An Overview of Smart Home Environments: Architectures, Technologies and Applications

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ABSTRACT

The aim of this research survey note is to provide a comprehensive overview of Smart Home Environments with a focus on their architectures and application areas, as well as utilized technologies, infrastructures, and standards. The main source of information was provided by past and existing research and development projects carried out in this area, while the main result of our survey is a classification of Smart Home Environments, as revealed by this projects' survey.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous

General Terms

Information Technology

Keywords

domotics, home network, smart environment

1. INTRODUCTION

The concept of Smart Home appeared at the beginning of the 20^{th} century, long before and independently of the revolution of information and communication technologies. Nevertheless, the Smart Home vision only became technically feasible with the spread of the recent developments in information and communication technologies related to computer networks, embedded systems, and artificial intelligence, and thus it became a market reality starting with the end of the 20^{st} century – start of the 21^{st} century [32]. The early paper [4] addresses the emergence of the Smart Home concept mostly from historical, social and philosophical perspectives.

The concept of Smart Home is closely related to the more established area of Home Automation, also known as Domotics, as well as to more recent areas of Ambient Intelligence and Smart Environments [15]. The concept recently evolved to the idea of Smart Home Environments – SHE hereafter. SHE are envisioned as being able to exhibit various forms of "artificial intelligence" by enhancing traditional Home Automation systems with new "smart functions" addressing diverse high-level goals of well-being like increasing comfort, reducing operational costs, and guaranteeing safety and security for the house holders.

Consequently, starting with the 90's, the advances in networking technologies, as well as the device miniaturization coupled with the increase of computational power in pervasive and ubiquitous computing, gave a significant impetus to SHE research. This tendency was even more evident during the last decade with the spread of the new area of *green computing* that aims for the development of a novel environmentally sustainable computing paradigm with a high impact onto the environment and energy, as well as for the preservation of natural resources and for supporting a sustainable and "green" economic growth.

In this context, the aim of the present research was to identify the most important research problems and trends in terms of research goals, methods, achievements and challenges in SHE by carrying out a thorough review of the most recent research literature covering a relevant number of publications and projects in this area. The main outcome of our initial research is a classification of SHE according to several orthogonal characteristics including their architecture, components, technologies, application areas and computational methods (in particular artificial intelligence and computational intelligence methods) employed.

We are aware of the large number of research projects and publications in this area, especially occurred during the last decade. Nevertheless, we hope that by focusing on what we considered to be significant endeavors in SHE, we could offer a comprehensive and usable image to the reader who is seeking to embark on SHE research.

The paper is structured as follows. In section 2 we propose a classification of SHE and we briefly characterize the features used by this classification. In section 3 we provide a brief overview of several SHE research projects offering a good coverage of the classification proposed in this paper. The last section concludes and points to future works.

2. CLASSIFICATION OF SHE

According to our literature review, SHE constitutes an important interdisciplinary research area of computer engineering that is placed at the intersection of computer networks, embedded systems and applied computing. In particular, the focus on "smart" functions oriented the research community to the application and experimentation of various intelligent agent-based computing methods [15] for enhancing the performance of SHE.

SHEs are complex heterogeneous environments comprising [25, 31]:

(i) A Home Automation System that contains a set of *home appliances*. They are electric and electronic devices that fulfil several functions in the house for the well-being of the house holders, including for example:

washing and cooking machines, refrigerators, heaters, thermometers, lighting system, power outlets, energy meters, smoke detectors, televisions, game consoles and other entertainment devices, windows and doors controllers, air conditioners, video cameras, sound detectors, a.o. Their functions can be roughly divided into sensors, actuators or both. More advanced "smart devices" are constantly being developed, like for example: smart floors and smart furniture (bed and chair) [34].

(ii) A Control System that combines human with software-based control by using the information provided by the sensors and the instructions sent to actuators in order to achieve one or more high-level goals or functions of the SHE, as required by home holders.

(iii) A Home Automation Network that assures that all the SHE components, including the Home Automation System and the Control System, can exchange status and control information.

There is a quite large amount of research literature addressing SHE during the last decade, as well as recent reviews of SHE architectures, components, technologies and applications [13, 3].

The most recent review of SHE is provided in [3]. Differently from our work, its authors focused mainly on SHE projects, as well as on the SHE building blocks including components, devices and networks. However, their paper lacks a classification of SHE from the point of view of their application areas.

Paper [13] offers only a project perspective of the current SHE research. In our review we combine the classification and projects' review approaches to offer a more complete image of SHE research to the interested reader.

SHEs are composed of a large variety of hardware and software components, employing different types of algorithms stemming from areas like control systems or artificial intelligence. Consequently, for a systematic overview, SHE can be classified according to many different criteria. In this paper we propose a classification of SHE according to the following set of orthogonal characteristics: structure, architecture, middleware, application, and computational methods.

2.1 Structure

As already mentioned, a SHE is composed of the following constituents: Home Automation System, Control System and Home Automation Network.

The Home Automation System may contain a large variety of home appliances that are chosen depending on specific applications. The technology and market of home appliances is progressing very fast and the new concept of *smart object* emerged in the literature [21] to more accurately describe advanced devices, including home appliances. According to [21], a smart object is made up of three important parts: (i) the physical part that represents the object in the real world; (ii) the hardware infrastructure that is necessary for ascribing smart capabilities to the object; (iii) the software layer that actually provides the smart capabilities of the object.

The Home Automation Network is characterized by physical technology and communication protocols. Home Network technologies are categorized in three main classes: powerline, busline and wireless. Powerline home networks are reusing the in-house electrical network. They are historically the oldest, cheaper, although less reliable and scalable. Busline home networks use a separate physical media for transporting electrical signals. They are more difficult to configure and less pleasant for the home occupants because of the wiring system. Wireless home networks use wireless communications, for example infrared or radio frequency, and have the advantage of being more pleasant for the users, as they do not require any cabling.

There are many communication protocols available for home networks [22]. They can be roughly classified into: (i) proprietary protocols, owned by private companies and not disclosed to the public; (ii) public protocols, usually maintained by a company or consortium, but open to the public; (iii) standard protocols that are recognized by standardization bodies. Some of the most widespread standards for home network protocols are: IEEE 802.15.4/ZigBee, EIB/KNX ISO/IEC 14543-3, IEEE 802.11/Wi-Fi, a.o. [22].

The Control System is probably the most complex part of a SHE. Its capabilities can be as simple as providing reactive behavior to specific events, like for example smoke detection, temperature variation, or far more complex strategies by mixing reactive and proactive behaviors for the achievement of high-level goals of the home occupants, like maximizing comfort and minimizing costs, or of the society, like minimizing pollution and environment protection. A large variety of computational methods were proposed in the literature for the design and development of sophisticated Control Systems of SHE, many of them using results of artificial intelligence, multi-agent systems and automation control.

2.2 Architecture

The architecture of a computing system defines the types of system components together with their interaction patterns. The architecture of SHE is strongly influenced by the computational capabilities of their components. We distinguish two main architectural styles of SHE: (i) centralized, and (ii) distributed. With the advances in ubiquitous and pervasive computing that resulted in the increase of computational power of miniaturized domotic devices, the tendency of SHE architectures is to evolve from centralized to distributed.

Note that most of the computational requirements of SHE are related to the achievement of the functions of its Control System. So, basically, the architecture of SHE is defined by the architecture of its underlying Control System.

2.2.1 Centralized Architecture

In a centralized SHE architecture, the Control System is realized by means of a computer system that is responsible with data acquisition from sensors, user interfacing, as well as with the implementation of control algorithms and sending instructions to actuators. The central computer of the SHE is sometimes called Home Gateway [40]. Additionally to the control function, it is responsible with interfacing the SHE with the outside world via Internet, as well as with providing services to the home residents. An option is to limit the capabilities of the Home Gateway to data acquisition, software interfacing with domotic devices and basic processing, while most significant part of the processing of the Control System is delegated to more powerful servers outside the home [36].

2.2.2 Distributed Architecture

In a distributed SHE architecture, the software of the Control System is conceptualized and implemented as a distributed computing system [16]. The distributed architecture benefits from the computational resources of smart objects to embed software components into the nodes of the Home Automation Network. Optionally, the SHE architecture can be only conceptually distributed, while still physically centralized into the Home Gateway. Distributed architectures can use a service-oriented approach [11] or a mobile agent approach [40].

2.3 Middleware

Home automation technologies are evolving from centralized and proprietary systems with limited capabilities to distributed and open systems incorporating heterogeneous and more powerful domotic devices. The integration and interoperability of heterogeneous domotic devices is achieved by an intermediary software layer called *middleware* [16] that is responsible for: (i) interfacing with device drivers and (ii) for providing interoperability using standardized interfaces and protocols. The software part of the Control System is implemented at the *application layer* on top of the middleware layer.

The SHE middleware can be (i) proprietary or (ii) based on open standards, as well as (i) general purpose or (ii) dedicated to domotic applications. Most often, proprietary middleware is dedicated to specific domotic applications, while general purpose middleware is based on open standards. Moreover, based on our literature review, we observed that for the development of distributed SHE the tendency is to base the implementation on software objects, components or services using open standards.

According to our literature review, the most relevant open standards used for the development of SHE middleware are:

- *Open Services Gateway initiative* [1] – OSGi. This is an open standard for a service-oriented dynamic software component model that simplifies the software engineering life cycle. In particular it offers enhanced support for activities of installation/removal, update/replacement and start/stop of software components and services organized into bundles.
- *Foundation for Intelligent Physical Agents* [2] – FIPA. This is an open standard for agent-based component middleware that provides dynamic support for components' (known as agents) management and standardized interaction protocols.
- *Web Standards* [3] – WS. This is a set of standards and standardized practices for the development of Web applications. It includes Web Services standards [4], as well as standardized practices like *REpresentational State Transfer* – REST architectural style or the vision of the *Web of Things* – WoT. In our opinion these standards and practices are more useful for interfacing the SHE with the outside world, either for providing services to home occupants and external users, as well as for integration with external systems, like the Smart Grid [35].

Two examples of general-purpose middleware platforms used in SHE projects are Eclipse Equinox [5], based on OSGi standards, and JADE [6], based on FIPA standards.

Examples of dedicated middleware platforms for the development of SHE, built on-top of OSGi-compliant middleware are: (i) LinkSmart middleware[7] developed by the *Heterogeneous physical devices in a distributed architecture* – HYDRA European research project [8] [18], and (ii) *DOmotic OSGi Gateway* – DOG [5].

2.4 Application Areas

The list of SHE applications is open-ended, being limited only by the human imagination. Based on our literature survey, we have identified four major application areas of SHE, namely:

(i) Elderly / Aging / Home Care.

(ii) Energy Efficiency.

(iii) Comfort / Entertainment.

(iv) Safety / Security.

The areas are not necessarily disjoint (for example safety can be related with aging and elders). Moreover, functions belonging to one or more different application types can be found within the same SHE. Finally, these applications can share computational approaches. For example, applications related to alders and safety very often use computational methods for video surveillance [8].

2.4.1 Elderly / Aging / Home Care

This application area occurred to address the pressing requirements caused by the phenomenon of population aging that is present in many developed countries of Europe and all over the world. Actually, this application trend is part of a more general interest for the development of new smart technologies for addressing the problems of the elders related to health, loneliness, disability, cognitive limitation, a.o. According to [37], two main sub-areas were identified within this application area:

(a) *Ubiquitous assistance* that focuses on *task role level* for assisting elders during their daily activities, as well as by addressing their disabilities and cognitive limitations, and

(b) *Ubiquitous care networking* that addresses elders' *social limitation* by providing them with services and facilities for social inclusion to reduce their sense of loneliness.

2.4.2 Energy Efficiency

Reduction of energy consumption became a very important desiderate in the context of the explosive technological development of the modern society with a major impact on

[1]http://www.osgi.org/Specifications/HomePage
[2]http://www.fipa.org/
[3]http://www.w3.org/
[4]http://www.w3.org/standards/webofservices/
[5]http://www.eclipse.org/equinox/
[6]http://jade.tilab.com/
[7]http://sourceforge.net/projects/linksmart/
[8]http://www.hydramiddleware.eu/

the future development of the mankind. On the one hand the technological progress requires the use of more energy, while on the other hand energy became a limited resource.

It is appreciated that in Europe 40-45% of total energy consumption occurs in buildings and the residents' behavior strongly impacts energy wasting, thus having a significant potential for reducing energy consumption [23].

On the other hand, the power grid is evolving into a new smarter network known as Smart Grid [9]. It enhances the traditional electricity delivery system with advances in information and communication technologies [35] for balancing the demand and supply of electricity consumption, as well as for exploiting renewable energy sources.

This state-of-affairs explains the rapid growth of the interest of the scientific community for researching new methods, technologies and systems exploiting results of artificial intelligence and control systems, as well as achievements in the area of smart devices, for energy conservation.

In our literature review we identified two major application areas related to energy efficiency:

(a) *Energy saving* that aims at using sensors and actuators from SHE for controlling energy savings by switching off or to low-power mode the consumer appliances currently not in use or according to the user preference settings. A recent review of smart environments for energy saving is [38].

(b) *Smart Grid integration* that addresses the integration of energy-aware SHE into the Smart Grid [24].

2.4.3 Comfort / Entertainment

A special class of functions of SHE address user comfort and entertainment. Typical examples are ambience control (for example lighting and background music), advanced user interfaces (for example based on voice or gestures), increasing the level of automation of routine activities, a.o.

2.4.4 Safety / Security

Safety refers to the detection of abnormal situations inside SHE, like for example fires, floods, accidents (eg. falls of disabled or elders), a.o. Security refers to the detection of malicious behaviors with respect to SHE, like for example burglars, unauthorized access, a.o. For the detection, signalling and response to such safety or security violation situations, SHE are equipped with sub-systems for video surveillance, remote monitoring, alarming, and emergency response.

2.5 Artificial Intelligence Methods

SHE turned out to be a fruitful experimentation ground for the variety of computational methods and techniques proposed by artificial intelligence and multi-agent systems communities. They can be roughly classified along two orthogonal axes into: (i) centralized and (ii) distributed approaches, as well as (i) symbolic and (ii) sub-symbolic approaches.

Centralized approaches are usually coupled with centralized SHE architectures. They usually involve intelligent algorithms and methods (combining the symbolic and subsymbolic approach), including fuzzy logic, neural networks [38], clustering, pattern mining [36], Markov decision processes [14], a.o. Distributed approaches involve the use of multi-agent systems coupled with ontologies and rule-based reasoning (symbolic approaches), as proposed by [6, 39].

Based on our literature review, we concluded that the general tendency is to use:

(i) Reasoning and knowledge representation as ontologies and rules, for representation of devices and home services.

(ii) Machine learning for activity recognition.

(iii) Multi-agent systems for distributed intelligence and semantic interoperability.

(iv) Other intelligent methods including planning, intelligent control, adaptive interfaces, optimization, for various tasks inside SHE.

3. SHE PROJECTS

In this section we present a brief overview of several research projects and results in the domain of SHE. Our intention was to produce an as good as possible coverage of the classification proposed in this paper, trying also to have a good geographical coverage, by reaching projects on as many continents as possible, including Europe, America, and Asia.

Most of the projects are targeting the first two application areas, namely *Elderly / Aging / Home Care* and *Energy Efficiency*, with some of them considering also functions from the other two areas *Comfort / Entertainment* and *Safety / Security*. Therefore we decided to topically organize our review according to the first two application areas, while mentioning, whenever necessary the third and the fourth areas.

3.1 Elderly / Aging / Home Care Projects

AssistiNG ELders At Home – ANGELAH addressed both *Ubiquitous assistance* and *Ubiquitous home care* within a single research project for assuring elders in-house safety [37]. Two main design principles were behind the ANGELAH framework: elders' context awareness and group-based collaboration. The framework integrates sensing and monitoring services on top of the OSGi infrastructure. A research novelty of ANGELAH is a new multi-attributed decision making – MADM algorithm for volunteers' selection to cope with an emergency situation. The framework was evaluated using a case study for elders affected by severe vision impairments. The deployment for this case study included the following appliances: RFID readers with coverage of all the house, video cameras, sound sensors, smart door lock, microphone and speakers for interaction with the system. The system tracked elders' location and detected abnormal behaviors (falls, unusual activity / inactivity pattern) using methods of computer vision and Gaussian Mixture Models.

Context-Aware Service Integration System – CASIS addressed both *Ubiquitous assistance* and *Ubiquitous home care* for enhancing the quality of care for elders' daily life [34]. The CASIS project explores the elders interaction with smart furniture objects, including: smart floor for location tracking, smart chair for vital signs monitoring and smart table for tracking food and nutrients. CASIS integrates a variety of domotic appliances using an OSGi-compliant Home Gateway that also provides a Web-based interface to the

[9] `http://smartgrid.ieee.org/ieee-smart-grid`

external world. CASIS provides context-dependent services using rule-based reasoning. CASIS also context-aware information services provides to the elder via an intelligent telephone and an intelligent reminder.

TigerPlace project addressed *Ubiquitous assistance* for "aging in place" and maximizing independence of senior residents [36]. The main challenge was to provide a real home environment for real elders, capable of continuous functioning with minimum of maintenance. The project employed smart home technology based on physiological and video sensor networks including: motion sensors, stove sensors, bed sensors (for sleep restlessness, pulse, respiration), and video sensors. The project goals were to identify alert conditions and to extract daily activity patterns representing physical and cognitive health conditions for recognizing abnormal activities. The physiological sensor network was able to detect: presence in a particular room, presence in bed, respiration, bed restlessness, movement. Patterns of activities and their changes were detected using algorithms for *temporal clustering*. The video sensor network detected patterns that could not be detected by other sensors, like: gait pattern, walking speed, balance, posture, and detection of falls. Also it could distinguish between different people, visitor and resident. The computational methods were silhouette extraction and fuzzy rule-based systems. TigerPlace had an alerting module based on temporal state machines.

Ubiquitous Care networking – U-CARE system addresses the problem of *Ubiquitous home care* by combining contextual and activity data for estimating the elders' health status based on their activity, context and demographic profile [29]. The U-CARE system applies model-based and rule-based reasoning to generate a diagnosis and care service recommendation based on sensed and analyzed data about the activity and context of the elder. For the experiments, the SHE was equipped with gas leak detector, absence button, smoke detector, activity sensor and Home Gateway. Data acquisition is performed centrally in the Home Gateway, while the processing is achieved in servers located in the U-CARE monitoring center, outside the house.

3.2 Energy Efficiency Projects

Authors of [24] proposed an energy aware SHE based on HYDRA middleware [18]. HYDRA allows the development of networked embedded systems and provides a distributed architecture based on P2P and Web Service technologies. Devices are classified as able and not-able to host parts of the middleware. Restricted devices are integrated using software proxies. Their system integrates wireless smart power meters and provides facile user mobile and stationary interfaces for monitoring and controlling appliances. Mobile user interfaces are based on the UbiLense concept that allows recognition and direct access and interaction with the appliances via the mobile device. The system was tested by integrating 4 types of devices that were able to host parts of the middleware into a distributed system: (i) a host implemented as a Desktop Computer that integrates the basic infrastructure, as well as the smart power meters's control; (ii) two Table PCs representing a static monitoring device and a controllable washing machine; (iii) an Android G1 mobile phone implementing the UbiLense technology.

SEmantic SmArt MEtering Ű Services for Energy Efficient Houses – SESAME-S project [10] is a continuation of the former *SEmantic SmArt MEtering - Enablers for Energy Efficiency* project [19]. The projects were focused on the initial development of smart meter and sensor-enabled solutions for public buildings and private households, as well as on adapting them for commercialization in real-life settings. The novelty was the use of Semantic Web technologies and semantically linked data [11] for assisting end-users to make informed decisions for controlling their energy consumption. The project developed a usable SHE containing: smart meters, sensors (light, temperature, humidity), smart plugs, multi-utility management (electricity, heating), and user interfaces. The software employed Semantic Web technologies including: a semantic repository and a number of ontologies: SESAME Automation Ontology, SESAME Meter Data Ontology, and SESAME Pricing Ontology. Decision making was provided via rule-based policies.

ThinkHome project [12] and system aims at ensuring energy efficiency and comfort optimization for home owners [33]. ThinkHome system has two main parts: a comprehensive knowledge base (KB) and a multi-agent system (MAS). ThinkHome project identified several use cases:

(i) *Thermal comfort* by correlating rooms' heating with the weather prognosis.

(ii) *Visual Comfort* by combining the exterior lighting conditions with the house lighting system.

(iii) Energy efficient operation of household appliances and consumer electronics.

Multi-Agents Home Automation System – MAHAS proposed the use of a multi-agent system for distributed power load management according to users' comfort, energy price, and CO_2 emissions [1]. MAHAS models appliances (single or in group) as services that consume or produce energy. They are classified as permanent services (i.e. they are active for the whole duration of the energy assignment plan) and temporary services (i.e. they have a certain duration and end time). The user comfort is mathematically modeled using satisfaction functions that represents the user satisfaction for a certain service based on the service characteristic variable(s). The MAHAS system has two control levels: anticipative mechanism and reactive mechanism.

Authors of [27] proposed a solution for a Web-based energy-aware SHE that is capable of adapting to the demand-response mechanism of the Smart Grid. This mechanism assumes a smart pricing scheme that is set for a certain amount of time that is influenced by the load demands and energy market prices. The authors introduced a RESTfull Web application framework that enables smart appliances and smart power meters to the Web. With this approach, applications can be created as physical mashups that combine services offered by physical devices thus allowing the direct incorporation of data from smart appliances into their client applications. Integration with the Smart Grid can be achieved via specialized devices called *smart grid controllers* that can use the Web API of Web-based SHE. For the demonstration of demand-response functionality, the authors of [27] developed a simulator of an electric utility offering dynamically changing tariffs.

[10] `http://sesame-s.ftw.at/`

[11] `http://www.w3.org/standards/semanticweb/`

[12] `https://www.auto.tuwien.ac.at/projectsites/thinkhome/overview.html`

Authors of [30] introduced a distributed algorithm for residential energy management in Smart Grid. The algorithm models the energy demand-supply problem of a residential neighborhood as an energy market. Each home is envisioned as a SHE equipped with energy management and domotic appliances' coordination functions. The market aims (i) to improve the consumption of locally produced energy by solar panels and wind farms found in the residence neighborhood, as well as (ii) to reduce the energy costs of the residence using load shifts of smart devices inside the house when energy prices are low.

3.3 Other Projects

Paper [17] is focused on Ambient Ecologies of interconnected smart objects that cooperate to assist human users for achieving their daily tasks. Existing middleware solutions are constrained by the limited computational capabilities of the underlying hardware of their smart objects. Authors of [17] proposed a new middleware platform called *Embodying Virtual Agents Toward Autonomous Robots* – EVATAR based on the new concept of *Ubiquitous Agent* – UA. An UA is composed of: (i) *Virtual Agent* – VA that usually runs on computationally powerful devices, and (ii) Avatar that represents a smart object embedded into a physical environment, with limited computing capabilities. EVATAR is based on *Generalized Onto-Logical Environments for MAS* – GOLEM [13] [9]. EVATAR was used for experimenting with the "Easy" SHE application scenario that integrates the following hardware infrastructure: two wireless cameras for motion detection and photo acquisition, wireless microphone, wireless actuator for lights, wireless speaker, as well as email sender (in fact an actuator) and time sensor (both implemented with the help of a PC connected to Internet). These facilities allowed the implementation of a "left on holidays" scenario for home security, as well as an automated light control scenario. These scenarios employed a logic-based activity recognition framework that used the reasoning capabilities of VAs.

Paper [20] introduced a decentralized and embedded agent oriented framework for the management of intelligent buildings based on Wireless Sensor and Actuator Networks (WSAN) called *Agent based Building Management Framework* – A-BMF. The framework defines several agents organized into a hybrid hierarchical and P2P architecture:

(i) *Building manager agent* (BMA) running at control workstation.

(ii) *Coordinator agents* (CA) running at base stations and sensor agents.

(iii) *Sensor/Actuator agents* (SA) running on sensor and/or actuator nodes.

The relation between several CAs is P2P, while the relations between BMA and CAs, and between CA and its cluster of SAs are hierarchical. Several SAs form a cluster that dynamically defines a multi-hop ad-hoc network rooted at the master CA. A-BMF is based on *Mobile Agent Platform for Sun SPOTs* – MAPS [2]. MAPS is an agent framework for WSN applications running on Sun SPOTs (Sun Small Programmable Object Technology) [14] equipped with Java Virtual Machine. The authors present a simple application for monitoring workstation usage in a laboratory using: light sensor, user presence Infra Red (IR) sensor, and Berkeley Wireless AC Meter/Switch (ACme) sensorboard [26]. The goal of this experiment was monitoring and understanding users' behavior.

[5] and [6] introduced an Intelligent Domotic Environment based on (i) DOmotic OSGi Gateway – DOG, (ii) DogOnt ontology [15] and (iii) Semantic Web rule-based reasoning that addresses the heterogeneity of different domotic networks and devices. DOG is able to bridge different domotic networks, as well as to capture the structure of the house together with installed components and their states using the DogOnt domain-specific ontology. This ontology allows the reasoning about the properties of SHE from two perspectives: (i) *type of information* perspective, involving structural and state properties, and (ii) *reasoning complexity* perspective, i.e. reasoning processes involving: direct, recursive and multi-stage inference rules.

Smart hoMes for All – SM4ALL [16] project developed an embedded middleware platform for pervasive and immersive environments (thus including SHE) that allows the inter-working of smart embedded devices for home automation through the use of service composability [11]. The SM4ALL approach operates at three conceptual levels: (i) *user layer* that employed brain-computer interaction technologies, deemed for interaction of disabled persons with the devices "through their mind", (ii) *service composition layer* based on high-level interaction among software components using Web Services and the Roman composition model [10], and (iii) *pervasive layer* that enables the low-level interaction among devices through the Universal Plug and Play – UPnP concept.

The *Managing An Intelligent Versatile Home* – MavHome [17] project aimed to create a SHE that acts as an intelligent agent by maximizing inhabitant comfort and minimizing operational cost [14]. MavHome system monitors and record inhabitant-home interaction events, identifies patterns of events, predicts inhabitant actions and generates automation strategies for the intelligent environment using reinforcement learning. MavHome was tested using two experimental settings: (i) workplace environment, and (ii) on-campus apartment. They were equipped with a powerline Home Automation Network of lights and various appliances, as well as with a sensor network for light, humidity, temperature, smoke, gas, motion, switch settings perception, and inhabitant localization.

IntelliDomo is an expert system that aims to control the behavior of a SHE using ontologies and rule-based reasoning [39]. IntelliDomo is interfaced with a domotic database that captures state values of domotic devices via a software module connected to a busline EIB/KNX Home Automation Network. The expert system is able to do inferences based on the contents of the database, as well as to perform updates of the database for controlling the domotic system. Paper [7] proposed a learning model of individuals' habits that is able to generate rules for the IntelliDomo expert system for predicting that anticipate the users' activities.

Paper [12] proposed an agent approach for the implemen-

[13] `http://golem.cs.rhul.ac.uk/`

[14] `http://www.sunspotworld.com/`

[15] `http://elite.polito.it/dogont?start=3`

[16] `http://www.sm4all-project.eu/`

[17] `http://ailab.wsu.edu/mavhome/`

tation of the Control System of a SHE. The proposed system uses the *Butler agent* metaphor that acts by inferring user's goals, selecting most useful workflows for fulfilling them and interpreting user's feedback in order to self-improve its future performance. The system is implemented as a multi-agent system that contains: (i) Sensor Agents for sensing the house and user context; (ii) Effector and Interactor Agents for controlling actuators, either automatically or via interaction with the user; (iii) Housekeeper Agent that acts as a yellow pages by knowing all the active agents and their capabilities; (iv) Butler Agent that controls the SHE.

Authors of [28] were focused on maximizing user comfort and utility by controlling music and ambient lighting in a SHE. The music service is described by the following features: genre (eg. blues, classical, a.o.), mood (calm, happy, a.o.), and volume (low, medium, a.o.), while the lighting service is characterized by: pattern (eg. cloudy, starry, a.o.), color (eg. purple, blue, a.o.), and brightness (eg. bright, medium, a.o.). The system is monitoring the user using sensors that record the user location and activity at a given time. The preferred music and lighting settings are learned using reinforcement learning based on explicit or implicit user feedback.

4. CONCLUSION

This paper identified a set of features for the comprehensive classification of SHE research projects and systems proposed in the literature. Based on this classification, we reviewed some research projects with the goal to provide the reader with a more complete understanding of the research problems, challenges and results in the domain of engineering SHE. Although our review is not and cannot be exhaustive, we identified a number of essential issues that must be considered for successful SHE research in terms of employed technologies, standards, and computational methods, as well as useful SHE applications.

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