ORIGINAL ARTICLE

Towards the Evolution of Smart Home Environments: A Survey

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(**Received** 2 October 2015; **Accepted** 9 December 2015; **Published on line** 1 September 2016)

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DOI: 10.5875/ausmt.v6i3.1039

Abstract: Current lifestyles and technologies have inspired new ways to manage home appliances free of restrictions previously imposed by distance and time. So-called home automation technologies allow users to control and schedule common home tasks, often without human intervention. Several types of home automation systems have been proposed and classified according to their functionality, mode of user interaction, scheduling systems and cost-effectiveness. This paper reviews proposals in the smart home field from the last five years, considering both technical and functional aspects. The paper seeks to define automated or smart home systems by identifying common aspects of current such systems.

Keywords: smart home, domotics, evolution, human-computer interactions

Introduction

Smart home environments have emerged as a serious field of research and commercial development over the last decades. A range of applications have been developed to provide improved convenience, energy savings, security and entertainment for residents, and special environments have been developed to improve the living standards and autonomy of the elderly and disabled. The current paper aims to integrate current research trends such as activity and speech recognition, natural user interfaces, mobile communications, and ontology systems. The philosophy of these systems is now focused on what the home can do all by itself rather than expecting a remote command in order to initiate a process.

Home automation solutions are developed based on currently available technologies. Since 1975 the X10 industry standard has played an important role in the development of networking devices and appliances plugged in to household power lines. More recent protocols and standards like Insteon, KNX, ZigBee Home Automation, and ZWave have been presented in several academic and research proposals for smart home systems, and new designs emerge with the development of more recent platforms, communication standards and networking architectures, including proposals based on telephone [1]–[4], Java [5] and Bluetooth [6], [7]. Also, the need for remote controlling sensation brought home gateways [8]–[10] that let users command household appliances at a distance by remote interfaces.

However, such technologies cannot directly offering the interactions and lifestyle rush users are accustomed to since the explosion caused by the Internet and mobile (handset and tablet) devices. Nowadays, it is required that the smart home system enables the user to have absolute control of all the connected appliances, scheduling several tasks to be performed, receiving real-time information about the home environment, and being notified by automatic alarms sent to the user once an event occurs.

Despite these continuing innovations, smart home technologies have yet to achieve mass market penetration due to several barriers including cost of technology and implementation, privacy concerns, lack of standardized devices, and the wide spectrum of mechanisms and protocols involved. As Peine noted, "In spite of the fairly long history of the Smart Home idea itself, its diffusion in terms of market share and routine implementations is still emerging. Prototype applications such as test and demonstration houses exist but the field has not moved very far in the direction of mainstream applications. In other words, the innovation process of the Smart Home has not yet fully stabilized" [11].

Takayama and Barry [12] found that smart home system early adopters were drawn to the technology out of concern for improved security, lighting control, energy conservation, climate control, irrigation and entertainment. Implementing such technologies also improved family communication, freed up time for personal activities, enhanced respect for personal zones, and optimized consumption.

The design of such systems must center around the quality of the user experience and user satisfaction. Any alert generated or event detected by such a system is designed to prompt user action, and user-system interaction is a crucial design aspect. On the other hand, system design must anticipate conditions which may prompt user input or action. For example, tracking systems are designed to monitor residents and summon assistance if needed, but such systems can easily result in invasions of privacy. Choe et al. [13] found that smart home users are poorly prepared to deal with such privacy concerns, and tolerance for intrusion into one's personal space varies among individuals, making it difficult to provide standard or default solutions.

Several surveys have examined issues related to home domotics, home automation and smart home environments. Cook and Das [14] reviewed how several smart home system development integrates expertise from different technological domains including location-awareness, mobility tracking, natural user interfaces, decision making, and health monitoring and assistance. Following the same approach, Chan et al. [15] reviewed leading smart home projects in terms of how smart homes and their related applications are viewed on a regional basis (i.e., U.S.A, Asia, Europe, Australia and New Zealand), their legal and ethical implications, and their socio-economic impact. Grinter et al. [16] reviewed several studies from the UK and US to assess "the work householders engage in to embed computing in domestic life and thus make the home network work". Sadri [17] surveyed the related technologies and their ethical implications. He also considered the application of the Ambient Intelligence (AmI) concept for smart home system hardware and knowledge representations.

This review focuses on the evolution of smart home environments in terms of purpose and human-computer interactions. Therefore, the objectives for the survey are twofold:

1. To identify low-cost technologies (e.g. embedded systems, cellphones and regular web cameras) and the way they are implemented in the system.
2. To assess user-interface mechanisms implemented in such cases, considering crucial aspects such as user type and user command intuitiveness.

The paper begins with a description of the model applied in current smart home environments (Fig. 1), including environment implementation and user interface design. The analysis concludes with the new tendencies towards intelligent smart environments and how researchers are working with the applications of the new relevant concepts.

The rest of the paper is organized as follows: Section II describes the methodology applied while searching through databases and publications; Section III presents generalities of smart home environment architectures, considering basic technologies, communication protocols, and system structure. Section

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IV discusses the implementation of smart home environments. Section V discusses home automation proposals for elderly and disabled users. Section VI presents a range of implemented user interfaces. Finally, Section VII concludes with a discussion about the evolution of smart home environments and current challenges in the field.

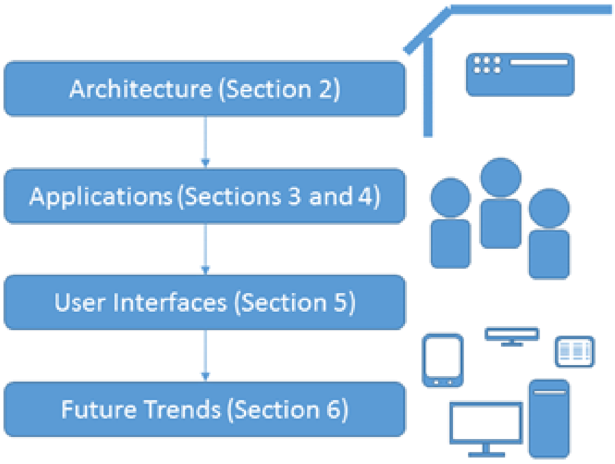

Figure 1. Flow sequence of the survey content.

Research Methodology

The content review was conducted by following a three-step methodology: (i) planning, in which the scope of the survey was defined; (ii) execution, where papers from journals and relevant conferences in the field were considered; and (iii) data extraction and filtering, which consisted of the scrutiny of the material and excluding those papers with irrelevant content for this review.

For the planning process, the following questions were proposed as research guidelines: 1) what was the purpose of the smart home systems and home automation environments proposed in recent years? 2) What user-interface mechanisms were implemented in those systems? And 3) what are the current research trends regarding smart home systems design and development?

The motivation for the first question is to know what the users can actually do with the recently proposed smart home systems once it is fully operational in the house. This information is useful for determining any problem researchers have been dealing with in recent years and the proposed solution defined by an automated home environment. Solving this question helps to describe the state-of-the-art in smart home systems.

The second question was propounded by the need for information concerning the defined mechanisms for users to give instructions to the smart home environments. Considering the new affordable technology for human-computer interactions, the review interest includes how effective such technology is in terms of daily living and user assistance.

Finally, the interest for knowing which new concepts are appearing in the field is the motivation for question 3. Answering these questions helps researchers to know which concepts are currently being considered when defining new proposals in terms of smart home environment implementation and human-computer interaction.

Content Search and Filtering

A manual search was done in the following databases: ACM Digital Library, IEEE Xplore and ScienceDirect. The review was carried out from April 2014 to November 2014. Only results from the last five years were considered in order to keep the review within recent proposals in the topic. The following keywords were used while searching: smart home, home domotics, home automation and home environment.

Despite the considerable amount of publications that the search queries returned, only those with information regarding the purpose of the proposed system and/or user-interface mechanisms for sending commands to the system were considered. Material centered in technical issues were discarded (the term technical issues references the content focused on device communications, networking protocols, circuit design, software modelling, hardware design and implementation).

In order to bring complementary information to the content, the following keywords were included on the search queries: Kinect, Leap Motion, user tracking and natural-user interfaces. A total of 166 papers were initially considered for the review. An extensive analysis over the obtained publications was performed in order to exclude irrelevant material (descriptions of the system/user interactions without implementations and research extensions of previous proposals tightly scoped on specific problems). After excluding the above mentioned material, 134 papers were chosen to be considered for the final review.

Results

The selected publications are composed of 50 journal papers and 84 conference proceeding papers. In Table I. the searched journals are listed with their respective quartile and H-index rank. Ranking information of the journals was obtained from the Scimago Journal & Country Rank (http://www.scimagojr.com). Fig. 2 shows the number of publications per journal. IEEETCE has the most prominent number of publications in the field followed by PUC and

PCS.

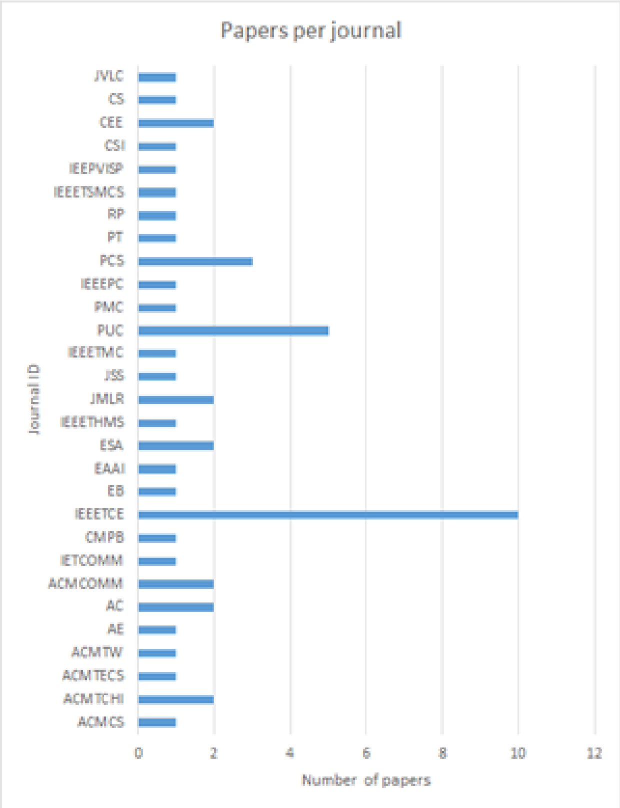

Figure 2. Number of reviewed papers per journal.

Fig. 3 shows the number of publications from 2009 to 2014. An increasing tendency is found every other year. For 2013, the trend topics concerning smart home environments were focused on user interactions considering specific populations such as the disabled and the elderly. In the same way, the consolidation of new user-tracking devices (e.g. Kinect and Leap Motion) brought an important number of proposals where systems are capable of bringing assistance according to the actions of the users. This approach is studied under the concept of Context-Aware Systems (considered in Chapter III).

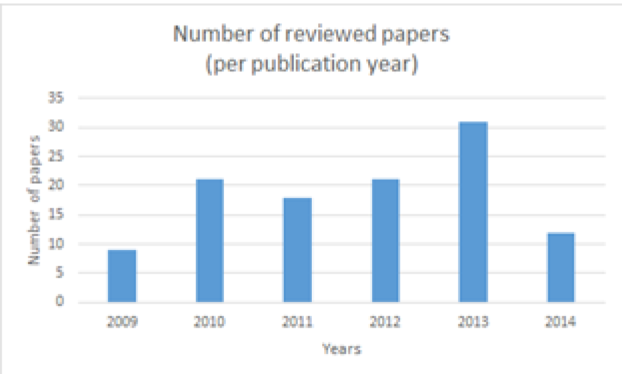

Figure 3. Number of reviewed papers by year of publication.

Table 1. Searched Journals.

ID	NAME	QUARTILE	H-INDEX
ACMCS	ACM Comput. Surv.	Q1	90
ACMTCHI	ACM Trans. Comput.-Hum. Interact.	Q2	40
ACMTECS	ACM Trans. Embed. Comput.	Q2	49
ACMTW	ACM Trans. Web	Q1	26
AE	Applied Energy	Q1	67
AC	Automation in Construction	Q1	48
ACMCOMM	Commun. ACM	Q1	131
IETCOMM	Communications, IET	Q2	37
CMPB	Computer Methods and Programs in Biomedicine	Q2	53
IEEETCE	Consumer Electronics, IEEE Transactions on	Q1	69
EB	Energy and Buildings	Q1	76
EAAI	Engineering Applications of Artificial Intelligence	Q1	54
ESA	Expert Systems with Applications	Q1	85
IEEETHMS*	Human-Machine Systems, IEEE Transactions on	-	-
JMLR	J. Mach. Learn. Res.	Q1	94
JSS	Journal of Systems and Software	Q2	60
IEEETMC	Mobile Computing, IEEE Transactions on	Q1	80
PUC	Personal and Ubiquitous Computing	Q2	31
PMC	Pervasive and Mobile Computing	Q1	28
IEEEPC	Pervasive Computing, IEEE	Q2	69
PCS**	Procedia Computer Science	-	15
PT*	Procedia Technology	-	-

RP	Research Policy	Q1	129
IEEETSMCS	Systems, Man, and Cybernetics: Systems, IEEE Transactions on	Q1	76
IEEPVISP***	Vision, Image and Signal Processing, IEE Proceedings	Q2	39
CSI	Computer Standards & Interfaces	Q2	38
CEE	Computers & Electrical Engineering	Q2	26
CS	Computers & Security	Q1	51
JVLC	Journal of Visual Languages & Computing	Q2	34

* No ranking information available.
** No quartile information available
*** Last available ranking information from 2009

The classification of the reviewed publications was done by defining six categories: (i) Introduction; (ii) Smart Home Architecture; (iii) Applications; (iv) Systems for Specific People; (v) User Interfaces; and (vi) Evolution. Such categories are considered as content chapters in the review. Fig. 4 shows the percentage of publications per category.

We chose the previous categories to group the researched papers because they consider current topics of human-computer interaction research, and smart applications, which are the base of any important research work interested in the development of new smart home technologies.

Current Smart Home Architecture

Within the last decade, smart home environments have evolved in two ways: the purpose of the system and the user interaction with the system. When the purpose of the system is considered, it can be found that new pillars, like economy savings, inhabitant caring, and context-aware recognition are replacing traditional ones, like entertainment and luxury. On the other hand, user interaction has several mechanisms based on natural language processing and natural user interfaces that people can utilize with the purpose of having total command of each device connected to the system. Both branches of evolution merge together in order create a fully functional environment, capable of bringing automatic assistance based on the recognition of the daily activities performed within the house.

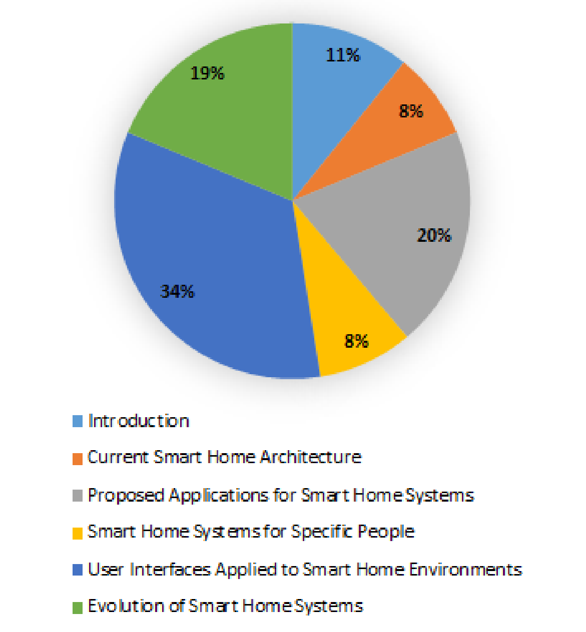

Figure 4. Number of reviewed publications per category.

Nowadays, users are accustomed to immediate responses from every activity where computers and mobile devices (smart phones and tablets) are used as the universal tool. On the Smart Home field, such immediate responses require 24/7 systems with external communication capabilities, which increases the complexity of the system as new functionalities are required. Additionally, current mobile and web applications let users define their own settings (user name, authentication mechanism, communication procedures, rules and tasks, to name a few) besides the standard configuration. Therefore, it is required to design this type of interaction with the smart home systems in a way that users can define their own settings and behavior according to their preferences. This aspect is strongly tied to the user interface that grants such type of configuration. At the moment, mobile and web applications are the preferred mechanisms to enable user-system interaction, setting aside PC programs and wall-mounted displays: classical interfaces of previous generations of smart home environments.

This evolution also reaches the communication networks since there are several types of devices; each of them with their own functionality, purpose, and sharing data using their own protocols. This situation, although not recent, is problematic due to the different standards that have emerged in the field. Commercial solutions could be based on open/closed technologies and offer their own functionalities despite the formal regulations defined in open standards. Considering a system capable of interacting with several of these devices and standards considerably increases the complexity of the system.

Several researchers have worked on this problem [18], bringing solutions via M2M (Machine-to-Machine) and OSGi (Open Service Gateway Initiative). Still, this is a hot topic in the field.

In order to summarize the common aspects of the reviewed systems, the main components of a current smart home system are sketched in Fig. 5. Considering what researchers have proposed towards the satisfaction of the mentioned evolution, current smart home systems tend to have the following parts:

Remote Access: When users are located beyond the network range of the system, it is possible for them to have access to the smart home environment using mobile apps or the web page provided by the home gateway. These capabilities let users know what is happening in real time within the house. Additionally, they can send commands and schedule different tasks which will begin automatically as they are specified.

Home Gateway: It is necessary to bring users remote access to the system. Besides giving and receiving information and instructions, home gateways implement access control via user authentication (which could bring additional functionalities like user profiles and restrictions).

Home Access: Just like remote access, home access is provided to users in order to check information and give commands to the system. The main difference with remote access is that, once the user is within the house, he or she is able to give commands using different types of interfaces. Some types of population (e.g. elderly and disabled persons) require non-traditional interfaces to interact with. For that reason, researchers and designers have proposed a number of prototypes and commercial solutions for their needs.

Desktop and Mobile Devices: Taking advantage of mobile devices (handsets, smartphones and tablets), users can check the information of the system, schedule different tasks in the system and send immediate commands to be performed. Desktops can be used as smart home controllers using the Intranet (provided by the home gateway) and give instructions to the devices if they are linked directly. Otherwise, they will be sent through the home gateway to the device manager.

User Interface Device: Devices with the capability of recognizing speech commands and hand gestures, and performing user-tracking for activity recognition fall in this category. They are also known as Natural User Interfaces (NUI) because they do not require physical contact between the user and the device. Furthermore, they are designed to follow the natural activity of the user. A number of proposals for elderly and disabled people are based on these types of interfaces.

System Display and Main Controller: This works as the central panel of the system. It is usually placed somewhere visible with easy access to any user. Its design tends to be intuitive for any kind of person, bringing a touch-screen or a display with a set of buttons for selecting options and giving commands. Sometimes they are replaced by desktop software if a direct connection with the device manager or the networked devices is included.

Device Manager: This is the central entity of the system where commands are processed and sent to the connected devices. Also, it receives information from sensors, cameras, microphones and other types of devices that generate data. When different types of networks are implemented in the smart home environment, the device manager centralizes all the network traffic in order to avoid collisions and delayed messages. A device manager capable of understanding and administering any kind of protocol designed for home domotics is still a research problem to be considered. Although there are several commercial solutions for this problem, sometimes they do not satisfy closed standards or any other device built for automation purposes.

Sub-networks and Connected Devices: New smart home proposals include mesh networks that increase the capabilities of the entire system. It is usual to find X10, KNX, ZigBee Home Automation, ZWave and LonWorks, among others, in the same home environment. Each of the previously mentioned protocols works with a limited set of devices and, sometimes, they enter in conflict due to a shared medium (usually the 2.4 GHz channel). This situation is also a current research problem considered for the device manager or the medium access sub-layer in networking.

Each one of the components of a smart home environment has its own complexity and they are considered individually as a topic of research. From the front-end part of the system, several proposals have been made for mobile devices and natural user interfaces. It is important for a system to determine what the user wants to do. Also, it is required to understand what the user is doing in order to bring assistance to a user's activities. Solutions like Spatio-Temporal binning [19] and Discriminative Hierarchical Modelling of Spatio-Temporally Human actions [20] are part of the current solutions for real-time human action recognition. These kinds of approaches are considered in Section IV.

At the back-end part of the system, several researchers found the home gateway as the core of the system that needs to be improved to satisfy user

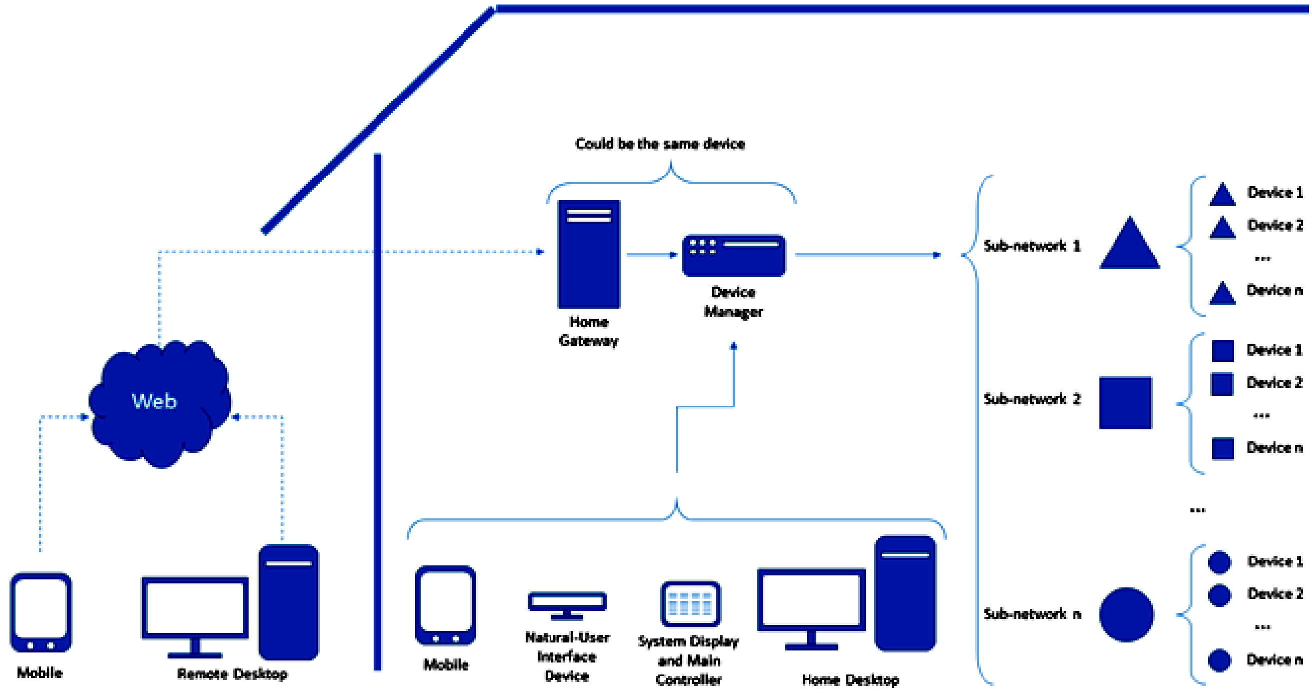

Figure 5. General architecture for a Smart home system.

demands. Certainly, this is an important point of view considering that home automation is often implemented in houses inhabited by more than one person, which means that several users will have access to the system (either by home or remote access) and will schedule their own tasks.

In order to find a solution to the above mentioned situations, additional memory management and reduction of overhead for communication protocols is required in order to obtain fast responses from the system and connected devices. In that sense, Kuroda et al. [21] considered the situation and proposed a new memory isolation method for OSGi-based home gateways. Their solution considers running multiple software components, called "bundles", on the virtual machine and to manage them in order to lower memory consumption and guarantee other bundles will work within the home gateway. On the other hand, Mantoro et al. [22] presented a web-based framework for wireless communication between devices and the commands from the user. From their perspective "The wireless nodes will minimize the mess of wiring and the system can be optimized to a point where it becomes plug and play and can be set up in any home".

It is possible to describe the architecture at deeper levels if the type of household appliances plugged in to the environment are considered. Allerdign et al. [23] classify the appliances in two distinctive groups:

Observable: Those "appliances that depending on the installed sensory equipment or their self-explanatory properties, their current state or the current energy consumption or production can be observed, but there is no possibility to influence any parameter of the appliance, directly". This category can be subdivided into two subgroups:

Predictable: Appliances that are used regularly, following a usage pattern. As an example, stoves are classified in this group as they are used for cooking any meal, usually following a regular schedule.

Unpredictable: Appliances used randomly or without any kind of usage pattern. Multimedia devices are considered in this category.

Controllable: They have the "capability to respond to predefined external requests", an additional characteristic over observable devices. Also, this group can be subdivided into two subgroups:

Permanent service: This category considers such appliances that "are active all the time, but only consuming or producing energy for specific time periods". It can be found that deep freezers and warm water boilers fall into this classification.

Timed service: These devices are induced by a previous user interaction and they work for a limited amount of time. Devices like a washing machine or a dryer are considered for this category.

It could be said that home domotics is the result of combining Software Development, Computer Networking and Human-Computer Interactions on behalf of users and their daily living. However, mixing all of these research fields is not a simple task due to multiple factors such as development environments, communication protocols, software engineering, Graphical User Interfaces (GUI) design and User Experience (UX), system architecture and product testing, to mention a few. Authors like Kaldeli et al. [23] and Keyson et al. [25] proposed entire architectures starting from the interconnectivity level until the higher application level. On the other hand, several authors have proposed development frameworks which help to define new smart home systems without considering technical aspects. Sanchez et al. [26] developed a framework for developing home automation systems following the model-driven approach. As a regular development framework, it comes with a domain language which is later translated to the specific code according to the selected platforms to work with. Even with this kind of solution, at the development level, it carries additional research topics for guaranteeing a complete interoperability between platforms and protocols. Despite this type of achievement, closed technologies avoid defining a common framework or development layer concerning domotic systems. Following the same path, Sommaruga et al. [26] presented DomoML, a suite of XML based languages which can be used for interconnecting heterogeneous devices. Such interoperability is obtained by applying semantic web technologies and RESTful web services. This approach allows to define scenarios and rules for executing specific tasks. Similarly, Miori et al. [28], considering this situation, proposed the domoNet architecture for interoperability between devices from different vendors.

The philosophy of a single device (device manager) for handling different communication protocols (Figure 6) is a current hot topic in the field. In this aspect, several commercial solutions can be found such as Revolv Smart Home Automation Solution, SmartThings, Insteon, Vera and Wink, bringing interoperability to several supported devices and protocols. Each one of the mentioned solutions offers its own mobile app for enabling the smartphone to become the main remote control of the system even if the user is outside the house, which makes the solution a fully functional plug-and-play home gateway. However, it is not an impediment to allow researchers to propose their own solutions. As an example, Walch et al. [29] introduced homeBlox, a server for device management based on SOAP (Simple Object Access Protocol) which uses a mobile app to let users configure their own rules using a kind of semantic flowchart based on "AND" and "OR" connectors.

Now, in aspects related to software, it is important to keep in mind the definition of data structures in a way that internal data management is reliable despite the number of devices in the network or the number of tasks

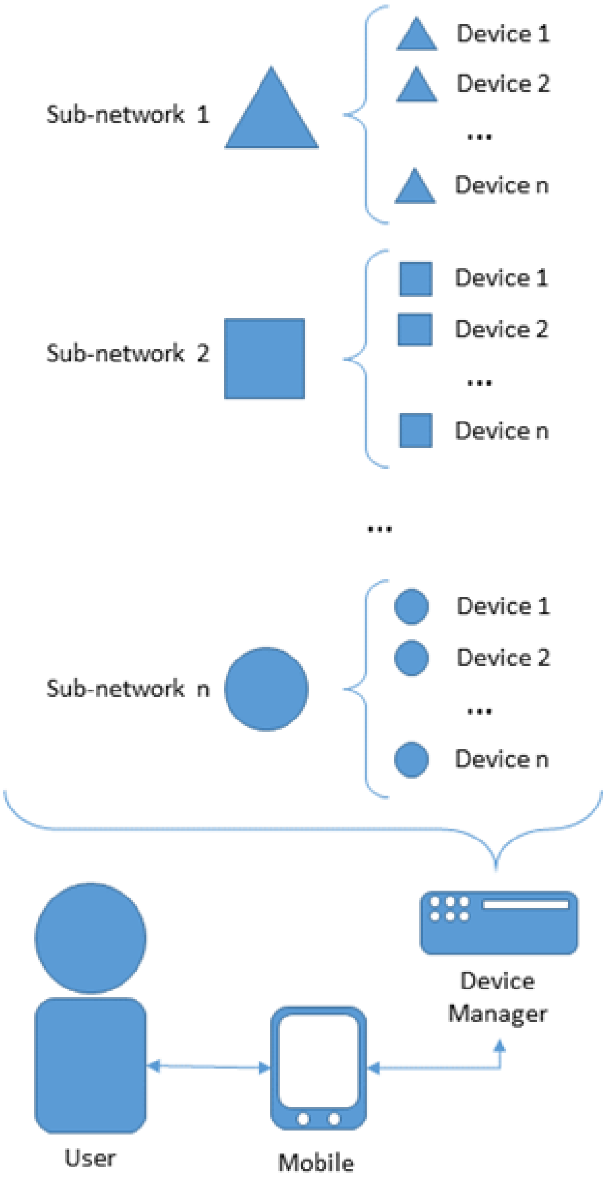

Figure 6. Device manager environment.

commanded by the users. Kamilaris and Pitsillides [30] considered request queues as a communication mechanism with embedded devices. According to their conclusions, "request queues become more useful in scenarios with multiple, concurrent users and an increased percentage of transmission failures at the pervasive space". Additionally, the capability of the system could be enhanced by employing queueing theory, which could bring good responses when the number of input data increases. On top of that, memory monitoring should be considered in order to prevent foreign devices and users from interacting with the system and exploiting memory problems. Attouchi et al. [30] proposed a solution based on resource accounting rules between tenants for OSGi based systems. Their solution required a modified version of an experimental Java Virtual Machine for the implementation of memory monitoring features. Their results, obtained by the DaCapo benchmark [32], shows that the overhead of the system was below 46%, which "is acceptable in development and testing time, and it is tolerable in slow pace applications which are frequent in the Smart Home".

Proposed Applications for Smart Home Systems

The evolution of smart home environments has been accompanied by the new upcoming proposals and technologies in computer networking, embedded systems, human-computer interfaces and wireless sensor networks, bringing new expectations and interpretations about what a smart home system is expected to do. The common aspects of the reviewed papers and publications display that a quick answer to this expectation could be "real-time monitoring of the house and its inhabitants at distance". This type of monitoring could be found in two main groups: 1) House monitoring, regarding domestic utilities and ambient variables, and 2) People monitoring, which is mainly focused on children, disabled and elderly.

Following the evolution of smart home systems requires awareness of the most striking proposed functionalities. In Table 2 the main aspects of several proposed smart home environments are shown regarding their implemented functionalities. The following are the considered aspects for the comparison:

Speech Command: the system is capable of recognizing a number of predefined speech commands and/or it enables the users to define their own. The required actions to be performed should also be possible to set up.

Visual Tracking and Activity Identification: using any kind of camera, the system follows, in real-time, any recorded pattern for event activation, alarm management and surveillance. These techniques could be applied to tracking the inhabitants (e.g. people or pets).

Context Aware: based on the obtained information, the system is able to recognize what is happening at the moment and perform the required action automatically. Performing the required actions in case of alarm or giving assistance to users depending on the situation are examples of context aware systems.

Environmental Monitoring: supported by a set of sensors deployed throughout the house, it is possible to check internal values such as temperature, humidity level, light/sound intensity and user/object movement, among others.

Home Monitoring: could be applied as a utility measuring system or an automatic reaction system when a task has been performed completely.

User Monitoring: the system is capable of tracking someone within the house to prevent an accident or to bring assistance in certain activities. Also, the system could be applied to see remotely what somebody is doing at the moment.

Home Control: the user can send remote tasks to be executed in a certain time. Additionally, the user can verify the current state of the connected devices.

User Authentication: it is possible for several users to access to the system using any kind of authentication mechanism, preventing unauthorized users from interacting with the system.

Scheduling: it is possible to set several tasks to be performed in a certain time (as the home control category) and to repeat it as set by the user.

Energy Saving / Green House Systems

An important factor in domestic economy is service consumption which can be reflected in terms of value per service and costs. Several proposals for smart home systems include energy saving systems based on environment sensing, task scheduling or remote control.

Kim et al. [33] introduced a cost-effective home energy saving system implemented by porting OpenWrt onto a wireless router. The system, focused on lighting control, gives remote controlling to people using their iPhones whether or not they are in the house. Using OpenWrt adds functionality to the wireless router, which means it could be used as an embedded system with network capabilities. Control functionality is complemented using an Arduino UNO which receives the ON/OFF commands and the location where lights are connected.

Baraka et al. [33] designed and implemented a "remotely controlled and energy-efficient smart home" system. Based on low cost-technologies, like an Arduino micro-controller and an Android Tablet, the system offers connectivity with the electronic devices connected in the house network. This network, built over X10 and Zigbee, aims to be reliable and allowable for integration with low cost controllers. The system is built for energy saving and scheduling different tasks assigned by the user. For the energy saving aspect, the system contains a list of conditions that triggers specific events if they are satisfied. The conditions are set by environmental values or by appliance statuses. The system allows the user to set different tasks, assign them a description, duration and priority over other scheduled tasks. A scheduling algorithm automatically sorts the tasks and assigns them the starting and ending time slots according to the given specifications.

Energy saving systems offer estimated values of consumption for regular actions in home. Di Giorgio et al. [35] proposed a smart home controller focused on efficient management of electric energy. Considering several variables (requests by the user, peak and average load profiles, available power threshold, and energy prices) the system is able to provide the forecast of power consumption for the actions required by the user. The collected data is used to determine the optimal order to tailor the controller actions for economy saving, in cases of time of use, tariff or demand side management. At the end, the user is free to follow or ignore the indications given by the system.

Keyson et al. [25] designed a home energy and comfort management system in order to help users manage residential energy. Given the basic design of its wireless module, the residential gateway and the mobile app, the authors proposed that this portable is system capable of measuring electricity usage in real-time. By checking the mobile phone app, users can verify the amount of electricity that is being consumed, which will help them to identify the cost of working devices when outside the house.

Mrazovac et al. [36] presented an "intelligent device-level residential energy monitoring and controlling platform based on interactive outlets and light dimmer-switches". The system, focused on energy saving and safety, could be used for monitoring several events at the same time, such as who is using a specific device or the status of any household appliance after leaving the house. Additionally, users could receive notifications (on mobile devices or by web) of energy consumption of the house. Safety is achieved by monitoring devices once they are plugged in, storing consumption data, and establishing priorities according to type. Such priorities are considered when the device has exceeded in energy consumption, sending a request to turn off the device or switching it off in the case that nobody is in the house.

Context-Aware Systems

Determining what the user is doing or what he or she is intending to do is the main challenge that a number of researchers are trying to solve in smart home environments. At the same time, other researchers consider that a smart system should be aware when something is not happening according to what was specified by the user or through environmental information. These types of systems are aimed at determining what is happening and what is being intended by the users in order to anticipate an action or an undesirable situation.

A Context-Aware system may be applied to the automatic reaction between devices. Yu et al. [37] proposed a home automation service based on indoor service robots and wireless sensor networks. Placing several sensors in different places of the house, a mesh network was built in order to establish a communication platform between the nodes. A mobile sensor node placed in a service robot is used for home monitoring. This mobile node is focused on complementary measuring of barometric pressure, temperature, humidity and illumination. The robot works autonomously based on vision cameras, ultrasonic sensors, infrared sensors, ranged finders, gyroscopes, and odometers. The users can access the information of the monitoring system using mobile devices like PDAs and smart phones. Also, users can receive real-time video streams of the indoor environment which is captured by the robots and transmitted by the network. Using the mobile app the users can send control commands to service robots if an action has to be done. Thanks to the mesh network, it is possible to identify the nearest service robot closest to any static sensor node of the network.

Patricio and Gomes [38] presented a low-cost system based on COTS (Commercial Off-The-Shelf) which is capable of generating C code in order to be implemented in a IOPT (Input Output Place Transition) Petri Net model using PNML (Petri Net Markup Language) which could be used to communicate with the devices of the network. The purpose of the system is to enable user interaction with the devices in the network using a set of logic rules (based on "AND" and "OR" operations) for setting actions to be triggered when the required conditions become true. The system can be used for any kind of monitoring, including home automation and wireless sensor networks.

Determining the context of a situation is not an easy task; it is as complex as giving enough intelligence to the computer in order to let it determine what is happening based on the input data. Sometimes, it is only necessary to have a set of camera devices to know if something is missing. Using image processing algorithms it is possible to determine the differences of the actual image compared with a base image. This approach is used by Hsu et al. [39] who prototyped a refrigerator which is capable of determining if a certain food or element is running out and contact the respective supplier. Using a set of CCD (Charged-Couple Device) cameras, the system can determine if the quantity of any kind of food (with regular or irregular shape) is below previously specified expectations. This recognition is performed when the user asks for a specific food via speech command. Also, the main system could be used as a commander for other household appliances when an action is required by the user using a cell phone.

On the other hand, in order to determine if a user is available, according to what he or she is doing, it demands for the system to recognize the user's actions and willingness to be interrupted. In that sense, Bjelica et al. [40] proposed a context-aware system focused on announcing the availability of users in different contexts. The system determines such availability based on tracking users using optical and 3D cameras, accelerometers, microphones and PC activity monitors, to name a few. Authors state that it is easier to determine the availability of the user in an office context, while in a home context it is not so easy. Based on the listed sensor and tracking devices, the system is capable of tracking the surroundings of the user (people counting, face tracking, voice detection, and basic gestures). The information of the user is sent to a web server which estimates the willingness of the user to be interrupted. Instead of using a busy-flag system to indicate if a user is available, a light system is presented. If a user is busy, then the system sends a RGB indicator to a DMX adapter associated with the user. The color of the light determines if the user is available or not (red is for unavailable; yellow and green are for moderate and high availability respectively).

Monitoring certain types of devices lets users know concrete values of the device and its repercussion in the nearby environment. Lin et al. [41] considered a HVAC (Heating Ventilation Air Conditioning) monitoring system based on LonWorks and KingView. In their research, they could track the changes of temperature throughout the time since the initial input from the user. Such changes are received by the system for opening and closing the required valves as necessary.

Prediction is a way to determine if an appliance is going to be used in the future and can be achievable by learning from user's regular activity. Knowing the habits and routine of the inhabitants of the house, the system is capable of measuring and reducing costs of household utilities such as electricity and water. This approach was considered by Basu et al. [42] who built a learning algorithm which received usage data and statistically predicted the energy consumption and requests for the next day (24 hours). They successfully achieved a model that can learn from the behavior of new residents in the house. A similar approach was considered by Kang et al. [43] who proposed monitoring home appliances in order to develop a scheme for "translating association rules among appliances mined from their usage information into service scenarios". At the end, users can choose their favorite scenario where appliances work without any kind of interaction. Similarly, Englert et al. [43] proposed an approach to let buildings to be aware of the presence and activity of any electric appliance. These detections are based on the measurement of electrical current, voltage, and a feature extraction. The prediction system uses machine learning techniques in order to identify the device and to differentiate its consumption among other appliances, obtaining prediction precision up to 99.8%. The authors of the proposal assure that this type of implementation increases the building's knowledge of what is happening within and strengthens the concept of smart buildings.

Similar to prediction, activity recognition has become an interesting challenge for current and future smart home environments. For a healthy user it would be easy to perform daily activities, like cooking or watching TV, however, for a user with Alzheimer's such activities would not be so easy. Considering this situation, Belley et al. [45] suggest that recognizing what the user is doing is possible based on how electric devices are being used. Their method is based on the analysis of load signatures and power analysis at the steady-state in order to determine what the user is doing with the considered device. However, when detecting what the user is doing is not a simple task and it is actually a hot topic for visual recognition purposes. Applying this concept to smart home environments means that the user has to train the system in order to increment the probabilities of recognition of his or her activities. Such work demands time to define a set of activities and to check if they were accurately recognized by the system; which is contrary to what users expect from the system which is supposed to identify the actions automatically without any kind of training. Considering this problem, Fanello et al. [46], from the image processing point of view, proposed "an effective real-time system for one-shot action modelling and recognition". Their proposal guarantees that using a single shot is enough to teach a new action and to define the corresponding descriptors to identify the action. This kind of approach is related to the interactions between users and things within the house, especially when a single object could be used in different ways according to the situation (a chair under a light bulb may be used as an assistance to reach the ceiling if changing the light bulb is required, or to obtain better light conditions for reading or any other kind of activity). Although many assumptions could be made according to the situation, the systems have to determine precisely what object is being used and its corresponding spatial relationship with other objects inside the house. Bouchard et al. [47], [48] proposed an unsupervised learning technique to discover such spatial relationships and their sequential patterns inside the home. The mentioned technique is based on GSP (Generalized Sequential Pattern), RFID localization and data mining algorithms for extracting spatial patterns. The obtained information is contrasted with previously defined plans of the house which helps the system to define certain rules about the location and possible meaning of the detected objects.

Access Control, Authentication and Security Systems

One of the promising goals in smart home systems is the capability of ensuring access control and user authentication. In order to determine if a person is allowed to enter the house, the system should implement some kind of user identification mechanism (user-password combination, card reader or bio recognition).

Ahmed et al. [48] developed two systems, based on low-cost cell phones. The first system aims at keeping operational costs very low while the second system includes additional features such as image capturing and intrusion detection. Using SMS with a specific format and miscalls, the system communicates with users and receives the commands to be executed. The miscall mechanism works using the number of rings that the system generates or receives. Each specific number of rings indicates a message or a command to be executed by the system. The received commands are sent to the main controller using Bluetooth which sends the command to the corresponding actuator. The authors state that the system could be modified to recognize speech commands instead of SMS or miscalls in order to make it more accessible to the elderly.

Das et al. [50] also proposed a low-cost system focused on access control and appliance management based on environmental sensing. The system, implemented in Atmel ATmega 8, is capable of detecting the presence of a person using IR sensors which warns the system indicating if the person is entering or leaving a room. On the other hand, environmental sensors check light and temperature values for turning ON/OFF lights and fans connected to the system. For restricted areas, a keypad is linked to the system for entering passwords which grants access to authorized users.

User authentication could be performed by what the user has or what the user is. Following the first way, an ambitious goal for authentication systems is to use a person's mobile device as an access key to the house. Lian et al. [51] consider that smartphones could be used as identity management systems when mixing them with low-cost technologies. Their system, named "Home Safety Handwriting Pattern Recognition" (HSHPR), is a web-based system which provides real-time recognition. Users can access the house when they authenticate using their smartphones drawing a gesture from a valid IP address. The recognition system is designed to be installed on an Arduino board which is connected to a control panel and rely on modules which lock/unlock the door when the user requires. Although the proposed system firstly aims at user authentication, it could be used as a monitor station for temperature and humidity values of the house. Those values are obtained from several sensors and the data is sent to the main controller using the ZigBee protocol. Considering what the user is, there are several means to identify any biological characteristic such as voice or facial recognition. Saeed et al. [52] introduced a facial recognition system applied to domotics where basic tasks like controlling and monitoring are performed once the user is identified by facial recognition. The system is designed to classify certain faces in two categories: trusted persons and unknown persons. If a trusted person is identified, then actions can be performed, otherwise an instruction from the main user is required by the system. If a person is not found in the system, he or she is considered an unknown person. Therefore no action is followed and access is not granted.

Current smart home environments are aimed at granting remote access to users through a variety of devices plugged in to the environment network. Not handling this functionality appropriately could generate risky situations where intruders (users or alien devices) access the network with no control. This is a typical problem when plug-and-play behavior is desired for the devices once they are detected by central systems and protocols through discovery processes. Without specific regulations, any kind of device could be part of the network, which could be used as back-doors to the system, generating security problems such as data leaking, hacking or resetting user configuration. Hjorth et al. [53] designed the Trusted Domain, a security platform for secure communications between the assorted devices of a smart home environment. Based on the IP information of the devices, their platform grants access to devices which belong to the system, which means that neither unfamiliar nor unauthorized devices are able to interact with the network.

Smart Home Systems for Specific People

A number of proposed smart home systems are aimed at assisting people with mental or physical limitations. Such limitations could be generated by accidents, cognitive impairments or advanced age. Such systems help users in the activities of daily living (ADLs) and instrumental activities of daily living (IADLs).

Camier et al. [54] designed a "non-intrusive load appliance monitoring for supervising simple actions realized by patients". The system uses the information from the electrical panel for recognizing the appliances by measuring the overlapped real power consumption patterns in real-time. The authors tested the system with the cooking activity which requires different types of appliances to be turned ON/OFF (microwaves, stove, crusher and espresso machine).

Human interfaces for elderly and impaired users are generally adapted as Ambient Assisted Living (AAL) systems. This kind of system reacts to the presence of users and assists them in specific situations based on the actions of the users. Due to the great number of actions performed every day and the types of movements of disabled people; it is very complex to define recognition mechanisms for movement patterns and the set of responses for each one of such patterns.

The Elderly

Seniors are especially considered due to the many advantages that smart home environments offer to them. Considering that this population requires extra assistance in daily living and health topics, researchers consider that automated environments bring significant improvements like remote activity monitoring and vital signals monitoring, also, the collected data could be accessed in real time by doctors and relatives. Despite such benefits, this population requires comfortable places to live independently without intrusive technology. Mohammadi states that assisted homes for the elderly have to offer a balance between the activities performed by the people and by the technology. Furthermore, integration with life patterns is a challenge to be dealt with at the moment of implementation [55]. Sanchez et al. [56] said that "the most commonly reported case of smart home technology is in the area of elder care. The reason for this [close relationship] can be explained considering the high cost of health care and the desire of the elderly to be self-sufficient".

Remote monitoring or tele viewing is becoming an essential characteristic of health care systems. As stated by Cucchiara et al. "People's safety at home can be monitored by computer vision systems that, using a single static camera for each room, detect human presence, track people's motion, recognize behavior (e.g. using posture), assess dangerous situations completely automatically and, if necessary, alert the appropriate authorities" [57].

Georgoulas et al. [58] proposed a robotic furniture system aimed at assisting elderly people bringing an intelligent storage space, a health assistant and a communication terminal. Their first aspect seeks to assist users with a robotic furniture system which helps to retrieve stored items. Using RFID tags and RFID antennas, the system allows users to know where items are located in the furniture. The tracking system, based on a Microsoft Kinect and an Arduino microcontroller board, follows the user's actions in order to adjust the height of the cabinets until they are reachable from a seated position. The health assistant system monitors vital signals and health statuses such as body fat, body water, muscle mass, heart rate, body temperature and blood glucose. The acquired data is sent to a measurement gateway which stores data. This data can be accessed remotely by a registered physician using an on-line website which allows to check the information of the user. The system was evaluated in terms of ergonomy, achieving 20% percent less space utilization in order to bring enough space for mobility of users with rollators or wheelchairs.

Smart home environments for the elderly still have many challenges to face considering the relationship between users and automated environments. It is important to define these types of systems according to the actual needs of this specific population. In that sense, Talamo et al. [59] summarizes in the next seven points the relationship between technology and seniors:

1) Although the elderly are accustomed to technology, like sewing machines, it is not necessarily the case with digital devices.
2) Social mediation from relatives and friends is required at the moment of introducing new tools.
3) Technologies have to be perceived as useful in everyday life as they are introduced in the proper period of life of the person. Authors explain this point mentioning that cell phones start to be considered as useful to older persons as the children once said children leave the house.
4) Even if users have no problem at all, technology has to be practical and solve problems in case that something occurs and nobody is close to assist them.
5) Some seniors see technology as "presence builders" by providing communication with the outside world.
6) Technologies cannot replace their cognitive functions.
7) High-Tec aesthetics may not be the right choice at the moment of designing user interfaces. It is recommended to use wood themes.

Another crucial aspect to be considered is the effect caused by cameras and assistive technology on privacy of older adults. Caine et al. [60] found that such technology certainly alters their perception of privacy, therefore, they change their regular behavior. Authors tested three different types of devices (cameras, stationary robots and mobile robots) in order to determine how much the behavior is changed according to the type of monitoring and assistance mechanism. They found that comfort decreases in activities like taking a shower, blowing the nose and doing personal finances. On the other hand, activities like doing exercise, drinking alcohol and watching a movie increased the level of comfort when assistance and monitoring mechanism are implemented. Such considerations together with the ones previously described by Talamo et al. should be considered when developing mechanisms to support the elderly.

Disabled People

Just like the elderly, people with any kind of impairment are a special population that can benefit from smart home environments given their characteristics of remote monitoring and real-time data sent to the respective requester. In this aspect, doctors, nurses, or any other specialized person can follow the daily activities of this population and prevent an undesired situation based on the information provided by the system.

Gnanasekar et al. [61] introduced a home system for physically challenged persons. Based on speech commands, the user is capable of turning ON/OFF loads and checking appliance status on a display when required. A three color scheme indicates if a device is turned ON, OFF or under a fault condition (using green, yellow and red respectively). The system allows the creation of user profiles for improvement of speech command recognition accuracy. Zigbee wireless environment is used for lowering costs. It is required to install an application on a PC where speech commands are stored and processed. No external control interface is given, so the user is required to be in the house in order to send commands to the system.

Many of the affected persons are confined most of the time to a single room where their only source of entertainment is a TV. Taking advantage of the situation, Rifon et al. [62] proposed a tele-assistance system which uses the TV as the main user interface where the patient can control any device connected to the system. Also, it offers additional features like remote monitoring of vital signs, centralized control of any installed device, and "intelligent adaptation of services and interfaces according to the level and type of disability". The system makes use of an HTPC (Home Theatre Personal Computer) as the central device of the system, which can be connected to any device using Bluetooth guaranteeing medical devices to be connected to the system. Authors consider their solution as a low-cost system given that it only requires a TV and a PC to be implemented.

An important aspect of this kind of system is the fact that regular technology fails to bring the respective assistance. A crucial factor of specialized devices is the high cost of commercial solutions, which is caused by the low demand of such devices. Committed to the welfare of this population, Schuler et al. [63] designed several low-cost prototypes of useful devices for people with different kinds of impairments. Such type of prototypes include braille displays, a cane tip that detects puddles, a digital game that helps the visually impaired in rehabilitation, an Android application for blind people to access Twitter, a capacitive touch switch, an adapted computer mouse, a computer keyboard key-guard, a home automation system with web interface and a proposition for digitally creating audio/video description, to name a few.

User interfaces for this population are also an important aspect to be considered. Cofre et al. [64] presented a domotic tool prototype for controlling the artifacts and devices in their surroundings using a touchscreen-based mobile device. The concept of this device comes from the user perspective and what is required for any person with motor disabilities. In that sense, authors summarize in four points the requirements of their device which could be applied to any other user interface for this population:

1) Users must recognize the tasks and have the capability of performing them.
2) Sufficient mobility is required so the users can interact with the mobile device.
3) Users should have supporting people like family and roommates which can help him/her through the process.
4) Supporting people should be willing to interact with new technology and create the instances to support the improvement of the user's life quality.

Sometimes, mechanisms for specific impairments are considered by researchers. Plaza et al. [65] presented "an electric and mechanical prototype for quadriplegic people provided that they can perform [a] specific grade of mobility". Using the jaw as an oral mouse, or fingers in case they can be moved, the mechanism grants mobility to the user by commanding a wheel chair. Authors conclude that people "do not consciously send commands to every muscle in each leg in order to walk and do not think where to step to avoid an obstacle. Similarly, a wheelchair-bound user of the project simply has to send the signal to go in a certain direction and the chair figures out how to get there".

User Interfaces Applied to Smart Home Environments

As smart home environments become more sophisticated, equally sophisticated user interfaces are required in order to let them have complete interaction with the system. There is no consensus for the required specification for user interfaces in smart home systems as long as they bring the necessary options and functionalities. Mantoro et al. [22] states that "in order for smart homes to improve the lives of occupants through socially appropriate and timely assistance, they will need to sense, anticipate and respond to activities at home".

User interfaces could be as simple as a remote control or a mobile app, and complex as tracking systems and air gestures and speech command recognizers. User interfaces are proposed according to the main focus of the system. It was found that systems for the elderly tend to implement user tracking mechanisms for determining where the user is and what he or she is doing. In some cases using a mobile app (for home and remote access) is enough for controlling and receiving information from the system. Despite such differences, it was found that designing easy user interfaces is a must. Rotondi and Piccione [66] mentioned that "as more end-users start using smart devices (e.g. smartphones, smart home appliances, etc.) the need to have more understandable and easy to use access control mechanisms increases". This situation requires special solutions to create user interfaces which match the tastes and preferences of the inhabitants.

Combining different types of interfaces allows researchers and designers to develop complex systems for multiple purposes. As an example, Hsu et al. [39], previously mentioned in Chapter III, prototyped a smart refrigerator that can verify if the quantity of any food is below a specified number, also, it could be used as a command system to send instructions to other household appliances if an action is required. Three user interfaces were designed for the system: 1) A speech command recognition system which is used when the user asks the refrigerator for a specific stored food, 2) A phone interface which is capable of receiving instructions via phone calls, and 3) a PC-based graphic interface where users can interact directly with the system.

By 2004, mobile devices were changing from classic designs to sophisticated smartphones with multiple new options to be found in the device by the common user. Despite these new approaches, users were accustomed to relatively small cell phones with basic user interfaces based on the standard elements brought by J2ME API. By that time, Koskela et al. [67] studied three different types of user interfaces applied to smart home systems based on common technologies: PC, media terminal and cell phones. In their research it was found that users associate different kinds of functionalities regarding the user interface. They classified two main types of activity patterns depending on the UI solution: 1) Pattern control, based on PC and media terminals where users tend to predetermine and plan different tasks to be performed by the system, and 2) Instant control, where using cell phones the users take immediate control over a real-time context. Additionally, authors found that users were interested in centralized control using mobile phones, which is clearly an expected functionality for mobile devices nowadays.

Some researchers propose to solve the problem of multiple user interfaces by defining a single interface with adaptive capabilities according to the type of interaction. Song et al. [68] present a context-adaptive user interface which uses Bayesian networks to predict the requirements of the devices given the context and required functions. Similarly, Kartakis et al. [68] developed a home controlling application that is capable of generating user interfaces according to the type of device connected to the system. What both proposals have in common is that automatic discovery of devices is performed by the control without user intervention. Additionally, GUI must adapt to the identified functionalities of the detected device. These kinds of interfaces are closely analyzed in the Control Interfaces subsection.

It is important to state that not all smart home systems need complex user interfaces in order to interact with them. In these cases, systems learn from daily user actions without receiving specific information by the users. Generic user interfaces are desired for common situations, however, they are not easy to implement due to the huge number of variables to consider that are coming from devices, environments, and user preferences. Deriu et al. [70] introduced XPlaces (eXtensible Places), a multi-platform framework for enabling interactive applications for distinctive environments. This approach could be classified as a generic open architecture for any smart home system, which can be used to gain access to different types of devices in a familiar way according to the situation. Technically, XPlaces is "a message-oriented middleware written in ISO C++ based on Linux distribution". Their purpose is to collect data from different situations, classifying them in different scenarios and providing the most appropriate behavior for each scenario.

In the case of security systems, they only need to do tracking of users and enabling access when requirements are fulfilled. Das et al. [48] proposed a low-cost system focused on security and appliance management. Using IR sensors, the system is capable of detecting if a person is entering or leaving a room. For access control, a keyboard is implemented where users enter a password which indicates if he or she is allowed to enter the restricted area. These kinds of systems require minimal interactions with the user in order to work.

Energy saving systems are focused on reducing consumption costs, which means they use real-time data as input for forecasting values and consumption profiles. The system proposed by Di Giorgio et al. [35] falls into this category. No complex user interfaces are required for these environments, just simple control panels where users can check the information and authorize the calculated schedule. Usually, a web page is provided by the home gateway as a control panel.

Finally, much more sophisticated user interfaces have been proposed using Brain-Computer Interfaces (BCI) for communication and control. Aloise et al. [71] considered BCI and implemented a prototype for performing four basic actions: turn ON/OFF a webcam, open a door, and turn ON/OFF a light and a fan. At this moment, BCI are intrusive interfaces as they require the user to wear additional garments in order to interact with devices. At the same time, Kanemura et al. [72] considers that Brain-Machine Interfaces (BMI) can assist aging societies and improve human welfare by enabling robots to do whatever the user wants. Their proposal is focused on the elderly and consists of a wheelchair that assists the user in mobility throughout the house. Several waypoints are deployed in specific spots, containing a list of possible actions that the user may choose in order to be executed. Such implementation guarantees that the system will not perform any undesired action far beyond a user's range of action.

When considering gesture-based interfaces, it is important to recall that gestures design is not a trivial task, considering that not all users may understand a single gesture in the same way (this could happen because of cultural background or academic literacy). Ashbrook et al. [73] mentioned that designing a gesture system requires three stages:

1) Design user studies and market research for considering which functionalities may be controlled with gestures.
2) Determine how gestures will activate a specific functionality of the device. It requires a set of test cases in order to be sure that a single gesture is used for the specific functionality. Additionally, it is required that the gesture fit in the user's everyday movements.
3) Perform final user testing and deploy the product.

Following the same idea, Kohlsdorf et al. [74] mentioned that designers should consider the user-defined gestures and the stored typical user gestures. Using their gesture developer framework, MAGIC (Multiple Action Gesture Interface Creation) Summoning's, they can verify if a proposed gesture is appropriate for a given task. Furthermore, the system is capable of suggesting a gesture pattern for mouse and trackpads. Sometimes it is desirable to give users the opportunity to define their own behavior scheme; however, average users are not familiar with rule environments or any other programming factor. Ur et al. [75] investigated how practical it is to let average users program their own rules for the smart home system using IFTTT (IF This Then That) rules. They found that the semantics for composing a multiple triggered rule is complicated due to the fact that triggers could contain an event, a condition, or a combination of both. Additionally, they found that certain user-defined rules may not work or be useless if anyone interacts with the objects considered in the rule before or after the action takes place.

Control Interfaces

It is common to find remote controls for any household appliance such as DVDs, TVs and ACs, among others. In such cases, the user has to learn different ways to interact with them as manufacturers design their own control interfaces with specific functionalities. Designing a generic remote control with fully interoperability, regardless of the type of end device, is an approach for user interfaces in smart environments. Although Universal Remote Controls (URCs) are supposed to satisfy the described problem, the truth is that they have significant usability problems for the common user as they have to be configured for each type of control. The interoperability is limited by the number of available buttons on the URC and they require pointing at the device, as with any regular IR remote control in order to interact with it. Bobeth et al. [76] studied how age is relevant when selecting a specific controlling mechanism. This is a serious problem that both designers and researchers have to keep in mind if a specific age is considered. Considering older adults, authors recommend "to avoid unnecessary display switches e.g. by mirroring the TV screen on a tablet".

For some smart home environments, researchers propose their own controls. Gill et al. [77] as mentioned before in Section II, proposed a low-cost smart home system based on ZigBee and Wi-Fi communications merged together in a single home gateway which enables communication between devices and grants user external control over the system. The system comes with a ZigBee remote control that enables direct interaction of the user with the ZigBee devices. For external control the home gateway enables user interaction using a web page where users can check the status of the system and switch ON/OFF devices. In the same way, Sandu et al. [78] proposed their own control applied to smart home environments, using an IEEE 802.11 compliant on an embedded web server and a Pocket PC smartphone as the mobile interface of the controller.

Bjelica et al. [79] and Garzotto and Valoriani [80] considered that single devices, like controllers and small displays, are the best option for controlling smart home environments given the requirements of mobility within the house and the easy access to a general controller of the system. Additionally, it is required that such a device needs to be capable of interacting with several communication protocols (in cases where no device manager is available) for absolute command of the system.

Sometimes it is desirable to have a single remote control to interact with every device and household appliance. Following what some authors have proposed on this topic, several common aspects that this type of controls needs to have were found. As seen in Fig. 7, URCs for home automation purposes need:

1) **Automatic recognition of communication protocol**: Controls should implement the essential mechanisms of several protocols in order to identify which of them is used by the device. By doing this, the compatibility with commercial electronics is granted. No additional settings must be performed when new appliances are installed in the house.
2) **Display**: Due to the fact that a set of buttons could be unnecessary or deficient, according to the functionalities of the device or household appliance, universal controls for smart home environments are proposed with some kind of display where users can visualize the incoming information of the device and the type of actions that he or she can perform using the control.
3) **Two-way wireless communications**: Regular commercial controls are one way only (user to device) which is inefficient considering that it is desirable to know all the functionalities offered by the device or household appliance. Proposed controls implement complex mechanisms for understanding what the end device could perform and how to give the instructions commanded by the user.

Although this type of control is complex to build, considering all the protocols and standards it has to follow, researchers have successfully developed several fully functional prototypes. Bjelica et al. [81] proposed an embeddable home control, based on POSIX/Linux, which is capable of adapting to different protocols. They consider that controlling itself is not enough for a home controller device, for that reason, their proposal includes the capability of creating and executing control macros for more complex commands. This solution supports X10 using a Marmitek X10 transceiver. Also, it supports ZigBee using a single ZigBee USB dongle.

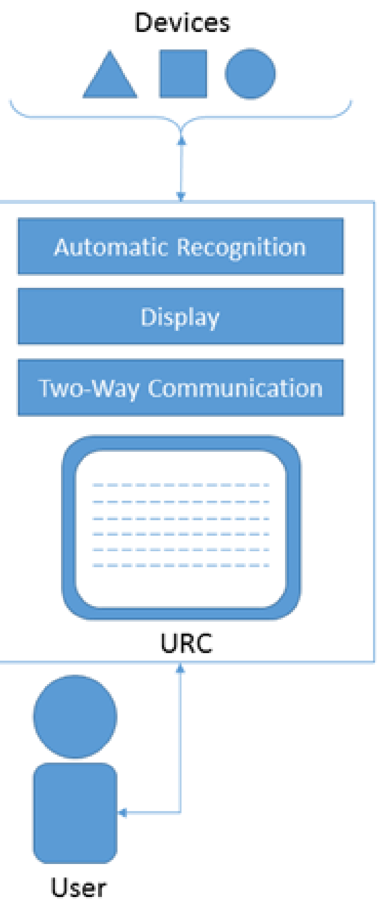

Figure 7. Proposed functionalities for a universal control.

Thinking about a URC compatible with as many devices as possible requires new implementations of classical mechanisms in order to work over well-known and stable standards. This is the case of Lai et al. [82] who designed a Radio Frequency for Consumer Electronics (RF4CE) which is capable of interacting with several devices when discovery and pairing processes were done successfully. Their controller has an integrated LCD display where the multiple options of the device are shown and which can be commanded from the controller.

In some cases it is common to find proposals from the videogame industry transformed into daily living interfaces. Pan et al. [83] presented the GeeAir, a remote control for controlling home appliances with a mix of modality of commands. This control, similar to the Nintendo Nunchuk in shape, uses buttons, gestures, a joystick, light signals and speech commands to help users indicate the device to control and give instructions. Authors remark that GeeAir is suitable for people with physical, hearing or vision impairments. Just like playing Wii games, users can control household appliances using the set of buttons offered by the control. In a very similar way, Rifon et al. [62], whose system for disabled persons was discussed in Chapter V, uses a Wii remote-like device for managing several features offered by the system.

Mobile, Phone and Web based Interfaces

Since the 90's, the boom generated by the Internet and mobile phones has enabled new ways of interaction between users and digital systems. Such new technologies brought immediate responses (in both data and communications) and the possibility of remote communications with real mobility. These interfaces bring remote access to the system through home gateways (reviewed in Chapter III). In Fig. 8, it can be seen how remote access can assist users to interact with the system. Such interaction can be classified as:

1) **Task Scheduling**: Users can set several tasks to be performed at certain times and be repeated at intervals of time. In such cases, it is only needed to specify the task once and the system will execute it as specified.
2) **Home Monitoring**: Real-time information will be available once the user enters the respective application. Users can verify the status of devices and even certain home inhabitants in special cases, like caring systems.
3) **Event Notification**: Once a special situation occurs within the home, users will be notified as soon as the event is launched. This interaction will bring updated information of what is happening in the system.
4) **Alert Notification**: Similar in functionality to Event Notification but different in meaning, this is when an undesired situation happens such as a fire, gas or water leak, or intrusion, the system will send an alert to the user who will take the required action.
5) **User Authentication**: Using a username/password combination or Near-Field Communications (NFC) technology, users can identify themselves and gain access to the house or the functionalities of the system.
6) **Remote Surveillance**: Accessing cameras and other security devices could be done by a mobile phone app or a web app. In this way, when the user is far away from home he or she can visualize what is happening within the house and in the surroundings.

Ahmed et al. [48], as mentioned before in Section II, developed a home monitoring system based on low-cost cell phones. Using several cell phones placed in different places across the house, the system is capable of monitoring several environmental variables and detecting intrusions. The system sends information and receives commands using either SMS with a specific format or miscalls. In order to communicate with the system, the user has to know the format in which the system understands what to do. The second mechanism is to make a number of rings to the main cellphone of the system. Each number of rings indicates an action to be done in the system.

Mobile apps for contemporary mobile OSs are also considered as solutions for user-system communications. A featured characteristic for this kind of solution is that it is possible to gain full control of the system directly by the options available on the app. Additionally, user profile configurations, task scheduling and event alarms may be configured in a similar way like setting up contacts or alarms on the mobile device.

Bittins et al. [84] developed an iPhone solution for KNX systems. Zhong et al. [85] proposed the HouseGenie control, a universal control based on smart phones for smart home controlling and monitoring. Baraka et al. [34] designed and implemented a low-cost system based on the Arduino microcontroller as a device communication system, and an Android Tablet as the user interface. The system was designed for energy saving and task scheduling. The tablet is used as the only mechanism for the user in order to know the status of the connected devices in the home network. Also, it provides the possibility to specify several tasks that the system must perform (i.e. switching ON/OFF devices) defining a time period and a priority value over other assigned tasks. The application allows the user to add new devices to the network and classify them by their type. Additionally, the application supports X10 and Zigbee protocols which guarantee a direct communication with the connected devices.

Kim et al. [33] introduced an energy saving system based on OpenWrt. Designed for lighting control, the system lets users manage the lights connected to the

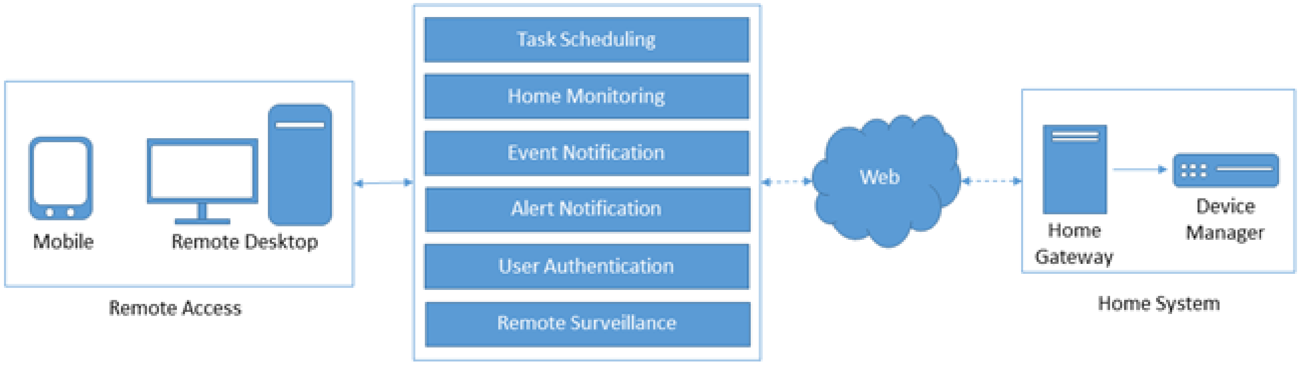

Figure 8. User actions performed remotely.

system using their mobile phones. Depending on the type of the light it could be turned ON/OFF or have its brightness level adjusted from 255 (light) to 50 (dark).

Some home monitoring systems are focused on context-awareness. Bjelica et al. [40] proposed a system capable of determining if a user is available or not. The system could be applied in both office and home environments; however, the authors state that it is harder to determine the availability of the user in a home context than the office context. Instead of using a flag mechanism to indicate availability, a color scheme is implemented. Using the red, yellow and green colors the system indicates that the user is not available, moderately available or highly available. The light, that could be placed anywhere, indicates to other people if the user is willing to be interrupted.

Georgoulas et al. [58] proposed an assistance system for the elderly. The system approach seeks to help users to reach stored items using a robotic furniture system which gradually changes the height of the modules in order to let the user reach items from a seated position. Also, the system works as a health assistant and a communication terminal. The system architecture is based on a Microsoft Kinect, an Arduino microcontroller board, an RFID reader, vital signal monitoring devices and a tablet PC. Using the Kinect sensor, the furniture system tracks the user's actions and the stored items. Once the user approaches the vicinity of the furniture, the system follows the user until it detects the cabinet where the desired item is stored. The user can specify the required item indicating its color by speech commands. Following the user actions and the speech commands, the robotic system adjusts the height of the cabinet until it reaches a reasonable height for the user. For the health assistance functionality, several sensors are placed on the user for vital sign and health status monitoring. The acquired data is sent to a monitoring gateway which enables remote access to the data through an online website. Using a username and password registering mechanism, any authorized physician can check the information of the user's vital signals and health status.

A different approach for mobile solutions is user authentication. This is achieved when smartphones, or any other type of mobile devices, are used as the required devices where users insert their authentication data in order to have access granted. The Home Safety Handwriting Pattern Recognition (HSHPR) [51], proposed by Lian et al., is aimed to the described philosophy. When a user needs to enter or leave the house, the smart phone is used to lock/unlock the door. Drawing a gesture, previously entered in the system, from a valid device (validation given by its IP address), which the system verifies. The system can be used as a humidity and temperature monitor when required.

Brain and Wearable Interfaces

Although not so common, brain and wearable interfaces have been proposed for domotic purposes. Such proposals tend to facilitate interactions with devices that users can wear anytime (like watch clocks or tiaras) in order to gain access to smart home systems.

In terms of brain interfaces, Carabalona et al. [86] studied the feasibility of BCI (Brain-Computer Interface) systems applied to smart home environments. Authors found that this type of interface is susceptible to fatigue and the health status of the user. Additionally, in their results, it was shown that feelings like frustration and disappointment may affect the results of the interaction.

Wearable devices are an interesting approach considered by several researchers. They include traditional elements like hand watches. Bonino et al. [87] introduced the dWatch, a wearable device for managing domotic systems using the Dog Gateway [88]. dWatch was designed to be a "personal wearable notification, sensing and control device". This device let the user know the status of the household appliances connected to the home network. Also, it lets the operation of appliances be controlled by gestures which are recognized by the wrist device. As a notification assistant, it lets a homeowner set alarms and reminders which could be activated once the dWatch detects a specific event. Another characteristic is to give control to multiple users over the same domotic network, such as parents and offspring. Using the main dWatch it is possible to give privileges and limitations to the other associated devices which can control the domotic environment. Additionally, dWatch allows one to establish a hierarchy of users over several domotic networks, such as building managers.

Cloth as user interface is also under consideration for smart home environments. Araujo and Salvado [89] presented the SmartVest, a clothing technology designed for application in home automation and health care. The device, used a as coat, is capable of recognizing speech commands and is context-aware, which means that it can recognize what the user is doing based on external information. Additionally, it can monitor vital signs which are sent to a server where data is processed and then sent to doctors or any other specified person. Ananthanarayan et al. [90] proposed a similar device focused "to empower people to design and build their own personal health visualizations". The system could be adapted to any visual representation and it tracks several internal and external signals that will let users know their real-time health status.

Natural User Interfaces

One of the key aspects of current smart home systems is to create the most natural interfaces possible, which means that the system should know what the users want by checking their movements and being the least intrusive to common actions. Using tracking devices like Microsoft Kinect, Leap Motion and Creative Senz3D, it is possible to track specific movements of the user. However, the system should differentiate between gestures (actions performed to give an order) and casual movements that are not intended for the system. This differentiation is complex to determine and it requires sophisticated algorithms and Artificial Intelligence techniques in order to be as accurate as possible. In Fig. 9, the main approaches for capturing a user's actions/commands are shown using natural user interfaces and classical user interfaces. Regarding this kind of interface, O'hara et al. [90] state that "Naturalness, here, is an occasioned property of action that social actors actively manage and produce together in situ through their interaction with each other and the material world".

Several solutions based on natural user interfaces have been proposed using cutting edge technologies like Kinect (Maggiorini et al. [92]) and Leap Motion (Vatavu and Zaii [93]). Wachs et al. [94] analyzed such mechanisms in terms of cost/benefits, price, responsiveness, user adaptability and feedback, learnability, accuracy, mental load, intuitiveness, and comfort. When considering such interfaces they state that "Lexicon design should avoid gestures that require intense muscle tension over long periods, a syndrome commonly called Gorilla arm".

Although air gestures could be configured to be daily movements (e.g. pushing a door or a window to open it), not many users prefer this type of interface. According to Ho et al. [95], young users (aged from 19 to 25) prefer unimodal gestures (only one type of input) to multimodal gestures (a combination on inputs from air, speech and touch interfaces). They also found that response time is a crucial aspect to be considered while designing gestures. In their words: "Preferred transition-duration and gesture-duration were correlated, along with the force of a participant's gesture".

The problem with air gestures is that they differ from user to user. Although there are significant similarities between them, not all gestures mean the same for all users. Kela et al. [96] formally found that not all people identify the same gesture for controlling a device. According to them, it is important to identify the suitability of gestures and the type of gestures for any specific home appliance and interactive virtual reality environment. For a smart home environment it is necessary to allow users set their own air gestures, which includes training the system by using several repetitions of the same gesture.

Gnanasekar et al. [61], mentioned earlier, developed a smart home system based on speech commands and RFID authentication for physically challenged persons. With a set of 40 speech commands, the user is capable of turning ON/OFF loads. The system allows the definition of user profiles in order to improve speech command recognition accuracy (going from 75% to 90%). Additionally, the system uses a desktop application where the user can check the status of each device in the system, indicating them with green, yellow or red if it is turned ON/OFF or if it is under fault condition.

User authentication could be made by either RFID or speech command. Vassev et al. [96] considered speech commands for their system based on wireless sensor networks. Milhorat et al. [98] applied speech commands as the main input mechanism for communicating with an assistance robot. They considered crucial aspects like external noises and false positives that are common issues in this kind of interface. Considering the elderly as the specific user, Portet et al. [99] found that "participants particularly appreciated the fact that this speech technology can bring more security by warning in case of hazardous situations or by allowing people to call for help in case of a fall".

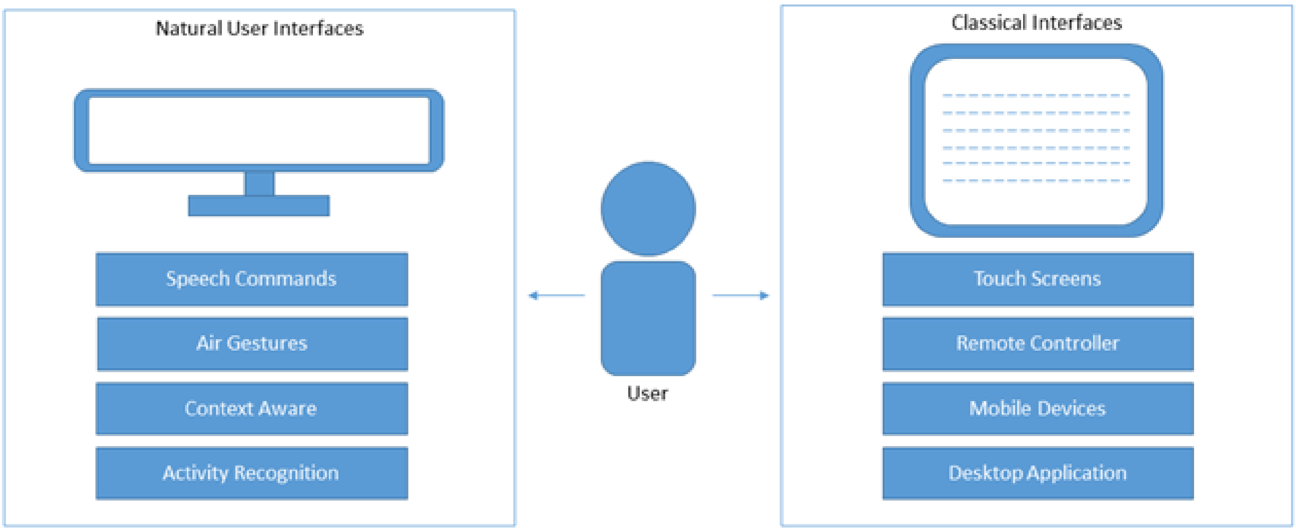

Figure 9. User Interactions with home environment according to the type of interface.

Virtual and 3D Environments

There are users who want to have more immersive interfaces of the controlled environments. Using 3D virtual worlds, researchers have proposed more interactive scenarios which bring a new level of interaction with the smart home systems, such as playing videogames. Still, the purpose of the system keeps on being a controlling interface for actual devices and loads. Han et al. [100] proposed a 3D virtual world interface for managing appliances. A 3D model, based on the user's actual house, is rendered for a complete visualization of connected appliances in the system. Using an avatar, the user can travel through the environment and interact with the devices. The proposed system uses an intermediate server which stores the models of both house and avatars to be used. Also, the server communicates to the home gateway all the actions performed by the user. Using this architecture, it is possible to do remote controlling from any PC with the desktop application of the system.

These types of interfaces are suitable for learning without taking risks in the actual house. Jimenez-Mixco et al. [101] designed a virtual reality interface for the elderly and disabled community, focused on immersing environments where they can learn some tasks and acquire habits before interacting with the actual ambient assisted living environment.

Other solutions, such as those provided by Drey and Consel [102], Luque et al. [103], Camacho-Guerrero and Macedo [104] and Mardanbegi and Hansen [105], focus on bringing visual environments, similar to the actual house, in order to help users to define actions and monitor events. Such environments are helpful to identify the location of sensors and actuators inside the architecture of the house and to determine how such devices interfere with their daily actions.

Evolution of Smart Home Systems

The reviewed systems were presented by their authors as home automation or smart home systems. Regardless of their approach or objective, those systems were proposed as alternatives that complement a user's actions and bring assistance to his/her daily situations. Several common aspects could be identified in each one of the systems which help to define the minimal requirements that a current home automated system should have. Kim et al. [33] described the basic aspects of current home automation systems. They say "A typical home automation system of today consist of a Wi-Fi router or an internet connection, a smart home gateway and multiple nodes (known as end devices). These systems can commonly be installed in standard homes, making the homes smart."

However, there is an important challenge yet to be faced in the topic. As Gill et al [77] stated: "These systems have made a significant contribution to the development of a home gateway. However, the existing network infrastructure within the home environment has not been taken into consideration when selecting the networks for integration with the respective home gateways. Moreover, the existing research has focused on the provision of remote connectivity and has largely neglected investigating the integration of existing local networks" [77]. This is a crucial aspect to be taken seriously if scalable systems are a desired design result regardless of the type of networking the devices and household appliances implement.

Activity Recognition

Knowing what the user is doing and bringing automatic assistance based on activity recognition is a promissory research field that is attracting the attention of many researchers in home automation and domotics. Approaches such as Belley et al. [45] and Aloise et al. [71] demonstrate that such interfaces are capable of being fully functional with any user. The major benefits of activity recognition can be found in assistive living and healthcare smart home systems. This type of system has been evolving from monitoring to full user tracking in a way that the system is capable of determining the kind of help it can provide according to the circumstances. There are still several problems to be solved such as the reliability of predictions [106], as well as the situation when the same action could be interpreted in different ways (sitting in the living room differs from sitting in the toilet or dining room). Many of the proposals in this category are ontology-based, which are considered in the next subchapter.

Intelligent Systems and Ontology-based Domotics

Bringing intelligence to the system is an interesting approach that has attracted the attention of designers and researchers. Concepts like agents, ontologies and semantic web have been considered to enhance interoperability between devices, user monitoring and context-aware solutions capable of determining with high precision what the users are doing. The concept of agents has been applied to domestic domotics. Moergestel et al. [107] proposed an agent-based architecture focused on expandability and hardware independence. Agents are deployed throughout the system and are tied directly to actuators, sensors and devices involved. By using agents, no direct communication with devices is required, instead, a single communication mechanism based on XML is used for this purpose. Similarly, Satterfield et al. [108] proposed agent architecture for recognizing activities and monitoring inhabitants in order to bring assistance when required. Additionally, an ontology encoded in Resource Description Framework (RDF) style was developed with the purpose of matching features and constraints when a well-defined event is observed in a home.

Cheng et al. [109] say that "it is more reasonable to make a home adapt to family member behaviors than a user adapt to limitation functionalities of a home". Keeping this in mind, they proposed the Adaptive Scenario Based Reasoning (ASBR) system, which is capable of learning the user's preferences and building different scenarios according to the situations. The description of such scenarios is stored in an ontology-based context information system where knowledge can be produced and evolved from regular updates.

Applying the related concepts of Semantic Web or Web 3.0 is a new path opened by Gu et al. [110] as an alternative intelligence mechanism applied to smart home environments. They started with a context-aware proposal for rapidly prototyping smart home environment applications based on reasoning and knowledge sharing coming from ontology-based context models. This approach has been the principal pillar of this particular area in home domotics. Authors like Hu et al. [111], Bonino et al.[112], Huang et al. [113], Kao et al. [114] and Abreu et al. [115] have proposed several architecture designs based on ontology systems which enable the evolution of the obtained knowledge, and match certain rules in order to determine contexts and scenarios where users may interact. Such a solution requires following the preferences of each user. However, the results are distinctive from one another and the results get better as the users interact with the system.

Ontologies have been considered for energy saving systems. Cheong et al. [116] presented an ontology-based reasoning approach applied to saving energy in a smart home while using a mobile phone as a generic sensor for collecting the user's contextual data. The data collected by the system is sent to a central server which reports the status of the requested device and its electricity level to the respective user. Grassi et al. [117], [118] introduced a couple of ontologies focused on description of devices and power generations and consumption for intelligent task management and energy consumption optimization. The collected information is related to a context, a device, and a service. With the analysis of the usage patterns of the device and data based on external variables like weather and temperature, the system is capable of scheduling automatic tasks at certain hours where energy consumption gets lower values depending on the priority of the task.

For the current problem of heterogeneous devices, Miori et al. [119] applied such concepts as looking at interoperability among different and incompatible devices, giving all of them a computational significance. This problem was also faced by Zhnag et al. [120] who discussed semantic based ontology models applied to smart appliances. They concluded that, at development and deployment levels, describing smart appliances using ontologies rather than other mechanisms makes such processes easier and more efficient. Ontologies gave them the impression that developers only care about the description of the devices instead of specific procedures. A similar approach was proposed by Xu et al. [121] who considered the diversity of household appliances and residents in the same house, hence, using an ontology-based framework facilitates the composition of appropriate applications for house appliances rather than configuring and adapting each of them in the smart environment. Additionally, they designed a template which can be edited by customers in order to specify their behavior within the environment. This last specification enables the composition of user profiles with a set of appropriate appliances according to the defined behavior.

Chikhaoui et al. [122] proposed a universal ontology aimed at dealing with the integration of ubiquitous computing in smart home environments. Their proposal solves the problem of referentiality (referential location and referential time [123]) and environmental change. Authors recognize that "Despite the huge efforts provided in the development of ontologies for smart environments, the development of a complete ontology remains a difficult task".

Considering context-aware situations, Cacciagrano et al. [124] combine an RFID-based framework with an ontology based knowledge model for locating objects in delimited spaces to prevent or detect dangerous configurations within the home. Additionally, they use the first order logic-based model for statistical detecting of both spatial and temporal configurations of objects that could initiate a dangerous situation. Zhao and L [125] compared three different methods (key-value, logic model and ontology) applied to context-aware systems in smart home environments. According to their conclusions, ontologies are helpful for sharing knowledge by defining relations and rules. Furthermore, it is the most formalized mechanism, so far, to improve sharing, reasoning and reusing context. Chen et al. [126] introduced an ontology-based hybrid for activity modelling using a domain knowledge-based model and a data driven learning model. Starting the process with a "seed", the system starts the recognition process by extending the knowledge using activity discovery and model update. Finally, ontologies have been considered for the design of context-aware solutions focused on disabled users. Sohn et al. [127] proposed a framework based on three ontologies: 1) generic service ontology, 2) personalized service ontology, and 3) service context ontology. Such ontologies interact with each other in order to recommend personalized services according to the context where the disabled person is.

Recognizing user activities is another problem using ontologies might solve. Wongpatikaseree et al [128] proposed a complex solution based in three tiers: 1) a context-aware infrastructure ontology to describe and model the context within the smart home where the users are located. 2) A set of rules to describe human activity and identify it by object-based and location-based concepts. And 3) an ontology-based activity recognition system for both recognizing the activity and finding its semantic information. Similar to other researchers in the field, they recognize that "although the system can recognize the human activity, it still needs to improve the complex rules for more specific activities".

Conclusion and Future Challenges

Over the last five years a number of important results have been obtained regarding smart home environments, and considering aspects such as the overall architecture, expectations of the current users and manifold ways to operate such systems. It can be observed that aspects like comfort and all-in-one controls are no longer the focus of researchers and designers, instead, the meaning of having an interconnected environment with the possibility of external monitoring has become the key concept of the most recent proposals.

Throughout mankind's history, technology has provided better working and living environments always trying to help people in their daily actions. Nowadays concerns, such as taking care of loved ones from a distant location, are now possible to solve thanks to monitoring systems. This type of care is enhanced even more by complete home environments that, as mentioned throughout this survey, have been conceived to be fully operational with any kind of user under any circumstances.

But technology itself is useless if no appropriate user interfaces are provided to work with it. In this aspect, recent proposals have moved from desktops and mobile phones to be much more flexible and intelligent systems. Currently, people are facing tracking technologies without even being notified (mostly, for security and surveillance reasons), and this kind of technology has been embraced by researchers who propose that the smart home should be capable of determining what the user is doing and how it can be of assistance. It is clear that such interfaces are not intended for everyone, so it is still common to find mobile solutions as the central alternative for controlling the entire system. As long as mobile devices are required for communications, they will continue to be the preferred interface by many users.

Even with such progress, the problem of several closed technologies generates confusion in the market and reduces the number of available applications for the general public [28].

From Table 2, the dominating topics in the area of smart home research can be seen. Authors have focused mainly on home and user monitoring for security purposes, and environmental monitoring. Another important topic has been home controlling or home automation. However, the following topics (as shown in Table 2) should become more relevant to researchers in order to be able to accommodate new trends that users are already experiencing with other technologies like smart health care, and smart entertainment:

Context awareness: people are getting used to receiving useful information from their personal devices which are more and more aware of each user's detailed behavior. Smart home systems should incorporate already gathered information from the user to improve their level of comfort and general quality of life during their home hours.

User authentication: people are acquiring high levels of Internet connectivity through differing smart devices like watches, refrigerators and TVs. And they are becoming less and less aware of the vulnerability of their personal information. Research on smart homes needs to include solutions to the security threats that increased levels of connectivity are creating for users.

Scheduling: this is a consequence of systems becoming more aware of their context. In general researchers should give more importance to this topic as proper management would reflect on the user's quality of life.

Smart health: another aspect of smart devices that is becoming more relevant to the user every day is the possibility of using smart technologies to improve and keep better records of their health. The explored research did not show any relevant connectivity with new smart health technologies. It is thought that smart homes should help the user in the purpose of improving their health. For example, smart refrigerators, smart exercise devices and smart TVs could collaborate in improving the user awareness about their need to: eat healthier, do more exercise and change sedentary routines.

The topics examined above are not covered as necessary in the literature but, if correctly implemented in smart home systems, they could make them more attractive to final users and accommodate current trends in smart technologies for the entire family.

Acknowledgments

This survey was supported by the Colombian Administrative Department of Science, Technology and Innovation Colciencias, under the program "2013 Call for forming eligible banks for high-level training for science, technology and innovation: young researchers, national and abroad doctorates, and job placement". The authors would like to thank the Universidad del Norte (Barranquilla, Colombia) and GReCIS (Grupo de Redes de Computadores e Ingeniera de Sistemas) for supporting this research.

Table 2. Comparison between proposed smart home environments.

Proposed by	***Speech Commands***	***Visual Tracking***	***Context Aware***	***Environment Monitoring***	***Home Monitoring***	***User Monitoring***	***Home Control***	***User Authentication***	***Scheduling***
Georgoulas et al.	X	X							
Ahmed et al.					X				
Yu et al.					X				
Baraka et al.					X				X
Bjelica et al.			X				X		
Das et al.		X		X					
Kim et al.						X			
Camier et al.					X				
Gill et al.					X	X			
Di Giorgio et al.				X	X				
Gnanasekar et al.	X					X			
Hsu et al.	X		X			X			
Lian et al.					X			X	
Allerding et al.					X				
Walch et al.				X	X		X		

Vassev et al.	X			X			X		
Patricio and Gomes				X	X		X		
Mantoro et al.			X	X	X	X	X		
Mrazovac et al.		X	X	X	X	X	X		
Su et al.				X	X		X		
Saeed et al.				X			X	X	

References

[1] E.-C. Wong, “A phone-based remote controller for home and office automation,” *Consumer Electronics, IEEE Transactions on*, vol. 40, no. 1, pp. 28–34, 1994. doi: 10.1109/30.273654

[2] B. Koyuncu, “PC remote control of appliances by using telephonelines,” *Consumer Electronics, IEEE Transactions on*, vol. 41, no. 1,pp. 201–209, 1995. doi: 10.1109/30.370328

[3] Z.-M. Lin, “A remote telephone-controlled home automation system,” in proceeding of *IEEE Southeastcon '98 'Engineering for a New Era*, Orlando, FL, USA, April 24-26, 1998, pp. 148–152. doi: 10.1109/SECON.1998.673314

[4] I. Coskun and H. Ardam, “A remote controller for home and office appliances by telephone,” Consumer Electronics, IEEE Transactions on, vol. 44, no. 4, pp. 1291–1297, 1998. doi: 10.1109/30.735829

[5] A. Al-Ali and M. Al-Rousan, “Java-based home automation system,” *IEEE Transactions on Consumer Electronics*, vol. 50, no. 2, pp. 498– 504, 2004. doi: 10.1109/TCE.2004.1309414

[6] K.-Y. Lee and J.-W. Choi, “Remote-controlled home automation system via bluetooth home network,” in proceeding of *SICE 2003 Annual Conference*, Fukui, Japan, August 4-6, 2003, vol. 3, pp. 2824–2829.

[7] R. Piyare and M. Tazil, “Bluetooth based home automation system using cell phone,” in proceeding of the *IEEE 15th International Symposium on Consumer ElectronicsSymposium*, Singapore, June 14-17, 2011, pp. 192–195. doi: 10.1109/ISCE.2011.5973811

[8] T. Saito, I. Tomoda, Y. Takabatake, J. Arni, and K. Teramoto, “Home gateway architecture and its implementation,” *IEEE Transactions on Consumer Electronics*, vol. 46, no. 4, pp. 1161–1166, 2000. doi: 10.1109/30.920474

[9] N. Kushiro, S. Suzuki, M. Nakata, H. Takahara, and M. Inoue, “Integrated home gateway controller for home energy management system,” in proceeding of *Consumer Electronics*, *IEEE International Conference* LA, CA, June 17-19, 2003, pp. 386–387. doi: 10.1109/ICCE.2003.1218986

[10] S. Ok and H. Park, “Implementation of initial provisioning function for home gateway based on open service gateway initiative platform,” in proceeding of *the 8th International Conference Advanced Communication Technology*, Phoenix Park, Korea, Feb. 20-22, 2006, vol. 3, pp. 1517-1520. doi: 10.1109/ICACT.2006.206273

[11] A. Peine, “Technological paradigms and complex technical systemsthe case of smart homes,” *Research Policy*, vol. 37, no. 3, pp. 508-529, 2008. doi: 10.1016/j.respol.2007.11.009

[12] L. Takayama, C. Pantofaru, D. Robson, B. Soto, and M. Barry, “Making technology homey: Finding sources of satisfaction and meaning in home automation,” in proceeding of *the 2012 ACM Conference on Ubiquitous Computing*, NY, USA, Sep. 05-08, 2012, pp. 511–520. doi: 10.1145/2370216.2370292

[13] E. K. Choe, S. Consolvo, J. Jung, B. Harrison, and J. A. Kientz, “Living in a glass house: A survey of private moments in the home,” in proceeding of *the 13th International Conference on Ubiquitous Computing*, NY, USA, Sep. 17-21, 2011, pp. 41–44. doi: 10.1145/2030112.2030118

[14] D. J. Cook and S. K. Das, “How smart are our environments? an updated look at the state of the art,” *Pervasive and Mobile Computing*, vol. 3, no. 2, pp. 53–73, 2007. doi: 10.1016/j.pmcj.2006.12.001

[15] M. Chan, D. Estve, C. Escriba, and E. Campo, “A review of smart homespresent state and future challenges,” *Computer Methods and Programs in Biomedicine*, vol. 91, no. 1, pp. 55 – 81, 2008. doi: 10.1016/j.cmpb.2008.02.001

[16] R. E. Grinter, W. K. Edwards, M. Chetty, E. S. Poole, J.-Y. Sung, J. Yang, A. Crabtree, P. Tolmie, T. Rodden, C. Greenhalgh, and S. Benford, “The ins and outs of home networking: The case for useful and usable domestic networking,” *ACM Transactions on Computer-Human Interaction*, vol. 16, no. 2, pp. 8:1–8:28, 2009.

doi: 10.1145/1534903.1534905

[17] F. Sadri, "Ambient intelligence: A survey," *ACM Computing Surveys*, vol. 43, no. 4, pp. 36:1–36:66, 2011.
doi: 10.1145/1978802.1978815

[18] J. E. Kim, G. Boulos, J. Yackovich, T. Barth, C. Beckel, and D. Mosse, "Seamless integration of heterogeneous devices and access control in smart homes," in proceeding of *the 8th International Conference on Intelligent Environments*, Guanajuato, Mexico, June 26-29, 2012, pp. 206–213.
doi: 10.1109/IE.2012.57

[19] V. Escorcia and J. Niebles, "Spatio-temporal human-object interactions for action recognition in videos," in proceeding of *2013 IEEE International Conference on Computer Vision Workshops*, Sydney, Australia, Dec. 1-8, pp. 508–514.
doi: 10.1109/ICCVW.2013.72

[20] I. Lillo, A. Soto, and J. Niebles, "Discriminative hierarchical modeling of spatio-temporally composable human activities," in proceeding of *Computer Vision and Pattern Recognition*, Columbus, OH, June 23-28, 2014, pp. 812–819.
doi: 10.1109/CVPR.2014.109

[21] Y. Kuroda, I. Yamasaki, S. Kondo, Y. Katayama, and O. Mizuno, "A memory isolation method for osgi-based home gateways," in proceeding of *the 17th International ACM Sigsoft Symposium on Component-based Software Engineering*, Lille, France, June 30-04, 2014, pp. 117–122.
doi: 10.1145/2602458.2602461

[22] T. Mantoro, M. A. Ayu, and E. E. Elnour, "Web-enabled smart home using wireless node infrastructure," in proceeding of the *9th International Conference on Advances in Mobile Computing and Multimedia*, Ho Chi Minh City, Vietnam, Dec. 5-7, 2011, pp. 72–79.
doi: 10.1145/2095697.2095712

[23] F. Allerding and H. Schmeck, "Organic smart home: Architecture for energy management in intelligent buildings," in proceeding of *the 2011 Workshop on Organic Computing*, Karlsruhe, Germany, June 14-18, 2011, pp. 67–76.
doi: 10.1145/1998642.1998654

[24] E. Kaldeli, E. U. Warriach, A. Lazovik, and M. Aiello, "Coordinating the web of services for a smart home," *ACM Transactions on the Web*, vol. 7, no. 2, pp. 10:1–10:40, May 2013.
doi: 10.1145/2460383.2460389

[25] D. V. Keyson, A. A. Mahmud, M. de Hoogh, and R. Luxen, "Designing a portable and low cost home energy management toolkit," *Procedia Computer Science*, vol. 19, no. 0, pp. 646–653, 2013.
doi:10.1016/j.procs.2013.06.086

[26] P. Snchez, M. Jimnez, F. Rosique, B. lvarez, and A. Iborra, "A framework for developing home automation systems: From requirements to code," *Journal of Systems and Software*, vol. 84, no. 6, pp. 1008 – 1021, 2011.
doi: 10.1016/j.jss.2011.01.052

[27] L. Sommaruga, T. Formilli, and N. Rizzo, "Domoml: An integrating devices framework for ambient intelligence solutions," in proceeding of *the 6th International Workshop on Enhanced Web Service Technologies*, Lugano, Switzerland, Sept. 14, 2011, pp. 9–15.
doi: 10.1145/2031325.2031327

[28] V. Miori, D. Russo, and M. Aliberti, "Domotic technologies incompatibility becomes user transparent," *Communications of the ACM*, vol. 53, no. 1, pp. 153–157, 2010.
doi: 10.1145/1629175.1629211

[29] M. Walch, M. Rietzler, J. Greim, F. Schaub, B. Wiedersheim, and M. Weber, "homeblox: Making home automation usable," in proceeding of *the 2013 ACM Conference on Pervasive and Ubiquitous Computing Adjunct Publication*, Zurich, Switzerland, Sep. 08-12, 2013, pp. 295–298.
doi: 10.1145/2494091.2494182

[30] A. Kamilaris and A. Pitsillides, "Using request queues for enhancing the performance of operations in smart homes," in proceeding of *the 7th ACM Workshop on Performance Monitoring and Measurement of Heterogeneous Wireless and Wired Networks*, Paphos, Cyprus, Otc. 21-25, 2012, pp. 1–6.
doi: 10.1145/2387191.2387193

[31] K. Attouchi, G. Thomas, A. Bottaro, and G. Muller, "Memory monitoring in a multi-tenant osgi execution environment," in proceeding of *the 17th International ACM Sigsoft Symposium on Component-based Software Engineering*, Lille, France, June 30-04, 2014, pp. 107–116.
doi: 10.1145/2602458.2602467

[32] S. M. Blackburn, R. Garner, C. Hoffman, A. M. Khan, K. S. McKinley, R. Bentzur, A. Diwan, D. Feinberg, D. Frampton, S. Z. Guyer, M. Hirzel, A. Hosking, M. Jump, H. Lee, J. E. B. Moss, A. Phansalkar, D. Stefanovi´c, T. VanDrunen, D. von Dincklage, and B. Wiedermann, "The DaCapo benchmarks: Java benchmarking development and analysis," in proceeding of *the 21st annual ACM SIGPLAN conference on Object-Oriented Programing, Systems, Languages, and Applications*, Portland, USA, Oct. 22-26, 2006, pp. 169– 190.
doi: 10.1145/1167473.1167488

[33] C. Kim and K. Kim, "Implementation of a

cost-effective home lighting control system on embedded linux with openwrt," *Personal and Ubiquitous Computing*, vol. 18, no. 3, pp. 535–542, 2014.
doi: 10.1007/s00779-013-0671-1

[34] K. Baraka, M. Ghobril, S. Malek, R. Kanj, and A. Kayssi, "Low cost arduino/android-based energy-efficient home automation system with smart task scheduling," in proceeding of *2013 Fifth International Conference on Computational Intelligence, Communication Systems and Networks*, Madrid, Spain, June 05-07, 2013, pp. 296–301
doi: 10.1109/CICSYN.2013.47

[35] A. D. Giorgio and L. Pimpinella, "An event driven smart home controller enabling consumer economic saving and automated demand side management," *Applied Energy*, vol. 96, no. 0, pp. 92 – 103, 2012.
doi: 10.1016/j.apenergy.2012.02.024

[36] B. Mrazovac, M. Bjelica, N. Teslic, and I. Papp, "Towards ubiquitous smart outlets for safety and energetic efficiency of home electric appliances," in proceeding of *IEEE International Conference on Consumer Electronics-Berlin*, Berlin, Germany, Sep. 06-08, 2011, pp. 322–326.
doi: 10.1109/ICCE-Berlin.2011.6031795

[37] C. Yu and X. Chen, "Home monitoring system based on indoor service robot and wireless sensor network," *Computers & Electrical Engineering*, vol. 39, no. 4, pp. 1276 – 1287, 2013.
doi: 10.1016/j.compeleceng.2013.03.002

[38] G. Patricio and L. Gomes, "Smart house monitoring and actuating system development using automatic code generation," in proceeding of *the 7th IEEE International Conference on Industrial Informatics*, Cardiff, UK, June 23-26, 2009, pp. 256–261.
doi: 10.1109/INDIN.2009.5195813

[39] C.-L. Hsu, S.-Y. Yang, and W.-B. Wu, "3c intelligent home appliance control system example with refrigerator," *Expert Systems with Applications*, vol. 37, no. 6, pp. 4337 – 4349, 2010.
doi: 10.1016/j.eswa.2009.11.065

[40] M. Bjelica, B. Mrazovac, I. Papp, and N. Teslic, "Context-aware platform with user availability estimation and light-based announcements," IEEE *Transactions on Systems, Man, and Cybernetics: Systems*, vol. 43, no. 5, pp. 1228–1239, Sept 2013.
doi: 10.1109/TSMC.2012.2235425

[41] W. Lin, Y. Huang and Q. Wu, "Study on monitor system of heating ventilation air conditioning based on lonworks technology," in proceeding of *International Technology and Innovation Conference*, Xian, China, Oct 12-14, 2009, pp. 1–5.
doi: 10.1049/cp.2009.1517

[42] K. Basu, L. Hawarah, N. Arghira, H. Joumaa, and S. Ploix, "A prediction system for home appliance usage," *Energy and Buildings*, vol. 67, no. 0, pp. 668 – 679, 2013.
doi: 10.1016/j.enbuild.2013.02.008

[43] K. J. Kang, B. Ka, and S. J. Kim, "A service scenario generation scheme based on association rule mining for elderly surveillance system in a smart home environment," *Engineering Applications of Artificial Intelligence*, vol. 25, no. 7, pp. 1355 – 1364, 2012.
doi: 10.1016/j.engappai.2012.02.003

[44] F. Englert, T. Schmitt, S. K¨o, A. Reinhardt, and R. Steinmetz, "How to auto-configure your smart home?: High-resolution power measurements to the rescue," in proceeding of *the 4th International Conference on Future Energy Systems*, Berkeley, CA, May 22-24, pp. 215–224.
doi: 10.1145/2487166.2487191

[45] C. Belley, S. Gaboury, B. Bouchard, and A. Bouzouane, "Activity recognition in smart homes based on electrical devices identification," in proceeding of *the 6th International Conference on PErvasive Technologies Related to Assistive Environments*, Island of Rhodes, Greece, May 29-30, 2013, pp. 7:1–7:8.
doi: 10.1145/2504335.2504342

[46] S. R. Fanello, I. Gori, G. Metta, and F. Odone, "Keep it simple and sparse: Real-time action recognition," *Journal of Machine Learning Research*, vol. 14, no. 1, pp. 2617–2640, 2013.
http://dl.acm.org/citation.cfm?id=2567709.2567745

[47] K. Bouchard, B. Bouchard, and A. Bouzouane, "Unsupervised discovery of spatial relationships between objects for activity recognition inside smart home," in proceeding of the *2012 ACM Conference on Ubiquitous Computing*, Pittsburgh, PA, Sep. 05-08, 2012, pp. 655–656.
doi: 10.1145/2370216.2370351

[48] K. Bouchard, B. Bouchard, and A. Bouzouane, "Guidelines to efficient smart home design for rapid ai prototyping: A case study," in proceeding of the 5th International Conference on PErvasive Technologies Related to Assistive Environments, Heraklion, Greece, June 06-09, 2012, pp. 29:1–29:8.
doi: 10.1145/2413097.2413134

[49] V. Ahmed and S. Ladhake, "Novel ultra low cost remote monitoring system for home automation using cell phone," in proceeding of *2011 International Conference on Computational Intelligence and Communication Networks*, Gwalior, India, Oct 07-09, 2011, pp. 569–573.
doi: 10.1109/CICN.2011.122

[50] R. Das, S. Dutta, K. Samanta, A. Sarkar, and D. Das,

"Security based domotics," *Procedia Technology*, vol. 10, no. 0, pp. 942–948, 2013. doi: 10.1016/j.protcy.2013.12.441

[51] K.-Y. Lian, S.-J. Hsiao, and W.-T. Sung, "Smart home safety handwriting pattern recognition with innovative technology," *Computers & Electrical Engineering*, vol. 40, no. 4, pp. 1123–1142, 2014. doi: 10.1016/j.compeleceng.2014.02.010

[52] U. Saeed, S. Syed, S. Qazi, N. Khan, A. Khan, and M. Babar, "Multiadvantage and security based home automation system," in proceeding of *UKSim 4th European Modelling Symposium On Computer Modelling and Simulation*, Pisa, Italy, Nov. 17-19, 2010, pp. 7–11. doi: 10.1109/EMS.2010.15

[53] T. S. Hjorth and R. Torbensen, "Trusted domain: A security platform for home automation," *Computers & Security*, vol. 31, no. 8, pp. 940–955, 2012. doi: 10.1016/j.cose.2012.07.003

[54] T. R. Camier, S. Giroux, B. Bouchard, and A. Bouzouane, "Designing a fNIALMg in smart homes for cognitive assistance," *Procedia Computer Science*, vol. 19, no. 0, pp. 524–532, 2013. doi: 10.1016/j.procs.2013.06.070

[55] M. Mohammadi, "Automated assisted homes for the elderly," in proceeding of *the 2nd International Convention on Rehabilitation Engineering & Assistive Technology*, Singapore, 2008, pp. 266–270. http://dl.acm.org/citation.cfm?id=1983222.1983294

[56] A. Sanchez and R. Tercero, "Smart home technologies: Uses and abuses," in proceeding of *the 9th Mexican International Conference on Artificial Intelligence*, Pachuca, Mexico, Nov 8-13, 2010, pp. 97–102. doi: 10.1109/MICAI.2010.10

[57] R. Cucchiara, C. Grana, A. Prati, and R. Vezzani, "Computer vision system for in-house video surveillance," *IEE Proceedings - Vision, Image and Signal Processing*, vol. 152, no. 2, pp. 242–249, 2005. doi: 10.1049/ip-vis:20041215

[58] C. Georgoulas, T. Linner, and T. Bock, "Towards a vision controlled robotic home environment," *Automation in Construction*, vol. 39, no. 0, pp. 106 – 116, 2014. doi: 10.1016/j.autcon.2013.06.010

[59] A. Talamo, S. Giorgi, and B. Mellini, "Designing technologies for ageing: Is simplicity always a leading criterion?" in proceeding of *the 9th ACM SIGCHI Italian Chapter International Conference on Computer-Human Interaction: Facing Complexity*, Alghero, Italy, Sep. 13-16, 2011, pp. 33–36. doi: 10.1145/2037296.2037308

[60] K. Caine, S. Sabanovic, and M. Carter, "The effect of monitoring by cameras and robots on the privacy enhancing behaviors of older adults," in proceeding of *the 7th ACM/IEEE International Conference on Human-Robot Interaction*, Boston, MA, March 05-08, 2012, pp. 343–350. doi: 10.1145/2157689.2157807

[61] A. K. Gnanasekar, P. Jayavelu, and V. Nagarajan, "Speech recognition based wireless automation of home loads with fault identification for physically challenged," in proceeding of *2012 International Conference on Communications and Signal Processing*, Chennai, India, April 04-05, 2012, pp. 128–132. doi: 10.1109/ICCSP.2012.6208408

[62] L. Anido Rifon, C. Rivas Costa, M. Gomez Carballa, S. Valladares Rodriguez, and M. Femandez Iglesias, "Improving the quality of life of dependent and disabled people through home automation and tele-assistance," in proceeding of *the 8th International Conference on Computer Science & Education*, Colombo, Sri Lanka, April 26-28, 2013, pp. 478–483. doi: 10.1109/ICCSE.2013.6553958

[63] E. Sch¨uler, B. P. Salton, A. P. Sonza, A. R. Fac¸anha, R. Cainelli, J. Gatto, L. Kunzler, and M. da C. C. Ara´ujo, "Production of low cost assistive technology," in proceeding of *the 5th International Conference on Management of Emergent Digital EcoSystems*, Luxembourg, Luxembourg, Oct. 29-31, 2013, pp. 297–301. doi: 10.1145/2536146.2536192

[64] J. Cofre, G. Moraga, C. Rusu, I. Mercado, R. Inostroza, and C. Jimenez, "Developing a touchscreen-based domotic tool for users with motor disabilities," in proceeding of *2012 9th International Conference on Information Technology - New Generations*, April 16-18, 2012, pp. 696– 701. doi: 10.1109/ITNG.2012.139

[65] M. Plaza, W. Aperador, and O. Aviles, "Technology in locomotion and domotic control for quadriplegic," in proceeding of *2013 29th Southern Biomedical Engineering Conference*, Miami, FL, May 03-05, 2013, pp. 99–100. doi: 10.1109/SBEC.2013.58

[66] D. Rotondi and S. Piccione, "Managing access control for things: A capability based approach," in proceeding of *the 7th International Conference on Body Area Networks*, Oslo, Norway, Sep. 24-26, 2012, pp. 263–268. [Online] Available: http://dl.acm.org/citation.cfm?id=2442691.2442751

[67] T. Koskela and K. Vnnen-Vainio-Mattila, "Evolution towards smart home environments: empirical

evaluation of three user interfaces," *Personal and Ubiquitous Computing*, vol. 8, no. 3-4, pp. 234–240, 2004.
doi: 10.1007/s00779-004-0283- x

[68] I.-J. Song and S.-B. Cho, "Bayesian and behavior networks for context-adaptive user interface in a ubiquitous home environment," *Expert Systems with Applications*, vol. 40, no. 5, pp. 1827 – 1838, 2013.
doi: 10.1016/j.eswa.2012.09.019

[69] S. Kartakis, M. Antona, and C. Stephanidis, "Control smart homes easily with simple touch," in proceeding of *the 2011 International ACM Workshop on Ubiquitous Meta User Interfaces,* Scottsdale, AZ, Dec. 01, 2011, pp. 1–6.
doi: 10.1145/2072652.2072654

[70] M. Deriu, G. Paddeu, and A. Soro, "Xplaces: An open framework to support the digital living at home," in proceeding of *2010 IEEE/ACM Int'l Conference on Green Computing and Communications & Int'l Conference on Cyber, Physical and Social Computing*, Hangzhou, China, Dec. 18-20, 2010, pp. 484–487.
doi: 10.1109/GreenCom-CPSCom.2010.40

[71] F. Aloise, F. Schettini, P. Aric`o, L. Bianchi, A. Riccio, M. Mecella, F. Babiloni, D. Mattia, and F. Cincotti, "Advanced brain computer interface for communication and control," in proceeding of *the International Conference on Advanced Visual Interfaces*, Rome, Italy, May 26-28, 2010, pp. 399–400.
doi: 10.1145/1842993.1843076

[72] A. Kanemura, Y. Morales, M. Kawanabe, H. Morioka, N. Kallakuri, T. Ikeda, T. Miyashita, N. Hagita, and S. Ishii, "A waypoint-based framework in brain-controlled smart home environments: Brain interfaces, domotics, and robotics integration," in proceeding of *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Tokyo, Japan, Nov. 03-07, 2013, pp. 865–870.
doi: 10.1109/IROS.2013.6696452

[73] D. Ashbrook and T. Starner, "Magic: A motion gesture design tool," in proceeding of *the SIGCHI Conference on Human Factors in Computing Systems*, Montreal, Canada, April 22-27, 2010, pp. 2159–2168.
doi: 10.1145/1753326.1753653

[74] D. K. H. Kohlsdorf and T. E. Starner, "Magic summoning: Towards automatic suggesting and testing of gestures with low probability of false positives during use," *Journal of Machine Learning Research*, vol. 14, no. 1, pp. 209–242, 2013. [Online]. Available:
http://dl.acm.org/citation.cfm?id=2502581.2502588

[75] B. Ur, E. McManus, M. Pak Yong Ho, and M. L. Littman, "Practical trigger-action programming in the smart home," in proceeding of *the SIGCHI Conference on Human Factors in Computing Systems*, Toronto, Canada, April 26-01, 2014, pp. 803–812.
doi: 10.1145/2556288.2557420

[76] J. Bobeth, J. Schrammel, S. Deutsch, M. Klein, M. Drobics, C. Hochleitner, and M. Tscheligi, "Tablet, gestures, remote control?: Influence of age on performance and user experience with itv applications," in proceeding of *the 2014 ACM International Conference on Interactive Experiences for TV and Online Video*, Newcastle Upon Tyne, United Kingdom, June 25-27, 2014, pp. 139–146.
doi: 10.1145/2602299.2602315

[77] K. Gill, S.-H. Yang, F. Yao, and X. Lu, "A zigbee-based home automation system," *IEEE Transactions on Consumer Electronics*, vol. 55, no. 2, pp. 422–430, May 2009.
doi: 10.1109/TCE.2009.5174403

[78] F. Sandu, M. Romanca, A. Nedelcu, P. Borza, and R. Dimova, "Remote and mobile control in domotics," in proceeding of *2008 11th International Conference on Optimization of Electrical and Electronic Equipment*, Brasov, Romania, May 22-24, 2008, pp. 225–228.
doi: 10.1109/OPTIM.2008.4602527

[79] M. Bjelica, I. Papp, N. Teslic, and J.-M. Coulon, "Set-top box-based home controller," in proceeding of *2010 IEEE 14th International Symposium on Consumer Electronics*, Braunschweig, Germany, June 07-10, 2010, pp. 1–6.
doi: 10.1109/ISCE.2010.5523704

[80] F. Garzotto and M. Valoriani, "Touchless gestural interaction with small displays: A case study," in proceeding of *the Biannual Conference of the Italian Chapter of SIGCHI*, Trento, Italy, Sep. 16-20, 2013, pp. 26:1–26:10.
doi: 10.1145/2499149.2499154

[81] M. Bjelica and N. Teslic, "A concept and implementation of the embeddable home controller," in proceeding of *The 33rd International Convention MIPRO*, Opatija, Croatia, May 24-28, 2010, pp. 686–690.
doi: 10.1145/2423636.2423648

[82] C.-F. Lai, M. Chen, M. Qiu, A. V. Vasilakos, and J. H. Park, "A rf4ce-based remote controller with interactive graphical user interface applied to home automation system," *ACM Transactions on Embedded Computing Systems*, vol. 12, no. 2, pp. 30:1–30:19, Feb. 2013.
doi: 10.1145/2423636.2423648

[83] G. Pan, J. Wu, D. Zhang, Z. Wu, Y. Yang, and S. Li, "Geeair: a universal multimodal remote control device for home appliances," *Personal and*

Ubiquitous Computing, vol. 14, no. 8, pp. 723–735, 2010.
doi: 10.1007/s00779-010-0287- 7

[84] B. Bittins, J. Sieck, and M. Herzog, "Supervision and regulation of home automation systems with smartphones," in proceeding of *2010 4th UKSim European Symposium on Computer Modeling and Simulation*, Pisa, Italy, Nov 17-19, 2010, pp. 444–448.
doi: 10.1109/EMS.2010.80

[85] Y. Zhong, Y. Suo, W. Xu, C. Yu, X. Guo, Y. Zhao, and Y. Shi, "Smart home on smart phone," in proceeding of *the 13th International Conference on Ubiquitous Computing*, Beijing, China, Sep. 17-21, 2011, pp. 467–468.
doi: 10.1145/2030112.2030174

[86] R. Carabalona, F. Grossi, A. Tessadri, A. Caracciolo, P. Castiglioni, and I. de Munari, "Home smart home: Brain-computer interface control for real smart home environments," in proceeding of *the 4th International Convention on Rehabilitation Engineering & Assistive Technology*, Shanghai, China, July 21-24, 2010, pp. 51:1–51:4. [Online]. Available: http://dl.acm.org/citation.cfm?id=1926058.1926109

[87] D. Bonino, F. Corno, and L. D. Russis, "dwatch: A personal wrist watch for smart environments," *Procedia Computer Science*, vol. 10, no. 0, pp. 300-307, 2012.
doi: 10.1016/j.procs.2012.06.040

[88] D. Bonino, E. Castellina, and F. Corno, "The dog gateway: enabling ontology-based intelligent domotic environments," *IEEE Transactions on Consumer Electronics*, vol. 54, no. 4, pp. 1656–1664, November 2008.
doi: 10.1109/TCE.2008.4711217

[89] P. Araujo and R. Salvado, "Smartvest: Integrating clothing with domotics, health care and information technologies," in proceeding of *2010 5th Iberian Conference on Information Systems and Technologies June*, Santiago de Compostela, Spain, June 16-19, 2010, pp. 1–6.

[90] S. Ananthanarayan, N. Lapinski, K. Siek, and M. Eisenberg, "Towards the crafting of personal health technologies," in proceeding of *the 2014 Conference on Designing Interactive Systems*, Vancouver, Canada, June 21-25, 2014, pp. 587–596.
doi: 10.1145/2598510.2598581

[91] K. O'hara, R. Harper, H. Mentis, A. Sellen, and A. Taylor, "On the naturalness of touchless: Putting the “interaction” back into nui," *ACM Transactions on Computer-Human Interaction*, vol. 20, no. 1, pp. 5:1–5:25, Apr. 2013.
doi: 10.1145/2442106.2442111

[92] D. Maggiorini, L. Ripamonti, and A. Scambia, "Videogame technology to support seniors," in proceeding of *the 5th International ICST Conference on Simulation Tools and Techniques*, Sirmione-Desenzano, Italy, March 19-23, 2012, pp. 270–277. [Online]. Available: http://dl.acm.org/citation.cfm?id=2263019.2263061

[93] R.-D. Vatavu and I.-A. Zaiti, "Leap gestures for tv: Insights from an elicitation study," in proceeding of *the 2014 ACM International Conference on Interactive Experiences for TV and Online Video*, Newcastle Upon Tyne, United Kingdom, June 25-27, 2014, pp. 131–138.
doi: 10.1145/2602299.2602316

[94] J. P. Wachs, M. K¨olsch, H. Stern, and Y. Edan, "Visionbased hand-gesture applications," *Communications of the ACM*, vol. 54, no. 2, pp. 60–71, Feb. 2011.
doi: 10.1145/1897816.1897838

[95] K. Ho and H. Weng, "Favoured attributes of in-air gestures in the home environment," in proceeding of *the 25th Australian Computer-Human Interaction Conference: Augmentation, Application, Innovation, Collaboration*, Adelaide, Australia, Nov. 25-29, 2013, pp. 171–174.
doi: 10.1145/2541016.2541095

[96] J. Kela, P. Korpip, J. Mntyjrvi, S. Kallio, G. Savino, L. Jozzo, and S. Marca, "Accelerometer-based gesture control for a design environment," *Personal and Ubiquitous Computing*, vol. 10, no. 5, pp. 285–299, 2006.
doi: 10.1007/s00779- 005-0033-8

[97] E. Vassev, M. Hinchey, and P. Nixon, "Prototyping home automation wireless sensor networks with assl," in proceeding of *the 7th International Conference on Autonomic Computing*, Xian, China, Oct. 26-29, 2010, pp. 71–72.
doi: 10.1145/1809049.1809060

[98] P. Milhorat, D. Istrate, J. Boudy, and G. Chollet, "Hands-free speechsound interactions at home," in proceeding of *the 20th European Signal Processing Conference*, Bucharest, Romania, Aug. 27-31, 2012, pp. 1678– 1682.

[99] F. Portet, M. Vacher, C. Golanski, C. Roux, and B. Meillon, "Design and evaluation of a smart home voice interface for the elderly: Acceptability and objection aspects," *Personal Ubiquitous Computing*, vol. 17, no. 1, pp. 127–144, Jan. 2013.
doi: 10.1007/s00779-011-0470-5

[100] J. Han, J. Yun, J. Jang, and K.-R. Park, "User-friendly home automation based on 3d virtual world," *IEEE Transactions on Consumer Electronics*, vol. 56, no. 3, pp. 1843–1847, Aug. 2010.
doi: 10.1109/TCE.2010.5606335

[101] V. Jim´enez-Mixco, J. L. Villalar Gonz´alez, A. Arca, M. F. Cabrera-Umpierrez, M. T. Arredondo, P. Manchado, and M. Garc´ıa-Robledo, "Application of virtual reality technologies in rapid development and assessment of ambient assisted living environments," in proceeding of the *1st international workshop on media studies and implementations that help improving access to disabled users*, Beijing, China, Oct. 19-24, 2009, pp. 7–12.
doi: 10.1145/1631097.1631101

[102] Z. Drey and C. Consel, "Taxonomy-driven prototyping of home automation applications: A novice-programmer visual language and its evaluation," *Journal of Visual Languages & Computing*, vol. 23, no. 6, pp. 311 – 326, 2012.
doi: 10.1016/j.jvlc.2012.07.002

[103] F. Luque, F. Luque, C. Lastres, A. Santamaria, I. Galloso, and J. Muria, "Virtual domotic systems: a 3d interaction technique to control virtual building devices using residential gateways," in proceeding of *2010 2nd International Conference on Image Processing Theory, Tools and Applications*, Paris, France, July 07-10, 2010, pp. 489–494.
doi: 10.1109/IPTA.2010.5586761

[104] J. A. Camacho-Guerrero and A. A. Macedo, "Html5, css3 and jquery mobile for intelligent home control," in proceeding of *the 19th Brazilian Symposium on Multimedia and the Web*, Salvador, Brazil, Nov. 05-08, 2013, pp. 9–10.
doi: 10.1145/2526188.2528539

[105] D. Mardanbegi and D. W. Hansen, "Mobile gaze-based screen interaction in 3d environments," in proceeding of *the 1st Conference on Novel Gaze-Controlled Applications*, Karlskrona, Sweden, May 26-27, 2011, pp. 2:1–2:4.
doi: 10.1145/1983302.1983304

[106] I. Fatima, M. Fahim, Y.-K. Lee, and S. Lee, "Classifier ensemble optimization for human activity recognition in smart homes," in proceeding of *the 7th International Conference on Ubiquitous Information Management and Communication*, Kota Kinabalu, Malaysia , Jan. 17-19, 2013, pp. 83:1–83:7.
doi: 10.1145/2448556.2448639

[107] L. Van Moergestel, W. Langerak, and J.-J. Meyer, "Agents in domestic environments," in proceeding of *2013 19th International Conference on Control Systems and Computer Science*, Bucharest, Romania, May 29-31, 2013, pp. 487–494.
doi: 10.1109/CSCS.2013.57

[108] S. Satterfield, T. Reichherzer, J. Coffey, and E. El-Sheikh, "Application of structural case-based reasoning to activity recognition in smart home environments," in proceeding of *2012 Eleventh International Conference on Machine Learning and Applications*, Boca Raton, FL, Dec. 12-15, 2012, vol. 1, pp. 1–6.
doi: 10.1109/ICMLA.2012.10

[109] S.-T. Cheng, C.-H. Wang, and C.-C. Chen, "An adaptive scenario based reasoning system cross smart houses," in proceeding of *2009 9th International Symposium on Communications and Information Technology*, Icheon, Korea, Sept. 28-30, 2009, pp. 549–554.
doi: 10.1109/ISCIT.2009.5341188

[110] T. Gu, H. Pung, and D. Zhang, "Toward an osgi-based infrastructure for context-aware applications," *IEEE Pervasive Computing*, vol. 3, no. 4, pp. 66–74, 2004.
doi: 10.1109/MPRV.2004.19

[111] H. Hu, D. Yang, L. Fu, H. Xiang, C. Fu, J. Sang, C. Ye, and R. Li, "Semantic web-based policy interaction detection method with rules in smart home for detecting interactions among user policies," *IET Communications*, vol. 5, no. 17, pp. 2451–2460, November 2011.
doi: 10.1049/iet-com.2010.0615

[112] D. Bonino and F. Corno, "Rule-based intelligence for domotic environments," *Automation in Construction*, vol. 19, no. 2, pp. 183–196, 2010.
doi: 10.1016/j.autcon.2009.10.008

[113] C.-M. Huang, H.-H. Ku, and Y.-W. Chen, "Design and implementation of a web 2.0 service platform for dpws-based home-appliances in the cloud environment," in proceeding of *IEEE Workshops of International Conference on Advanced Information Networking and Applications*, Biopolis, Singapore, March 22-25, 2011, pp. 159–163.
doi: 10.1109/WAINA.2011.32

[114] Y.-W. Kao and S.-M. Yuan, "User-configurable semantic home automation," *Computer Standards & Interfaces*, vol. 34, no. 1, pp. 171–188, 2012.
doi: 10.1016/j.csi.2011.08.002

[115] J. Abreu, P. Almeida, and B. Teles, "Tv discovery & enjoy: A new approach to help users finding the right tv program to watch," in proceeding of *the 2014 ACM International Conference on Interactive Experiences for TV and Online Video*, Newcastle Upon Tyne, United Kingdom, June 25-27, 2014, pp. 63–70.
doi: 10.1145/2602299.2602313

[116] Y.-G. Cheong, Y.-J. Kim, S.-Y. Yoo, H. Lee, S. Lee, S.-C. Chae, and H.-J. Choi, "An ontology-based reasoning approach towards energy-aware smart homes," in proceeding of *2011 IEEE Consumer Communications and Networking Conference*, Las Vegas, NV, Jan. 09-12, 2011, pp. 850–854.

doi: 10.1109/CCNC.2011.5766626
[117] M. Grassi, M. Nucci, and F. Piazza, "Towards an ontology framework for intelligent smart home management and energy saving," in proceeding of *2011 IEEE 20th International Symposium on Industrial Electronics*, Gdansk, Poland, June 27-30, 2011, pp. 1753–1758.
doi: 10.1109/ISIE.2011.5984327
[118] M. Grassi, M. Nucci, snd F. Piazza, "Ontologies for smart homes and energy management: An implementation-driven survey," in proceeding of *2013 Workshop on Modeling and Simulation of Cyber-Physical Energy Systems*, Berkeley, CA, May 20, 2013, pp. 1–3.
doi: 10.1109/MSCPES.2013.6623319
[119] V. Miori and D. Russo, "Anticipating health hazards through an ontology-based, iot domotic environment," in proceeding of *the 2012 Sixth International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing*, Palermo, Italy, July 4-6, 2012, pp. 745–750.
doi: 10.1109/IMIS.2012.109
[120] Y. Zhnag, Z. Wei, Y. Yang, and C. Song, "Ontology description of smart home appliance based on semantic web," in proceeding of *International Conference on Computer Science and Service System*, Nanjing, China, Aug. 11-13, 2012, pp. 695–698.
doi: 10.1109/CSSS.2012.179
[121] J. Xu, Y.-H. Lee, W.-T. Tsai, W. Li, Y.-S. Son, J.-H. Park, and K.- D. Moon, "Ontology-based smart home solution and service composition," in proceeding of *International Conference on Embedded Software and Systems*, Hangzhou, China, May 25-27, 2009, pp. 297–304.
doi: 10.1109/ICESS.2009.60
[122] B. Chikhaoui, Y. Benazzouz, and B. Abdulrazak, "Towards a universal ontology for smart environments," in proceeding of *the 11th International Conference on Information Integration and Web-based Applications &Amp*, Kuala Lumpur, Malaysia, Dec. 14-16, 2009, pp. 80–87.
doi: 10.1145/1806338.1806361
[123] J. F. Allen, "Planning as temporal reasoning," *Second International Conference*, vol. 3, no. 14, 1991.
[124] D. Cacciagrano, F. Corradini, and R. Culmone, "Resource home: An rfid-based architecture and a flexible model for ambient intelligence," in Systems (ICONS), 2010 Fifth International Conference on, April 2010, pp. 6–11.
doi: 10.1109/ICONS.2010.9
[125] J. Zhao and L. Lu, "Smart home model based on ontology and context-awareness," in proceeding of *IEEE International Conference on Granular Computing*, Hangzhou, China, Aug 26-28, 2008, pp. 830–833.
doi: 10.1109/GRC.2008.4664668
[126] L. Chen, C. Nugent, and G. Okeyo, "An ontology-based hybrid approach to activity modeling for smart homes," *IEEE Transactions on Human-Machine Systems*, vol. 44, no. 1, pp. 92–105, Feb 2014.
doi: 10.1109/THMS.2013.2293714
[127] M. Sohn, S. Jeong, and H. J. Lee, "Self-evolved ontology-based service personalization framework for disabled users in smart home environment," in proceeding of *the 7th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing*, Taichung, Taiwan, July 3-5, 2013, pp. 238–244.
doi: 10.1109/IMIS.2013.48
[128] K. Wongpatikaseree, M. Ikeda, M. Buranarach, T. Supnithi, A. Lim, and Y. Tan, "Activity recognition using context-aware infrastructure ontology in smart home domain," in proceeding of *the 7th International Conference on Knowledge, Information and Creativity Support Systems*, Melbourne, Australia, Nov. 8-10, 2012, pp. 50–57.
doi: 10.1109/KICSS.2012.26