Leveraging Ontology to Enable Indoor Comfort Customization in the Smart Home

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Abstract. This paper introduces the Future Home for Future Communities' Smart Home, a semantic-based framework for indoor comfort metrics customization inside a living environment. The Smart Home merges Ambient Intelligence, Ambient Assisted Living and Context Awareness perspectives to provide customized comfort experience to the dwellers, also leveraging on a ubiquitous interface. The smart home leverages ontological representations of inhabitants' health conditions, comfort metrics and available devices to provide dwellers with indoor temperature, humidity rate, CO_2 concentration and illuminance suitable for their health conditions and to the activities they want to perform inside the house. Dwellers interactions within the Smart Home are performed via the interface, while the ontologies composing the knowledge base are reasoned and hosted on a semantic repository. Two use cases depict the framework's functioning in two typical scenarios: adjusting indoor temperature and providing illuminance comfort while preparing a meal.

Keywords: Ontology · Indoor comfort customization · Ambient Intelligence · Ambient Assisted Living · Smart Home

1 Introduction

The Smart Home (SH) has emerged in recent decades as a promising paradigm to foster independent living among elderlies. This research field touches on Ambient Assisted Living (AAL) [1] and Ambient Intelligence (AmI) [2] and is aimed at enhancing the quality of life of elderlies and people with disabilities in order to foster their independent living. While most of the literature related to the SH focuses on its architecture [3], its functionalities [4] and the possibility to save energy [5], another branch of literature concentrates on the SH as a set of technologies able to help aging population to live independently and safely by proposing tailored services.

This idea of the SH requires the possibility to acquire information regarding the dwellers and their status, their activities, the contexts they live in, and their preferences. These pieces of information are even more important when considering dwellers afflicted by limitations and/or disabilities, a group of persons who could enormously benefit from tailored services while performing Activities of Daily Living (ADLs) [6].

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In this context, Semantic Web technologies can be a promising solution to tackle the knowledge representation of information coming from the above-mentioned domains [7]. Knowledge needs to be captured, processed, and interconnected to be considered as relevant. Thus, exploiting the ontology – i.e. a formal and explicit specification of shared conceptualizations [8] – to manage knowledge bases, and enriching these ontologies by deriving new facts using reasoning techniques, can be a robust solution.

This work introduces the Future Home for Future Communities (FHfFC) project's SH [9], an AAL system developed to help aging population and dwellers characterized by their impairments to live independently. FHfFC is an Italian research project aimed at creating the "house of the future", in which dwellers can rely on customized services to overcome some of their impairments while performing some ADLs. The proposed SH leverages on ontologies to represent relevant facts regarding the inhabitants and their health status, the devices deployed in the domestic environment (sensors, actuators, household appliances) and the comfort metrics that affect daily living (indoor temperature, humidity rate, illuminance, CO_2 concentration) with the aim of providing tailored comfort solutions to the SH's dwellers.

The remainder of this paper is organized as follow: Sect. 2 highlights some of the relevant works in the field of indoor comfort customization within a SH, focusing on solutions leveraging ontologies; Sect. 3 delves into the FHfFC's SH architecture, with a specific focus on the ontologies adopted to build the knowledge base; Sect. 4 depicts two use cases and highlights some of the SH features; finally, the Conclusions summarizes the main outcomes of this paper and sketch the future works.

2 Related Work

Comfort plays a pivotal role in SHs and several works can be traced in literature; however, most of these works focus on the possibility to produce energy saving and efficiency with regard to the indoor comfort metrics [10–12], thus neglecting the fact that indoor comfort is a necessary quality of the living environment – especially for elderlies and dwellers with disabilities. With regard to the issue of indoor comfort as a necessary quality for indoor environments, some works leveraged the use of ontologies to foster adaptation of indoor comfort metrics. Tila et al. [13] adopted ontologies to provide a description of indoor comfort metrics, domestic devices and context in an Internet of Things (IoT) framework queried with SPARQL [14] and SQL. Frešer et al. [15] exploited reasoning capabilities provided by semantic modeling to develop a decision support system to improve the quality of some indoor comfort metrics. Aeleke et al. [16] proposed an ontology for indoor air quality monitoring and control, formalizing some of the knowledge of the standard ISO 7730:2005. Stavropoulos et al. [17] developed BOnSAI, an ontology for smart buildings, encompassing some concepts related to comfort. More recently, ontologies have been adopted as a tool for representing knowledge related to the inhabitants inside a SH [18] with the aim of fostering the customization of comfort metrics. This approach is adopted also in [19], where the authors extend the semantic framework to the hotel industry – thus transforming a hotel room in a "smart" environment able to personalize indoor comfort metrics. Finally, ontologies for comfort customization have been adopted also in the field of ship cruise cabins [20], where the cabin environment fosters both energy saving and comfort personalization.

In the context of AmI and CA, the FHfFC's SH leverages ontological representation of the dwellers and their needs – exploiting an international health-related standard – to provide customization in several ADLs and daily-life activities. Moreover, the proposed SH hides its complexity to the dwellers, by adopting a simple interface that assists the dwellers in managing various aspects of the living environment.

3 The FHfFC Smart Home Architecture

This section describes the architecture of the FHfFC's SH framework and its modules in detail. As mentioned in Sect. 1, the possibility of enabling indoor environment responsiveness to the inhabitants' needs and comfort requirements plays a pivotal role in both AmI and AAL. With regard to these contexts, this work proposes a system that aims at providing customized comfort within the living environment; the system is also able to take into account diverse groups of people – including dwellers with disabilities. The proposed SH aims at adjusting the indoor comfort metrics according to the various activities the dwellers may be performing. In this regard, the first issue to be addressed is the physical environment and the set of smart devices deployed in it to ensure the inhabitants' comfort. The SH must be equipped with the necessary smart and ubiquitous devices to be prepared for exploitation by the framework. Thus, a solid network of sensors and actuators is needed to sense, measure, and exchange the data both from sensors to the application and from the application to the actuators. The FHfFC's SH leverages on the Home Interactive Controller (HIC) [21], a ubiquitous projected graphic user interface (GUI) providing the dwellers with a tool for controlling comfort metrics, appliances and systems within the SH. The SH also needs to "know" facts about the inhabitants, their needs and preferences, their activities, the comfort metrics (both indoor and outdoor); therefore, it requires a knowledge base to describe relevant facts and reasoning systems to provide tailored adjustments to the SH's services. The FHfFC's SH is composed of four different layers – as depicted in Fig. 1:

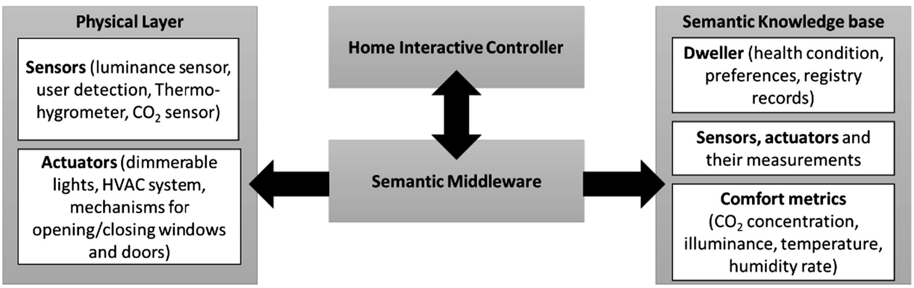

Fig. 1. The overall architecture of the FHfFC's SH and its four intercommunicating layers.

1. Physical living environment equipped with smart devices (sensors and actuators) to be connected to the HIC;
2. The HIC, a ubiquitous projectable GUI that can be used to control the indoor environment and provides assistance to the dwellers performing some ADLs;

3. The semantic knowledge base including the domain ontologies, hosted on a Stardog semantic repository [22] equipped with SL reasoner to run SPARQL Protocol and RDF Query Language (SPARQL) [14];
4. A middleware program to communicate between (b) and (c), translating the information from the HIC to the semantic repository (and vice versa), and also from the sensors and actuators to the semantic repository (and vice versa).

3.1 The Physical Layer

The FHfFC's SH is simulated within the Living Lab of Lecco (inside the CNR premises of Lecco, in Lombardy, Italy). The environment – which is a room of 4×6 m^2, as shown in Fig. 2 – is equipped with real kitchen furniture, while the household appliances are simulated using Augmented Reality.

Fig. 2. A picture of the furnished FHfFC's SH in Lecco's Living Lab

Also, some of the actuators are simulated – such as the HVAC (Heating, Ventilation, and Air Conditioning) system – while other devices are deployed inside the environment. The following sensors are positioned within the SH: an AM2320 digital temperature and humidity sensor; a TSL2561 digital light sensor; a 3709 Adafruit SGP20 air quality sensor breakout. Sensors measuring the outdoor comfort metrics are simulated, such as illuminance, air quality and thermo-hygrometric sensor for measuring comfort metrics outside the SH. Due to restrictions in the possibility of actuating the real HVAC system installed in the premises and the inability of actuating real windows and doors, the following actuators have been simulated using Virtual Reality: the air conditioning system and the heating system, as part of the HVAC system; a window opener actuator. While, as a real actuator, the FHfFC's SH adopts two dimmable Philips HUE lights, which allows changing the intensity (i.e. the illuminance) and the color of the light. The process of data exchange takes place exploiting embedded ZigBee-based IoT gateways – such as XBee [23] – which is mounted on a Raspberry Pi device [24].

3.2 HIC: The Home Interface Controller

The FHfFC's SH leverages on a simple interface that allows the dwellers to manage domestic appliances, indoor comfort metrics, dweller's personal calendar and that can assist the inhabitants in performing some ADLs, such as the preparation of a meal – as described further in Sect. 4.2. HIC helps to hide from the end-users the complexity of the SH's architecture (especially when they are elders or afflicted by impairments) in order not to burden them; however, the interaction with the SH is fundamental to provide benefits to the dwellers.

The HIC acts as an interactive multi-touch surface that can be run on every plain surface of the house thanks to an interactive projector EPSON EB1430wi. This device allows the users to operate with multi-touch gestures (tapping, pinching, zooming, scrolling, dragging, rotating with two fingers) thanks to an infrared emitting laser unit able to detect touches in an area up to 100 in. In addition, HIC can also be used via tablet or smartphone, so that dwellers can use HIC as a "remote" for the whole SH in every room – even those not provided with a projector. HIC allows regulating and managing different activities and utilities within the living environment: (a) adjusting the lighting within the house; (b) regulating the indoor temperature and humidity rate; (c) providing visual assistance for meal preparation (as further described in Sect. 4.2); (d) activating the HVAC system according to dweller's preset preferences.

3.3 Knowledge Base and Semantic Repository

The semantic knowledge base acts as a "control center" – with special sets of rules and reasoning logic – between the sensors and the actuators. In other words, sensors measure the data about indoor comfort, send them to the semantic repository to be saved and reasoned over in the knowledge base, and finally decisions provided by reasoning process are sent back to the actuators to initiate the required action. The SH's knowledge base, its different domains' ontologies, semantic repository, and reasoner are stored on a private server to be available anytime while being protected. Thus, the third layer of the FHfFC's SH architecture consists of the following: (a) a set of domain ontologies describing the dwellers, their health conditions, their registry records and their comfort preferences, sensors and actuators; the ontologies are modeled with W3C-endorsed language Resource Description Framework (RDF) [25] and Ontology Web Language (OWL) [26]; (b) a set of rules defined in Semantic Web Rule Language (SWRL) [27] to infer new pieces of information; (c) a semantic repository to upload the ontologies on the server to allow querying, retrieving and reasoning over data to infer new triples; and (d) SPARQL to query over the semantic repository and allowing to insert, retrieve, and delete the information modeled in the ontologies.

The domain ontologies are modeled according to NeOn methodology [28], which ease the identification of existing resources to be re-used. The following subsections delve into the description of the FHfFC's SH domain ontologies.

Inhabitant's Model

The dwellers are described leveraging the Friend Of a Friend [29] vocabulary to annotate their registry records. With regard to inhabitants' health condition, the domain ontology leverages on the International Classification of Functioning, Disability and Health (ICF) [30], a World Health Organization standard developed as a common language to describe a person's functional impairment. ICF provides a set of codes, each indicating a specific impairment that can be completed with qualifiers in order to state the magnitude of the impairment (1st qualifier) and – only for impairments in body structures – the origin of the impairment (2nd qualifier) and its location in the body (3rd qualifier). Moreover, ICF has been translated into a widely-reused ontology [31]. The following Fig. 3 provides an example of dweller modeling.

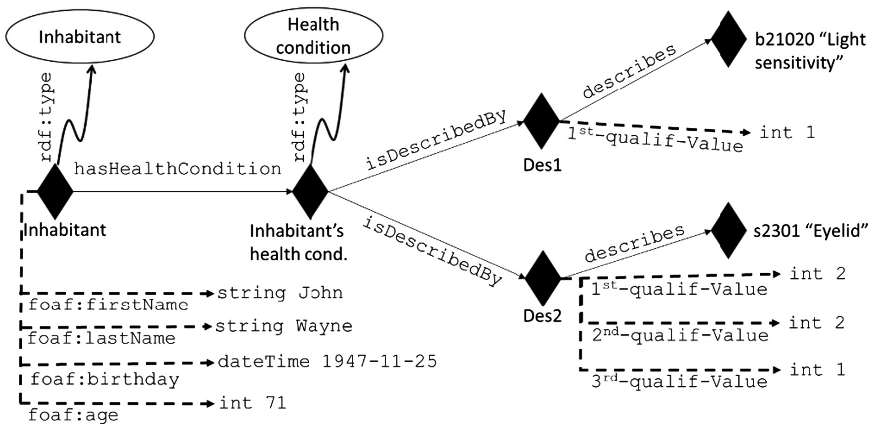

Fig. 3. An example of inhabitant's modeling. Diamonds represent individuals, circles represent concepts, arrows represent roles, dashed-line for datatype property, full-line for object properties.

Inhabitant's Comfort Preferences

For each inhabitant, comfort-related preferences can be saved in the ontology. Following the same ontology design pattern adopted for modeling health conditions, a dweller can specify his/her own preferences in terms of comfort metrics. The input of the preferences can be easily performed with the HIC and the result is the creation of an individual inside the semantic knowledge base. The compiling of the comfort preferences can be conducted by the dweller him/herself or – if he/she needs support due to some impairments – by the care-giver. If no customized preferences are set, the ontology relies on norms to provide the minimum amount of comfort. For visual comfort, it relies on the European norm EN 12464-1, which sets the minimum amount of illuminance to 200 lx (up to 500 lx when the dweller is working on the kitchen table, thus requiring more light); for indoor temperature and humidity rate, the ontology models the limits provided by the Italian law 74/2013 (which sets the maximum temperature for both winter and summer in a range between 20 °C and 22 °C). Similarly, the ISO 16000-26:2012 standard is adopted for indoor CO_2 concentration (which must be below 1000 ppm in living environments).

Sensors, Actuators and Appliances
Sensors and actuators are modeled relying on the W3C-endorsed Sensors, Observation, Sample and Actuator (SOSA) ontology [32], part of the Semantic Sensor Network (SSN) ontology [33]. SOSA is a lightweight and self-contained core ontology consisting of a set of classes and properties to describe sensors and actuators and their measurements (observations). For domestic appliances' description, the SH leverages on the Smart Appliances REFerence (SAREF) ontology [34], a model that provides concepts and properties to describe the functioning of devices and that shares many similarities with SSN [35]. The possibility of re-using SOSA enables the description of the measurements performed by the sensors, so that the measured values can be compared to the parameters defined by inhabitant's comfort preferences.

Set of SWRL Rules to Provide Tailored Comfort
A set of SWRL rules is developed to foster the actuation of tailored comfort metrics, constituting a rule-based system for the provision of tailored services within the SH. The rules can trigger the actuation of indoor lights and HVAC system. For example, referring to the user depicted in Fig. 3, who is afflicted by a vision-related problem, the SH can provide him with an adequate amount of illuminance by decreasing the amount of illuminance within the living environment; the actuation is supplied via HIC and triggered by an SWRL rule:

```
Dweller(?d), isInHealthCondition(?d, ?hc), HealthCondi-
tion (?hc), isDe-scribedBy (?hc, ?des),
HC_Descriptor(?des), involvesICFCode (?des, b21020),
LightSensitivity (b21020), hasBQual (?des, ?q), greater-
ThanOrEqual (?q, 2), isLocatedInRoom (?p, ?r), Room(?r),
Lighting device (?light), isDeployedIn (?light, ?r), In-
doorCustomizedIlluminance (?ill), ExternalIlluminance
(?exill), hasMeasurementValue(?exill, ?m), lessThan (?m,
250) -> setsLighting (?light, ?ill)
```

The triggering of this rule requires the SH to know the dweller's presence inside a specific room of the house (with an occupancy sensor), so that the provision of dweller's customized illuminance setting can be applied.

Middleware Program
The knowledge base, hosted on the Stardog semantic repository, is connected to the HIC with a middleware – a script designed and implemented in C#. The middleware gets an input JSON file containing the dweller's name as the user is detected within a room by sensors or as the dwellers declares his/her presence; the middleware generates a SPARQL query to retrieve the comfort preferences store in the repository and execute the query against the Stardog server, retrieving information to be sent back to the middleware via another JSON file – containing the required data retrieved from the knowledge base. In order to make this happen, a dynamic program has been written in C# language, to make the HIC application communicate and transmit data to/from semantic repository. The program receives a JSON file containing the inhabitant's

name, as the user is detected, and generates a proper SPARQL query to retrieve the comfort preferences and health conditions of this specific inhabitant from the semantic repository. The program then run the Stardog server – the semantic based data repository where the knowledge base is stored there – and execute the SPARQL query made by the program. Then, the information retrieved as a result will be sent back to the program in another JSON file.

4 Use Cases Scenarios

This Section introduces two use cases highlighting how the FHfFC's SH can help the dwellers in providing them tailored comfort and assist them while performing ADLs.

4.1 Tailoring Indoor Temperature and Humidity Rate

The first use case illustrates how the SH recognizes the indoor temperature and humidity rate in summer are exceeding the customized comfort modeled in the knowledge base. The HIC then warns the dweller and asks him whether to activate the air conditioning system to restore the inhabitant's preferred comfort, as depicted in Fig. 4. Although it may seem a simple actuation, the SH helps elderlies and people with respiratory or temperature-related impairments to benefit of a constant thermo-hygrometric indoor comfort that suits the dweller's health condition. The SH does not substitute the dweller's will by automatically actuating the HVAC; automatic actuation can be set for inhabitants characterized by cognitive impairments, who may benefit from a non-intrusive and automatic actuation to guarantee indoor comfort.

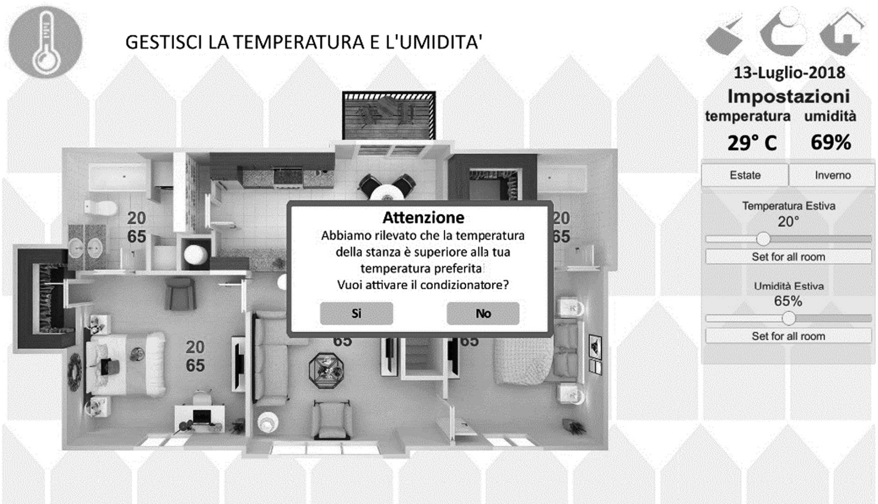

Fig. 4. A screenshot of the HIC warning the dweller that the indoor temperature and humidity rate have exceeded the comfort and asking him/her whether to activate the air conditioning to restore the tailored comfort.

4.2 Setting Illuminance According to the Activity

The second use case demonstrates how the SH can help the dweller in both providing tailored comfort and helping him/her in performing meal preparation, an instrumental ADL necessary for independent living. The dweller can, in fact, declare via the HIC that he/she wants to prepare a meal; therefore, the SH detects his/her presence inside the kitchen and sets the illuminance according to the preferences modeled in the semantic knowledge base. The inhabitants can then select a recipe using the HIC projected on the kitchen table and then the GUI guides the dweller in the preparation – as illustrated in Fig. 5.

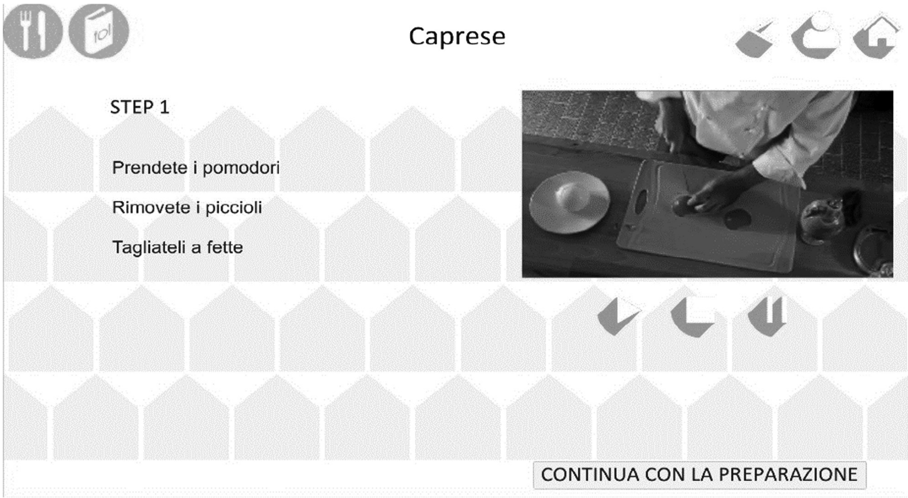

Fig. 5. A snapshot of the HIC illustrating the preparation of a recipe.

This feature allows, on the one hand, to perform an essential ADL (preparing a meal) relying on a cognitive support, while on the other hand, it ensures the most suitable comfort metrics to perform this activity. In fact, according to the EU norm EN 12464-1 it is of pivotal importance to provide an adequate illuminance on areas where the dwellers have to perform activities that require a certain amount of precision – such as cutting vegetables, reading labels of ingredients, etc.

5 Conclusion and Future Works

This work introduces the FHfFC's SH, a semantic-based framework aimed at enhancing indoor comfort for inhabitants. The framework relies on Context Awareness, Ambient Intelligence and Ambient Assisted Living paradigms to encompass also dwellers with disabilities' needs; semantic-based technologies provide a sharable and machine-understandable representation of dwellers' health condition and can trigger environmental actuation to help them in performing several activities. In addition, the proposed SH suggests a ubiquitous interface to ease the control of several domestic features. Future works foresee the validation of the SH framework and, in particular, the validation of the HIC using standard questionnaires and tests – such as the Mobile App Rating Scale (MARS) test [36], the Technology Acceptance Model 2 (TAM2) [37] and the System Usability Scale (SUS) [38]. It is indeed fundamental to evaluate the acceptance of these technologies among the target end-users (elderlies, people afflicted by mild cognitive impairment or specific impairments).

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