, user-defined functions (UDFs), and mechanisms for interprocess communication (IPC) and access control are employed to provide functionalities grouped into four related modules called storage, database interface, active rules and database extensions.

In this thesis, the active database was implemented using the PostgreSQL DBMS and the motivation for this choice is based on its features, previously presented in Section 2.2.

[8] www.npgsql.org. Accessed on April 2015.

[9] initd.org/psycopg. Accessed on April 2015.

The relational model in Figure 3.3 illustrates the main tables in the storage module and is described as follows (the alphabetic listing corresponds to the legends in Figure 3.3):

(a) Information about resources available in the environment;

(b) Corresponding resource adapter configuration;

(c) Location of resources in the environment;

(d) Notification mechanisms;

(e) Configuration of active rules associated with a particular resource;

(f) Data received or sent to resource adapters, as well as derived information;

(g) Support tables for in-database processing.

In the proposed architecture, each resource adapter has a corresponding table in the active database to store collected data or actions performed, or both. Developers implementing resource adapters do not have access to the internal storage model but to the database interface, which offers a programming interface with a set of methods for data access and manipulation (select, insert, update and delete), The database interface also contains the logic to provide syntactic *interoperability* among resource adapters. Database views, UDFs and IPC mechanisms are used to create the database interface, which is also used to notify client applications connected to the active database and that subscribed to particular channels of interest. To provide further *security* and *privacy* to internal database objects, authorization policies use the concept of roles to control or limit the access to functionalities in the database interface. By default, a new database user has no access privileges to database objects until the user is assigned to a particular role.

In the active rules module, database triggers, UDFs and IPC mechanisms are employed to support the reactive behavior of smart environments, i.e. to detect and respond to events taking place in the environment. These are particularly investigated in **Paper III**.

The sequence diagram in Figure 3.4 attempts to illustrate the runtime behavior of the system in a reactive scenario. The process starts with the initialization of resource adapters. This entails: i) loading configuration parameters (e.g. serial port, IP address) from the active database, ii) connecting to target device (e.g. motion sensors, light switch receivers) and iii) subscribing communication channels specific to the resource adapter (i.e. one-to-one) and global-to-all resource adapters (i.e. one-to-many). In the same diagram, the next sequence in the process corresponds to the reactive behavior and starts when a particular event is detected by the sensor. The resource adapter abstracting the sensor streams the event to the active database via the database interface. A sequence of active rules is triggered to handle the detected event.

If the trigger condition holds, a task must be sent and performed by the actuator. As a result, the database interface notifies the resource adapter abstracting the actuator about a particular task to be executed. The notification received is acknowledged by the resource adapter. Figure 3.4 can also describe the in-database interoperation between a given sensor and an actuator.

The database extensions module takes advantage of UDFs to perform in-database processing, i.e. the DBMS is extended with the logic to process stored data. This logic may correspond to the semantics of an application or method for machine learning, as presented in **Paper IV**. Improved *security* is an outcome of this, because no sensitive information is transferred to the outside of the active database. The overall approach facilitates the *portability* of resource adapters across distinct computing platforms as well as *extension* and *main-*

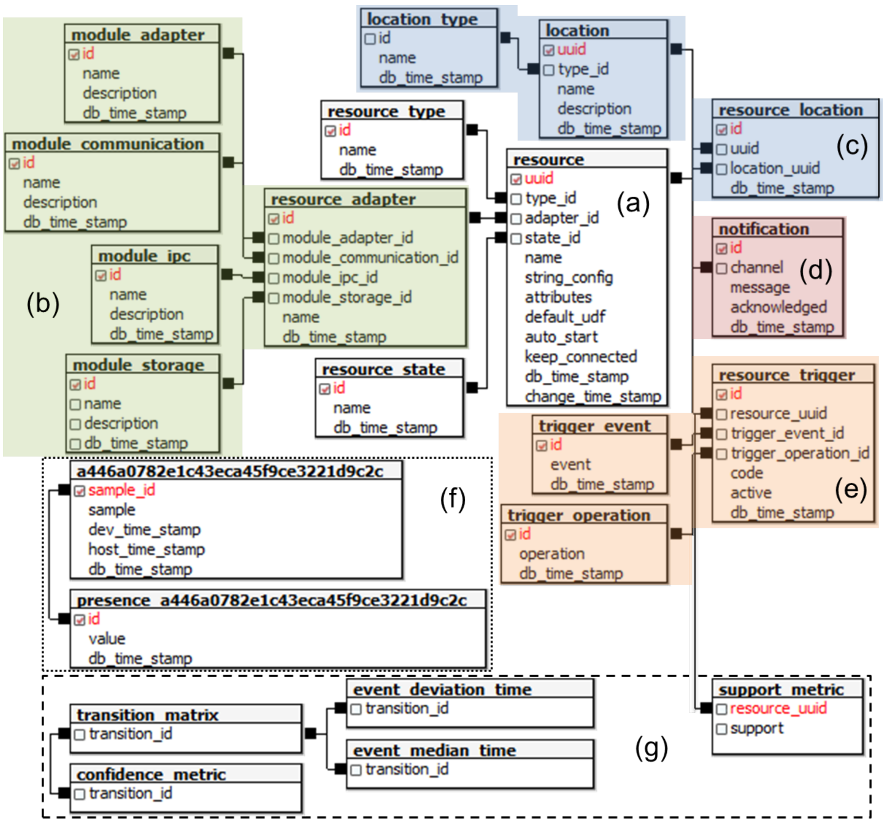

Figure 3.3: A simplified relational model of the storage module. The number of tables, similar to (f) and (g), grows as the number of resources or functionalities implemented in the system grow.

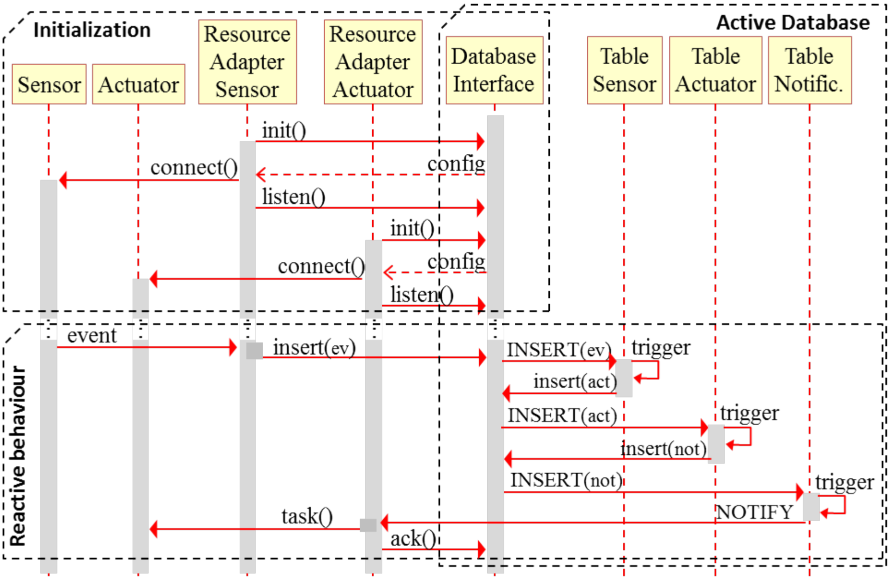

Figure 3.4: Sequence diagram for a reactive scenario. The diagram illustrates the interaction between i) resource adapters and the active database, ii) resource adapters and given devices (e.g. a sensor and an actuator) and iii) the sequence of operation in a reactive scenario.

tenance of functionalities because most of the functional logic is implemented in the active database. **Paper V** investigates such non-functional properties.

3.4.2 Feasibility Investigation

The feasibility of the proposed database-centric architecture and the use of a database management system as a platform for the development, deployment and management of smart home environments and AAL applications were investigated in **Papers III, IV** and **V**.

In **Paper III**, the feasibility of the proposed approach is proven with a concrete implementation of a “Smart Bedroom” demonstrator, which was developed as an active database system. In the demonstrator, resource adapters are employed to encapsulate and integrate different sensor and actuator technologies into the system, including an electric adjustable bed equipped with load sensing capabilities. **Paper III** emphasizes how heterogeneous technologies can interoperate through the active database, how active rules can support the reactive behavior of smart environments and how the proposed approach facilitates sharing and reuse of technical resources for different applications of their original purpose or application domain.

Paper IV investigates the use active in-database processing and database extensions for machine learning methods to support the development of home-based healthcare applications and to avoid disclosure of sensitive information. In the active database, active rules have been implemented to detect bed exits and to trigger the computation of transition probabilities of events happening during the night, which are used detect expected patterns and anomalies. **Paper IV** also investigates the use of MADlib to model sensor triggering transitions over a certain time span during the night. The MADlib implementation of the C4.5 algorithm was used to produce a decision tree that models early night behavior of older people living alone. The implemented services presented in **Paper IV** have been trained and validated with a dataset collected in real homes, and the overall approach attempts to analyze activity patterns and changes in the database management system rather than exporting and loading data into an external tool for data analysis. This can lead to improved performance, security and privacy.

Although **Papers III** and **IV** present the implementation of a number of different functionalities it was not known how the proposed architecture would behave when resource adapters and the active database are ported to different operating systems on distinct hardware platforms or when the number of deployed functionalities grows. To provide more insight about the feasibility of using a relational database management as a platform for smart home and AAL applications, **Paper V** evaluates the scalability of the proposed database-centric architecture on three heterogeneous computing platforms. Results reported in **Paper V** enabled identifying the maximum number of deployed functionalities executing concurrently on the three computing platforms. Results also showed which components in the system are most affected when the computational workload is increased.

Chapter 4

Smart Home Technologies in Healthcare

4.1 The Challenge for Tomorrow's Healthcare

Population projections estimate that in the next 40 years, the largest part of the global population growth will be among people aged over 65 [United Nations, 2013]. By the year 2050, about 16.5% of the world population is expected to be in that age group, and this is twice as large as today's number. By the same year, approximately one out of every four citizens in Europe will be 65 years and above.

In late adulthood, the incidence of chronic diseases (e.g. heart failure, dementia, diabetes, hypertension) and problems (e.g. falls, sleep disorders) increases and highly compromises a person's ability to live independently [Berleen and Watson, 2004]. For example, fall accidents and related injuries are common among older adults. Fear of falling is also a problem and limits the performance of daily routines, which may reduce mobility and physical strength, which in turn increases the risk of falling [Moylan and Binder, 2007]. Not all falls result in injuries, but most hip and wrist fractures are caused by falls and one out of five individuals reporting fall incidents require hospitalization and medical attention [Gillespie et al., 2003]. Tai Chi programs are effective in preventing and reducing the number of falls, improving balance and mobility, and in decreasing the fear of falling [Chang et al., 2004].

Sleep disorders are also common among older people [Phillips and Ancoli-Israel, 2001]. Older individuals typically report difficulties in falling asleep and maintaining sleep, early-morning awakening and excessive daytime sleepiness [Neubauer, 1999]. Sleep disorders are often associated with decreased quality of life, depression and increased risk of falling [Neikrug and Ancoli-Israel, 2009].

Hence, the ongoing demographic change towards a growing aging population can be translated to an increasing demand and cost for healthcare and social services because several individuals will be dependent on informal or professional care to maintain some level of independence [Berleen and Watson, 2004].

Several strategies emerged with the objective of better allocating resources and addressing future needs for healthcare and social services. For example, aging in place is a concept implying the ambition to enable individuals to continue at the residence of their choice in later adulthood, being safe and independent for as long as possible [Marek and Rantz, 2000]. Many individuals prefer to remain in their own homes throughout their lives, and some home modifications (e.g. removal of slippery surfaces and steps, bathroom aids) may help with that [Kochera et al., 2005]. Focusing on preventative policies and activities that encourage physical and mental health, as well as social participation, the concept of active ageing is defined as "the process of optimizing opportunities for health, participation and security in order to enhance quality of life as people age" [WHO, 2002].

Home care has become an integral part of health systems as an approach to preventing unnecessary institutionalization, maintaining older and disabled individuals in their familiar surroundings as long as possible [Tarricone and Tsouros, 2008]. Home care typically includes services and activities that promote health, prevent diseases, support rehabilitation and assist with household duties, personal care and socializing.

Although the aforementioned initiatives can help individuals to grow old and live in good health and be more independent in their own homes and societies, current healthcare and social systems, especially across European countries, face a shortage of financial and human resources, particularly in professionals specialized in geriatric and home care, which may lead to an increase in unmet healthcare needs and quality in the near future [Genet et al., 2012].

Over the past decades, there has been an increased interest in developing and employing home-based information and communication technologies (ICT) for healthcare purposes, primarily at-home monitoring and assistive technologies to support aging, disability and independence [Mann, 2005]. Rialle et al. [2002] refer to this as health "smart" homes.

4.2 Related Work

During the last decades, there has been a growing number of academic and industrial research initiatives towards the use of smart home technologies in healthcare, in particular to attend to future healthcare demands of a growing and aging population of older adults and because of the possibility to improve quality of life, alleviate costs, and enhance and complement healthcare delivery [Royal Society, 2006].

Although the outcomes and cost effectiveness of smart home technologies in healthcare are still not evident [Martin et al., 2008], in general these systems represent an alternative to current high-cost institution-based healthcare practices and have the potential to help people to live longer and independently in their own homes [Morris et al., 2013]. Home-based healthcare technologies can also avoid intermittent clinic-based assessments and labor-intensive procedures while conveying objective information for prevention and diagnosis [Wild et al., 2008].

Most research on smart home technologies in healthcare includes solutions for functional, safety, security and physiological monitoring as well as cognitive and social assistance [Demiris and Hensel, 2008].

In the literature, well known and influential smart homes supporting active ageing and aging in place include living laboratory houses such as the Aware Home [Kidd et al., 1999], House_n/PlaceLab [Intille, 2002; Intille et al., 2005], GatorTech Smart House [Helal et al., 2005] and CASAS [Rashidi and Cook, 2009] projects. A number of review papers on smart homes projects and related technologies and applications in healthcare have been published in the past years [Demiris and Hensel, 2008; Chan et al., 2008; Tomita et al., 2010; Kim et al., 2012].

In the "Aging In Place" project [Rantz et al., 2005], several apartments in a senior-living facility, known as TigerPlace, were equipped with sensors to monitor the activity levels and sleep patterns of the residents. The objective was preventing or detecting falls and alerting caregivers of emergency situations [Rantz et al., 2008].

Also in collaboration with real assisted living facilities, researchers at Oregon Health and Science University equipped beds with load sensing technology to conduct unobtrusive sleep assessment [Adami et al., 2003]. The same research group also investigated the use of unobtrusive smart home technologies, including digital games, to assess mobility problems and cognitive impairments in the homes of 265 older individuals for almost three years [Kaye et al., 2011].

In Europe, most smart home projects in healthcare are under the umbrella term of ambient assisted living (AAL), which includes the concepts of active ageing and aging in place. AAL also embraces technology-based solutions to support and complement formal caregiving (e.g. nurses) and informal caregiving (e.g. partner, relatives), as well as tools to enable remote healthcare services (e.g. telerehabilitation, telemonitoring). A summary of emerging technologies (e.g. smart homes, mobile and wearable devices, assistive robots) and services for older adults in the AAL domain is presented in [Rashidi and Mihailidis, 2013].

Innovative developments in healthcare are progressively adopting digital games in prevention and rehabilitation [Rego et al., 2010; Bartolome et al., 2011]. Gaming technology is also being increasingly integrated into the AAL domain [AAL JP, 2013]. The concept of serious games originated from the use of digital games for other purposes than entertainment [Zyda, 2005], and the main motivation behind such an approach is that video games are effective in engaging players and influencing attitudes and behaviors [Wortley, 2014].

In particular for older people, serious games can bring positive outcomes in fall prevention and balance rehabilitation [Clark and Kraemer, 2009; Prosperini et al., 2013]. Although further research is needed to examine the effectiveness of serious games in the healthcare context, positive results confirm the importance of such area and the need for further research [Baranowski et al., 2013].

For example, therapists could create and customize a rehabilitation games during a session with the patient, who can later play the game at home, as suggested in [Alankus et al., 2010; Pirovano et al., 2013].

4.3 Applications

4.3.1 The "Smart Bedroom" Demonstrator

Ideally, smart home technologies are attractive to people when they are young and supportive of them as they age [Coughlin, 1999]. To be attractive, smart homes must, at a low initial cost, integrate home-based technologies and provide personalized services while preserving the privacy of the residents. In order to be supportive to older adults, smart homes must be extensible enough to evolve as individual needs and preferences evolve over time. **Paper III** describes how such a vision can be realized and presents a "Smart Bedroom" demonstrator implemented following the database-centric system architecture. The presented approach takes advantage of existing technical resources in the home (e.g. electric adjustable beds, passive infrared motion sensors, remotely controllable on/off switches), and reuse or expand their capabilities to offer services to improve comfort, enhance independence and support continuous care. Implemented functionalities target not only the resident, but also caregivers and healthcare professionals. Bed exit detection, automatic light switching at night, weight, sleep and vital signs monitoring are a few examples of services developed in the demonstrator.

4.3.2 Home-based Monitoring Services for Nighttime Caregiving

In 2011, the "Trygg om natten" (Safe at night in English) project investigated how technology could assist home care beneficiaries and caregivers during nighttime supervision [Thörner et al., 2011]. Each home of 15 nighttime home care beneficiaries living alone was equipped with passive infrared sensors to detect motion in the home and contact magnetic switches to detect door openings, and could sense doors and windows openings and closings. Moreover, each participant's bed was equipped with an occupancy sensor as well as with load cells to measure weight. One of the outcomes of the project was a set of requirements for AAL services to complement nighttime caregiving, including detecting whether the resident was in bed and identifying common activity behaviors in the home during the night. The purpose, implementation and evaluation of these services are presented in **Paper IV** and are summarized as follows:

- **Bed presence or absence detection**
  This service has the potential to enable the night patrol team to remotely check whether individuals are in bed so nighttime home care visits would not disturb residents during their sleep. By analyzing the variance of load cell signal, an in-database method was implemented and successfully detected the presence or absence of the residents in bed.

- **Common event transitions during the night**
  This service attempts to detect abnormal activities by discovering associations between sensor events, such as bed entrances and exits and motion detections in rooms (e.g. bathroom and kitchen). Strong associations indicated common transitions (e.g. bed-exits are followed by motion detections in the bathroom), and deviations from such associations could enable the detection of anomalies.

- **Modelling early night behavior using decision trees**
  This service could be used by the caregiver to discover changes or trends in activity patterns, which can describe the level of independence of the resident being monitored. Decision trees have been used to model typical sensor event transitions and to identify and discriminate patterns that are more common from 10 p.m. to midnight than the ones from midnight to early morning.

4.3.3 Home-based Sleep Monitoring and Assessment

As an alternative to clinical-based, labor-intensive, expensive and obtrusive routines for sleep assessment, such as polysomnography, **Paper II** presents a home-based system for unobtrusive and continuous monitoring and assessment of sleep-related activities and patterns, such as awakenings, wakefulness, and sleep atonia. The approach presented relies on a finite-state machine that combines known facts about sleep with statistical features extracted from the signal of a load cell placed in the top left corner of a bed. The facts about sleep [Carskadon et al., 1994] are:

- During normal sleep, non-rapid eye movement (NREM) and rapid eye movement (REM) sleep states alternate cyclically across a sleep episode;

- Body movements usually precede REM episodes;
- NREM sleep is characterized by low muscle activity;
- REM sleep is characterized by muscle atonia, (i.e. absence of muscle activity).

Considering the bed equipped with load sensing capabilities, when the bed is occupied by a person, voluntary and involuntary body movements generate disturbances in the load cell signal. These disturbances are not present in the signal when the bed is unoccupied or loaded with static weight. Therefore, by computing the moving mean and moving standard deviation over a window of the load cell signal, a finite-state machine can continuously detect not only bed entrances and exits but also periods of high and low muscle activity of a person resting in the bed. As a consequence, a finite-state machine can be constructed to detect sleep-related activities. The state machine contains four finite states described as follows:

- **Bed Out state:** in this state the bed is unoccupied. The mean and the standard deviation of the signal are lower than estimated threshold values for these two features.
- **Awake state:** in this state the bed is occupied and the occupant is awake. The standard deviation of the signal is high and is associated with high muscle activity.
- **Atonia state:** in this state the bed is occupied and muscle activity is low or absent, which characterizes a state of sleep.
- **Awakening state:** in this state the bed is occupied and muscle activity has started to increase.

Besides revealing the above described states, the state machine also enables detecting bed entrances and exits, the time interval in each state and the estimation of sleep related parameters, such sleep latency and sleep efficiency (i.e. the ratio between the total time in the sleep atonia state and the total time in bed).

The dataset containing load cell data was collected during the “Trygg om natten” [Thörner et al., 2011] project and was used in this work to evaluate the proposed method for sleep monitoring and assessment. Results achieved are preliminary and might have been constrained by the fact that only one load cell was used to measure the load in the bed. Although the method still needs to be validated against polysomnography, the approach has the potential to enable remote sleep monitoring of individuals that require nighttime supervision [Thörner et al., 2011].

4.3.4 A Serious Game for Fall Prevention

Falls are a major health issue among older adults. Fall prevention interventions aim at decreasing the number and the risk for falls as well as improving balance, and Tai Chi is one example of such interventions. However, it might be difficult for some individuals to leave their homes to participate in Tai Chi programs and, due to the lack of specialized professionals and the financial resources, providing home visits for Tai Chi training is not feasible.

Early attempts to create Tai Chi games rely on or combine vision-based motion capture systems and wearable wireless inertial measurement units in an attempt to recognize Tai Chi movements. These approaches require complex equipment and settings, such as special lightning and background, which might be impractical or difficult to set-up in a home environment. Moreover, methods to recognize gestures typically require a great deal of time to create the models and data to train the system.

Alankus et al. [2010] and Pirovano et al. [2013] emphasize that serious games targeting home-based rehabilitation must address the following requirements: i) allow therapists to customize or personalize games according to the player's abilities, because the physical and cognitive abilities of players may vary widely, ii) monitor the player during the gameplay and provide feedback about the correctness of an action performed, i.e. continuous and instantaneous feedback and iii) provide the therapists with tools to analyze the outcomes and trends of the targeted intervention, i.e. follow-up. Games for home-based rehabilitation must also not require complex equipment or settings during the gameplay.

To overcome the previously described barriers and to address the above-mentioned requirements, **Paper I** presents a computer-based serious game that can assist individuals in playing Tai Chi and, most importantly, the method for developing such a game.

Paper I presents the development of the game using a camera-based system and wearable wireless inertial measurement units to record and measure the gestures of a Tai Chi instructor during a practice. In an off-line process, the recorded and measured data are segmented in time. Images are used to create a virtual instructor while the kinematic data to produce a set of gesture templates corresponding to performed exercise. The sum of absolute differences between adjacent images is used in the temporal segmentation process to decompose recorded and measured data into segments corresponding to postures and gestures.

During gameplay, the virtual instructor training Tai Chi is thus displayed and the player is challenged to mimic movements. Instead of cameras, wearable wireless inertial measurement units are used to measure the player's gestures. Each gesture is compared on-line with a pre-recorded gesture template corresponding to the displayed movement. Hence, instead of adopting methods for classifying or recognizing gestures, the approach employs an implementation of the longest common subsequence (LCSS) distance measure for continuous values [Vlachos et al., 2003] as a method to compute the similarity between gestures presented by the virtual instructor and gestures performed by the player. More specifically, the method computes on-line the similarity between the two sequences containing kinematic data measured from arm gestures. The computed similarity indicates how well the player can mimic the virtual instructor. The LCSS method can also be tuned to tolerance misalignments between two sequences in time (sequence length) and space (sequence amplitude). This feature of the LCSS method thus provides a mechanism to control the difficulty of the game. As a result, the game can be personalized according to the player's abilities.

Chapter 5

Conclusions and Future Work

Taking into account the current demographic change, the associated healthcare demands and the number of initiatives and proof of concept in the areas of smart homes and AAL in the last decades, it becomes increasingly evident that legislators and policy makers, as well as industry stakeholders, researchers and end-users, increasingly acknowledge the importance and the opportunity of use of home-based technologies in healthcare. However, the evolving diversity of people's needs and preferences, as well as the heterogeneity of home environments and technologies, lead to several challenges that hinder the development and adoption of smart homes and AAL technologies in real life. Hence, the development of platforms and underlying system architectures for smart homes and AAL has been the main topic of several industrial and academic research projects.

The main purpose of platforms for smart homes and AAL systems is to reduce the complexity and increase the flexibility in the development, maintenance, deployment and execution of applications, while the major purpose of system architectures for these platforms is to address non-functional requirements, such as interoperability and extensibility.

The main hypothesis posed in this thesis was that advancements in database technology could enable modern DBMS to function as a platform to support smart environment applications. This hypothesis led to questions about how such a platform should be architected and how functional and non-functional requirements would be addressed.

Related work typically adopts a multi-layer service oriented architecture implemented on top of a service framework, such as OSGi, and uses database management systems exclusively as a repository.

Therefore, and considering the aforementioned aspects and questions, in this thesis the problem of architecting smart home environments for healthcare applications was approached with a database-centric system architecture.

The programming model of the proposed system architecture is a collection of independent software components, called resource adapters, which communicate with a central database, referred to in the architecture as an active database. Resource adapters are modular software applications that abstract hardware and software technologies in the system and operate as a gateway between the environment and the active database. In the active database, different features of the database management system were exploited to address functional and non-functional requirements of smart environments. For example, the built-in event-driven mechanism of active databases was employed to support the on-line reactive behavior of smart environments. Requirements associated with interoperability between heterogeneous technologies, encapsulation of data access and manipulation, and processing of collected and stored data were implemented as database extensions.

Centralizing the domain logic into the active database provided several benefits. First, it simplified integratability in the system because technology abstractions, i.e. resource adapters, could follow a lightweight, less complex, programming language and platform independent model. The interoperation among heterogeneous technologies was also facilitated and is mediated by the active database. Because the logic for governing the behavior of the smart environment was contained within the active database, sensitive data were not transmitted or processed outside the database. As a result, active in-database processing led to increased data security and independence from external software applications for data analysis. Moreover, the technologies selected to implement the active database and resource adapters enabled the portability of the resulting database-centric system architecture across heterogeneous computing platforms. The feasibility of the proposed database-centric system architecture was summarized in Section 3.4.2.

This thesis was also concerned with the following questions associated with the development of smart home technologies for sleep assessment and fall prevention. *How to incorporate knowledge about normal sleep and load sensing into a method to detect sleep-related activities and patterns? How to accommodate the requirements for home-based rehabilitation games (e.g. customization, on-line feedback, follow-ups, easy set-up) in the proposed serious game for home-based fall prevention?* Generally speaking, from a research perspective, questions concerning the development of real world applications in healthcare provide an ideal opportunity to better understand user and system requirements and strategies to implement envisioned applications.

The question related to home-based monitoring and assessment of sleep was approached with the design and implementation of a finite-state machine to detect and estimate sleep-related events, such as bed entrances and exits, intervals associated with muscle atonia, awakenings, sleep latency and sleep efficiency. The proposed state machine takes as input features that are extracted from the signal of a strain gauge load cell. Features from the load cell signal are combined with known characteristics of normal sleep to define the conditions for state transitions. Results achieved are preliminary and were not validated against the gold standard of sleep assessment (i.e. polysomnography). Moreover, only one load cell was used to measure the load in the bed and consequently to evaluate the proposed method. A bed equipped with one load cell in each bed leg would allow not only an accurate measurement of the total load in the bed but also computing where on the bed the person is and the displacement of the center of mass on the bed over time. The proposed approach has the potential to enhance interventions targeting fall and pressure sores prevention, by detecting when individuals are leaving the bed, agitated in bed or at the same resting position for a long period of time. Moreover, a hypothesis could be whether such a measurement system could enable the prediction of sleep-related events, such as bed exits.

To address the question of developing a serious game for home-based fall prevention, the thesis designed and implemented a proof of concept prototype for a computer game in which a virtual Tai Chi instructor assists older people in practicing Tai Chi. In the process of developing the game, gestures of an instructor practicing Tai Chi were video recorded and measured with wearable wireless inertial measurement units. The dataset collected was used to create a virtual instructor and gesture templates. During the gameplay, the player is expected to mimic the virtual instructor. Instead of adopting methods for classifying or recognizing gestures, the proposed approach employed the longest common subsequence distance measure as a method to compute the similarity between gestures presented by the virtual instructor and gestures performed by the player. More specifically, the method computes on-line the similarity between the two sequences containing kinematic data measured from arm gestures. The kinematic data are measured using wireless inertial measurement units that are worn by the player. The difficulty of the game was controlled by adjusting the longest common subsequence tolerance in time (sequence length) and space (sequence amplitude). As a proof of concept prototype, the proposed serious game is currently limited to a warm-up exercise that only measures arm gestures. Moreover, because no cameras are used during the gameplay, the only on-line feedback to the player is the computed similarity index.

Concerning the proposed system architecture, a possibility for future work is to extend the active database with user-defined datatypes and support interoperability at the semantic level. Currently, the interoperation among heterogeneous technologies is handled internally in the active database at the syntactic level using primitive datatypes native in PostgreSQL.

There are no guarantees in the proposed architecture for database extensions and active rules not leading to inconsistent and unknown system states. Although modern database management systems, such as PostgreSQL, control concurrent access to database objects and can detect and handle deadlocks, a better approach is to verify the absence of problems during design time. Hence, a relevant question for investigation is how to verify user-defined database objects so that they do not compromise the system, such as the security of the smart environment and its occupants.

So far, the proposed architecture has been evaluated in terms of extensibility, portability and scalability. However, the method for evaluating these non-functional properties should be extended so a contribution can be made for the research community. Future work must also include a comparison between the proposed database-centric approach with other academic and commercial platforms for smart home environments. Because there is still no clear consensus about metrics for comparing platforms, an investigation of relevant metrics and methods is needed.

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