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A standard ontology for smart spaces

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Abstract: This paper presents a universal ontology for smart environments aiming to overcome the limitations of the existing ontologies. We enrich our ontology by adding new environmental aspects such as the referentiality and environmental change, that can be used to describe domains as well as applications. We show through a case study how our ontology is used and integrated in a self-organising middleware for smart environments.

Keywords: ontology; smart environment; ubiquitous computing; pervasive computing; semantic web.

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1 Introduction

Smart environments constitute a technological challenge of contemporary research. These environments integrate ubiquitous systems for their functioning. Ubiquitous systems are characterised by an integration of the information within the objects of the daily life (Weiser, 1999). The emergence of ubiquitous systems in smart environments like smart homes, hospitals, airports, universities, etc. became an inevitable reality. However, many problems arise from the use of this technology such as information sharing and reuse, and inter-operability of systems. For this purpose, several research projects address the ontology requirements to overcome the above problems and to ensure better inter-operability of systems. Ontologies based approaches appear as a promising solution in this field. The use of ontologies allows the creation of flexible models on which the reasoning and the inference can be assured (Meshkova et al., 2008). Ontologies are entering widespread use in many areas such as knowledge and content management, electronic commerce, medicine, biology, smart spaces and the semantic Web (Ranganathan et al., 2003; Lee et al., 2001). Moreover, the use of ontologies is not limited to reasoning and information sharing and reuse, their use can be extended to include other important aspects by providing support to other types of reasoning than logical inference. The hierarchy of concepts contained in an ontology can be seen as a space allowing among others to define metrics to compare the semantic proximity between two concepts.

The existing ontologies focus mainly on very specific domain aspects. For example, in the domain of smart environments, there exist ontologies which treat only the context modelling (Preuveneers et al., 2004; Xiao et al., 2004;

Wang et al., 2004b) or QoS related service properties (Maximilien and Singh, 2004), other ontologies focus on the smart meeting space modelling (Huq et al., 2007), and others emphasise the human home interaction (Sommaruga et al., 2005). Nevertheless, numerous problems remain unresolved and have not been addressed by the existing ontologies. Among these problems, we find the notion of referentiality in terms of localisation and temporality, the problem of environmental change, and the problem of environmental structure or schema. Moreover, given the needs of the Domus Laboratory¹ for enabling a plug-and-play integration of new devices in a smart environments, which is strongly related to self configuration that inevitably passes through a fast, easy and automatic integration of new hardware devices (Allen, 1984). In addition to the assistance of dependant persons either inside smart homes or outside. Hence, the development of an ontology that answers these concerns has become an essential and inevitable need. In this paper, we present an ontology for smart environments that allows to respond to our needs, overcome the disadvantages of the existing ontologies, and take into account the new notions namely the referentiality in terms of localisation and temporality, and the problem of the environmental change.

The paper is organised as follows. Section 2 gives an overview of the related works. In Section 3 we introduce the concept of referentiality, and the environmental change is introduced in Section 4. Section 5 describes our ontology concepts, followed by a case study in Section 6. Section 7 makes the conclusion of our paper.

2 Related works

Modelling ubiquitous environments through ontologies is difficult and time consuming task. Some research works have been done on pervasive and ubiquitous environments modelling (Bonino and Corno, 2008; Chen et al., 2004; Heckmann et al., 2005; Kofod-Petersen and Aamodt, 2006; IST Amigo Project, 2004; Román et al., 2002), context representation in ambient intelligence environments (Wang et al., 2004b; Huq et al., 2007; Preuveneers et al., 2004; Chen et al., 2003), household environments (Sommaruga et al., 2005), and other environments related to persons (Sutterer et al., 2008) and virtual spaces (Gao et al., 2004).

In the domain of pervasive and ubiquitous environments modelling, the SOUPA ontology is an example (Chen et al., 2004). It was designed to support mobile applications, its vocabulary is derived from other existing ontologies like Friend-Of-Friend ontology (FOAF) (FOAF provides a unified way for describing people and their basic data. Among properties like name, location or interests, FOAF allows to specify friendship relations),² and DAML-Time, which is an ontology for common knowledge about time and temporal events,³ spatial ontologies such as OpenCYC (Lenat and Guha, 1989) which defines a comprehensive set of vocabularies for symbolic representation of space, and Regional Connection Calculus (RCC) ontology, which consists of vocabularies for expressing spatial relations for qualitative spatial reasoning (Randell et al., 1992). Heckmann et al. (2005) developed an ontology for ubiquitous user modelling, which takes into account the tracking of the person inside as well as outside using a mobile device. The DogOnt ontology (Bonino and Corno, 2008) is designed with a particular focus on interoperation between domotic systems. It is deployed along

five main hierarchy trees: Building thing, Building environment, State, functionality and Domotic network Component.

A collection of ontologies like *ontology server* and *ontology explorer* are integrated into an experimental middleware infrastructure for smart spaces called GAIA (Román et al., 2002). GAIA is characterised by its capacity to bring the functionality of an operating system to physical spaces (Lee et al., 2001).

Some works focused more on constructing ontologies for context in a specific domain to reach the goal of knowledge sharing across distributed systems. In Wang et al. (2004b), the authors introduced an extensible context ontology CONON for pervasive computing environments. In Huq et al. (2007), the authors build an ontology for managing contexts in smart meeting space. The proposed ontology is divided into smart space and domain specific ontology. Preuveneers et al. (2004) introduced the extensible context ontology for ambient intelligence environment. This ontology aims at creating context-aware computing infrastructures, ranging from small embedded devices to high-end service platforms. The specified ontology has been designed to solve several key challenges in ambient intelligence environments, such as application adaptation, automatic code generation and code mobility, and generation of device specific user interfaces (Preuveneers et al., 2004). COBRA-ONT (Chen et al., 2003) is an ontology aimed at supporting knowledge representation and ontology reasoning in pervasive computing environment. COBRA-ONT focuses on modelling context-aware in smart meeting room environments (e.g., intelligent meeting rooms, smart homes, and smart vehicles). DomoML (Sommaruga et al., 2005) is an example of a full modular ontology for representing household environments. It includes three core ontologies: DomoML-env, DomoML-fun and DomoML-core. These three ontologies are used respectively for describing elements inside the house, describing functionalities of each device, and providing support for the correlation of elements described by both DomoML-env and DomoML-fun ontologies (Bonino and Corno, 2008).

Other research works are interested in modelling the person profile through ontologies. Sutterer et al. (2008) have developed a user profile ontology that is dedicated to describe situation-dependent sub-profiles. This ontology can be used by context-aware adaptive service platforms for mobile communication and information services to automatically trigger the situation-dependent personalisation of services (Sutterer et al., 2008). Kadouche et al. (2008, 2009) proposed an ontology to describe person's profile for an assistance system in smart homes. The authors proposed an approach for personalising complex environments for users with special needs such as persons with cognitive disabilities and elderly. The approach used formalisms based on Description Logic (DL) named Semantic Matching Framework (SMF) and designed on the matching of two models: an environment model, and a user model. The environment models describes specific objects in the environment such as sensors and actuators. The user model defines the user characteristics including type of disability, type of technical aids, hand force, hand workspace and preferences.

Ontologies have been used to describe other aspects in pervasive environments and other domains such as web services discovery and multimedia (Martino, 2009; Sriharee, 2006; Brut et al., 2008). Martino (2009) proposed an approach to semantic based Web service discovery. In this approach, a service request is described using an input ontology. The service request is then matched to Web services

descriptions at the ‘syntactic level’ using WSDL, or at the ‘semantic level’ using service ontologies described with OWL-S,⁴ WSMO,⁵ or other ontology languages. The author used a directed rooted graph to represent the different input schemas, WSDL descriptions, OWL-S, WSMO, and other components. The benefit of this representation remains in the fact that, different matching algorithms can operate such as structural-based algorithms and syntactical ones (Shvaiko and Euzenat, 2005). Sriharee (2006) proposed an ontology based-rating model for semantic Web services discovery. The proposed ontology is used to represent particular characteristics of the service such as rating. The author used a matching algorithm to retrieve services that will be ranked based on service consumers’ preference criteria. With ratings, service discovery allows to accurately locate quality services that fulfil the consumers’ requirements. Brut et al. (2008) proposed a service-oriented solution that exploits the ontology-based modelling of users and documents to provide users with the appropriate recommendations of resources. The authors adopted a hybrid recommendation technique that combines two approaches: a collaborative filtering and a content-based approach. In the first one, a Markov Decision Process is used for predicting the next concept that the user focuses on, whereas in the second one, a k nearest neighbours approach is used by considering the similarities between the user and document modelling.

Virtual spaces are very interesting field and have also been modelled through ontologies. In Gao et al. (2004), the authors developed an ontology aiming at facilitating interaction between humans and agents. In this ontology, better intent communication between humans and agents is realised, so that application users can control agents easily in real time (Gao et al., 2004).

The ontologies presented previously suffer from some shortcomings, which are summarised in the following points:

- In SOUPA ontology, many domain-specific concepts are lacking for modelling. For example devices and functionalities, which make it difficult to be directly applied to support interoperability for domotic systems (Bonino and Corno, 2008). However, these shortcomings can be surmounted by taking advantage of functionalities provided by the DomoML ontology, which perfectly described devices. The same remark is observed for the DogOnt ontology in which the description of objects is restricted to only the static side.
- The COBRA-ONT ontology does not have a upper level ontology model, and has implicit representation of time and temporal relations. These shortcomings can be surmounted by integrating COBRA-ONT into CONON ontology that has a upper level ontology model on one side, and integrating the DAML-Time ontology to manage the temporal relations on the other side.
- GAIA suffers from some drawbacks such as the coherence and clarity which limit the ability to share information and communication. GAIA also does not have detailed information about activity, person and location. The UbiWorld ontology is limited to the person localisation and does not take into account the localisation of objects in the environment. This ontology does not take into account also the description of the external environment when changing the environment.

Table 1 Table summarising the well known ontologies and their limitations

<i>Ontology</i>	<i>Domain</i>	<i>Objective</i>	<i>Major concepts</i>	<i>Limitations</i>
UbiWorld	Ubiquitous domain user modelling	Designed to model and query the characteristics of a user, including their activity, as well as the environmental context	ActionalElements, InferentialElements, PhysicalElements, SpatialElements, TemporalElements	Does not take into account indoor localisation of objects
Soupa	Ubiquitous and pervasive applications	Assist ubiquitous and pervasive applications developers who are inexperienced in knowledge representation	Agent, Action, Time, Device, Location, Policy, Person, Space, Event, BDI, Geo-M	Cannot be applied directly to support interoperability and intelligence in domestic systems. No primitives are provided for modelling devices, functionalities, etc. however it can be useful in a multilayered approach (Bonino and Corno, 2008)
CONON	Context in pervasive computing environments	Checking the consistency of context, and deducing high-level, implicit context from low-level, explicit context	Computational entities, location, person and activity	Does not take into account the environment, so it is unable to satisfy the queries on the environment (Huq et al., 2007)
COBRA-Ont	Intelligent meeting room environment	Supporting pervasive Context-aware systems	Person, place, intention, gender, Agent, EventHappeningNow, IntentionalAction, PresentationSchedule, Role, ThingInBuilding, ThingNotInBuilding	Does not have upper level ontology model (Huq et al., 2007), implicit representation of time and temporal relations, does not take into account indoor localisation of objects
Gumo	Intelligent semantic web enriched environments	Uniform interpretation of distributed user models in intelligent semantic web enriched environments	BasicuserDimensions, ContextDimensions, DomainDependentDimensions	Provides just a vocabulary (no axioms, restrictions)
GAIA	Smart spaces	Infrastructure for smart spaces	Includes ontologies such as: Ontology server, Ontology explorer	Lack of coherence and clarity, which limit the ability to share information and communication, has not detailed information about activity, person and location

Table 1 Table summarising the well known ontologies and their limitations (continued)

<i>Ontology</i>	<i>Domain</i>	<i>Objective</i>	<i>Major concepts</i>	<i>Limitations</i>
AMIGO	Aml home environment	To develop an ambient intelligent networked system that effectively integrates heterogeneous devices and services residing in the home domain	Device, Platform, Multimedia, PhysicalEntity, Non-PhysicalEntity, Capabilities, Domotics, Mobile	This ontology is not targeting self-management and almost no dynamic and runtime models of the underlying pervasive systems are considered (Hansen et al., 2008)
Managing context in smart meeting space ontology FIPA	Smart meeting space	Context ontology model for smart meeting space	Activity, Environment, Service, User, Location, Platform, CompEntity	Limited localisation, does not take into account the location of objects
DogOnt	Device ontology Domestic environment	Express the capabilities of different devices in an ubiquitous computing system Human home interaction, connect household to each other. It is designed with a particular focus on interoperation between domotic systems	Device, HardwareDescription, SoftwareDescription, ConnectionDescription, BuildingEnvironment, BuildingThing, DomoticNetworkComponent, Functionality, State	Issues like agent location and agent tracking are not covered. FIPA specification does not cover security (Poslad, 2006) Does not take into account the person and activity, limited localisation
DomoML-Env	Domestic environment	Human home interaction for ambient intelligence based on the semantic web	Building-Environment, Component, Core-foundation, Building-Equipment, Location	Does not address state modelling, does not provide facilities to query or auto complete models (Bonino and Corno, 2008). Limited localisation
FOAF	User context	Unified way for describing people	Person, Organisation, Group, Object, Agent, Document	Defines simple relationship between people (Wang et al., 2004a). Foaf ontology raises many issues like, Control data, track and guarantee provenance facts, partition data so some information remains private (Dumbill, 2002)
Virtual space ontology	Virtual environments	To facilitate interaction between humans and agents	Virtual space, Sound, Light, Graphics, Time, Weather	This ontology finds applications in computer graphics, virtual realities, video games and synthetic battlefields (Gao et al., 2004) does not address real environments

The well known ontologies developed for smart environments are summarised in Table 1. By noticing the ontologies presented in Table 1, most of them are limited in terms of location and time, and do not take into account the notion of referential localisation and referential time. Moreover, these ontologies do not take into account the environmental change, and are not interested to the general structure of the environment. These concepts are presented in more detail in the following sections.

3 Referentiality

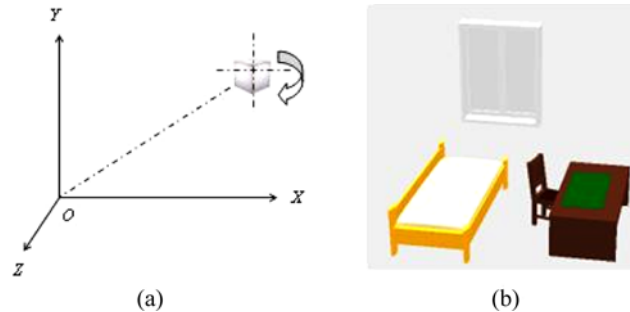
In this section we introduce the notion of referentiality, which is an important notion that should be taken into account during the development of smart environments ontologies. In our ontology, the referentiality encompasses two main categories, referential localisation and referential time.

3.1 Referential localisation

Several research (Wang et al., 2004b; Huq et al., 2007; Chen et al., 2004) use the location as a unique concept (absolute localisation). However, a significant weakness of this location remains in the imprecision, insufficiency and ambiguity. For example in a home, the fridge is located in the kitchen, and the oven is located in the kitchen, but there is no a clear idea about the physical disposition of both the fridge and the oven. None have taken advantage of the information that describes what surrounds a particular object and its relationship to other objects in the environment. Thus, unlike the absolute localisation, the referential localisation takes into account the localisation of the object in relation to the other objects in the environment. This localisation takes the form of (upTo, downTo, behindTo, inFrontTo, nearTo, inTo, Xpositive, Xnegative). The Xpositive and Xnegative are used respectively instead of the right and left side of the object according the angle with which the object is perceived. This kind of localisation allows us to know the physical disposition and arrangement of objects in the environment, and how they are interlinked between them. By knowing the physical arrangement of objects in the environment and how they are interlinked constitute additional information of great importance, which can be used thereafter among others for detecting and recognising activities, security aspects in the environment, detecting and avoiding obstacles for a robot, etc.

In addition to the referential localisation, we define the absolute location. Each objet in the smart environment has an absolute location, which represents the object's coordinates in the space, taking into account the rotations upon the three axis, *yaw*, *pitch* and *roll* in order to detect thereafter the volume occupied by the object. Therefore, the absolute localisation of each object in the smart environment is defined as follows (x, y, z , yaw, pitch, roll). Figure 1 shows an example of the absolute and referential localisation.

In Figure 1(a), the coordinates of the cube are expressed according to the three axis X, Y and Z , and the rotation upon each axis. In Figure 1(b), the bed is in front to the table, the chair is near to the table, the bed is behind the chair, the window is Xnegative (at the left) to the bed (according to a frontal view of the figure).

Figure 1 Example of the absolute and referential localisation: (a) absolute localisation and (b) referential localisation (see online version for colours)

Each object in the environment is a zone that represents the occupied volume in the environment. A zone can belong to one or more zones. For example, the TV is a zone that belongs to the living room zone.

The referential localisation is integrated in our ontology by the means of object properties offered by the the Web Ontology Language (OWL),⁶ using the Protégé-OWL ontology editor⁷ as shown in Figure 2. In addition, The absolute location is introduced in our ontology using the data type properties offered by OWL. Data type properties link individuals (physical objects) to data values (float, string, int, date, time, etc.).

Figure 2 Object property for the referential localisation

```
<owl:ObjectProperty rdf:about="#
    hasReferentialLocation">
  <rdfs:range rdf:resource="#Environment"/>
  <rdfs:domain>
    <owl:Class>
      <owl:unionOf rdf:parseType="Collection">
        <owl:Class rdf:about="#Being"/>
        <owl:Class rdf:about="#Dynamic"/>
        <owl:Class rdf:about="#Environment"/>
      </owl:unionOf>
    </owl:Class>
  </rdfs:domain>
</owl:ObjectProperty>
```

Example

Let us imagine in a smart home, the person is in the living room watching TV, and a digital photo frame is placed on the table at the right of the chair on which the person sits. when the person receives a message, it should be better that the message will be displayed on the TV, which is in front the person than the digital photo frame according to the person's position.

3.2 Referential time

The notion of referential time is inspired from the work of Allen (1991) about his theory of action and time. The temporal relations defined in his theory are applied for action. These temporal relations are integrated in our ontology to

describe temporal relations among activities. The referential time takes into account the time of an activity in relation to other activities either scheduled or deduced. It allows us to ensure that activities are realised in the good order which increases considerably the monitoring process. The referential time takes the form of (before, after, parallelTo, since, from, Overlaps, etc.).

Moreover, each activity has an absolute time that refers to the activity start time, and a duration that refers to the activity realisation time. The absolute time and duration are integrated in our ontology through the data type properties.

The referential time is also integrated in our ontology using object properties as shown in Figure 3.

Figure 3 Object property for the referential time

```
<owl:ObjectProperty rdf:ID="hasReferentialTime">
  <rdfs:range rdf:resource="#Dynamic"/>
  <rdfs:domain rdf:resource="#Dynamic"/>
</owl:ObjectProperty>
```

Example

Let us imagine in a smart home, we would like to ensure a good monitoring of an elderly person's health. The person takes regularly his drugs (x) and (y) respectively at 10 AM and 11 AM. Thus, the drug (x) must be taken *before* the drug (y). It might be very interesting to know if the person takes the drugs (x) and (y) at the right moments. Otherwise, the person's health may be threatened.

3.3 Formalisation of referential location and time

In this section, the term pervasive computing universe refers to a smart environment.

Definition 3.1: A **Pervasive Computing Universe (PCU)** $\mathcal{U}$ is a quadruplet (O, A, B, C) where

- O is a finite non-empty set of objects of the environment $\{O_1, \dots, O_n\}$
- A is a finite non-empty set of activities $\{A_1, \dots, A_m\}$
- B is a finite set of being $\{B_1, \dots, B_k\}$
- C is a finite non-empty set of clocks, i.e., sets of time stamp.

For example,

$$\begin{aligned} O &= \{Bed, Table, Chair, Computer\}, \\ A &= \{PreparingTea, TakeDrugs, Sleep\}, \\ B &= \{John, Marry\}. \end{aligned}$$

Definition 3.2: Let A and B be two sets and let R be a relation between A and B . A **constraints over** R is a pair two relations $(\mathcal{F}_{\subseteq}, \mathcal{F}_{\emptyset})$ of R where

- the inclusion constraint $\mathcal{F}_{\subseteq}$ is such that if two relations r_1 and r_2 of R are $\mathcal{F}_{\subseteq}$ -related then

$$\forall a \in A, \forall b \in B, (a, b) \in r_1 \Rightarrow (a, b) \in r_2$$

- the exclusion constraint $\mathcal{F}_{\emptyset}$ is such that if two relations r_1 and r_2 of R are $\mathcal{F}_{\emptyset}$ -related then

$$\forall a \in A, \forall b \in B, (a, b) \in r_1 \Rightarrow (a, b) \notin r_2.$$

Definition 3.3: Let $\mathcal{U}$ be an PCU. A **referential localisation** $\mathcal{R}_L^{\mathcal{U}}$ in the $\mathcal{U}$ is a couple $(\mathbf{R}_L, \mathbf{C}_L)$ where

- $\mathbf{R}_L$ is a finite non-empty set of relation on the objects $X = \mathbf{O} \cup \mathbf{A} \cup \mathbf{B}$ such that

$$\forall o_1 \in X, \exists o_2 \in X, \exists r \in \mathbf{R}_L, (o_1, o_2) \in r \vee (o_2, o_1) \in r.$$

- $\mathbf{C}_L$ is a finite set of constraints over $\mathbf{R}_L$.

The referential localisation is simply written $\mathcal{R}_L$, when the PCU is implicit. The relation r can take the following forms (upTo, downTo, behindTo, inFrontTo, nearTo, inTo, Xpositive, Xnegative, etc.). For example, $(o_1, o_2) \in \text{upTo}$ means that the object o_1 is upTo the object o_2 .

Definition 3.4: Let $\mathcal{U}$ be an PCU. A **referential time** $\mathcal{R}_T^{\mathcal{U}}$ in the $\mathcal{U}$ is a quadruplet $(\mathbf{R}_{Trel}, \mathbf{C}_{Tabs}, \mathbf{R}_{Tabs}, \mathbf{C}_{Trel})$ where

- $\mathbf{R}_{Trel}$ is a finite non-empty set of relation on the activities $\mathbf{A}$
- $\mathbf{C}_{Tabs}$ is a finite set of constraints over $\mathbf{R}_{Trel}$
- $\mathbf{R}_{Tabs}$ is a finite non-empty set of relation between the activities $\mathbf{A}$ and a time of the main clock $\mathbf{C}$
- $\mathbf{C}_{Trel}$ is a finite set of constraints over $\mathbf{R}_{Tabs}$.

A referential time $\mathcal{R}_T^{\mathcal{U}}$ verifies the following properties:

$$\begin{aligned} \forall a \in \mathbf{A}, (\exists b \in \mathbf{A}, \exists r \in \mathbf{R}_{Trel}, (a, b) \in r \vee (b, a) \in r) \vee \\ (\exists c \in \mathbf{C}, \exists t \in c, \exists r \in \mathbf{R}_{Tabs}, (a, t) \in r). \end{aligned}$$

The referential time is simply written $\mathcal{R}_T$, when the PCU is implicit. The relation r can take the following forms (before, after, parallelTo, since, from, Overlaps, etc).

For example, $(a, b) \in \textit{before}$ means that the activity a is realised before the activity b . In the same way, if t is a time stamp, then $(a, t) \in \textit{since}$ means that the activity a is realised since t time.

4 Environmental change

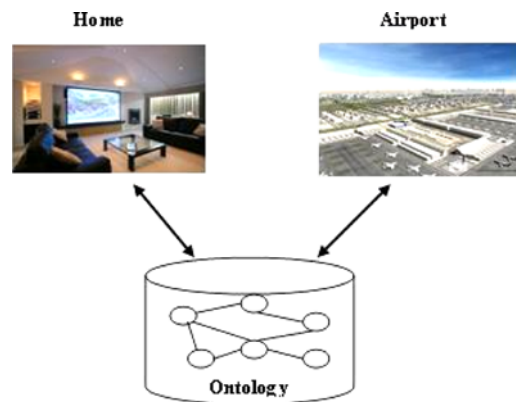
The notion of environmental change takes into account the case of multiple environments. In this case, the ontology should take into account the new environment and adapt accordingly. Therefore, we need an ontology that covers the concepts used in different environments, knowing that there exist some concepts used in an environment and not necessary used in the other. On the other hand, there are still some shared concepts between both environments, this will be helpful to keep information in both environments and to ensure continuity of services when moving from one zone (environment) to a new zone.

Example

Let us imagine it is Friday two PM. John planed to go in vacation for 15 days. John takes the plain at six PM. The ubiquitous system detects that John will leave the house for 15 days, and it reconfigures the electrical appliances such as TV, Fridge, oven, air conditioning, etc. for energy saving. John takes his luggage and goes to the airport. When he arrives, John puts his luggage in a luggage trolley. It is endowed with a weight sensor. The luggage trolley detects that John's luggage weight exceeded the limits allowed for the aircraft, and notifies John for that.

We suppose that the house and the airport share the same ontology as shown in Figure 4.

Figure 4 Example of two environments sharing the same ontology (see online version for colours)

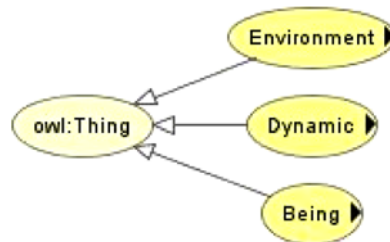


This example shows that the energy saving system is very important at the home environment, but not at all important in the airport environment, and the same thing for the luggage weight which is very important in the airport environment. However, the common concepts such as devices, alliances, networks, and the being can e used to ensure the continuity of services between the two environments.

5 Description of our ontology concepts

This section describes our ontology concepts, and how these concepts are chosen, starting from the top level ontology until the low level one. The design of our ontology is based on the general idea which states that, a *being* lives and interacts in an *environment* with a certain *dynamic*. From here, we can extract the major concepts of our top level ontology, which are: Being, Environment and Dynamic. Figure 5 shows these three concepts. To ensure interoperability with existing technologies, most of our subconcepts classifications are based on international standards such as World Health Organization (2001), Song and Lee (2008), and WIPO (2008).

Figure 5 Top level concepts of our ontology (see online version for colours)



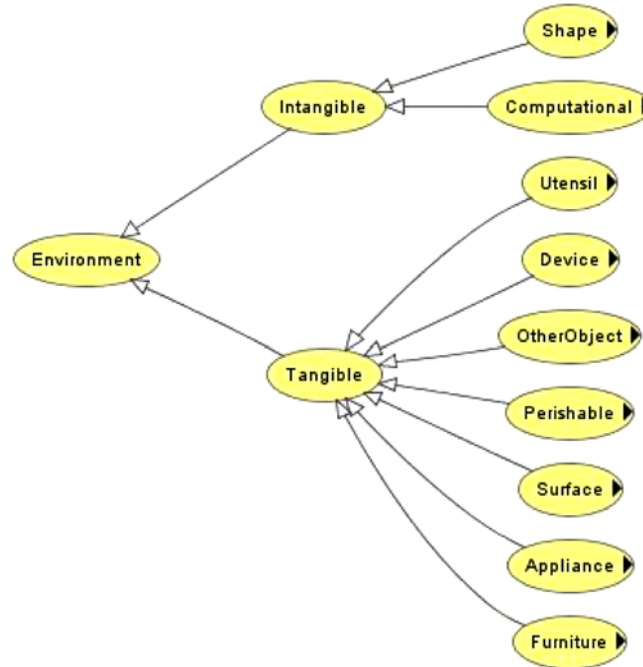
5.1 'Environment' ontology concept

The environment modelling is achieved in many ontologies found in the literature (Bonino and Corno, 2008; Sommaruga et al., 2005), but in our ontology, this concept is differently formalised to overcome the limitations of the existing modelling works described in Table 1. The concept of Environment refers to the environment in which a Being evolves. This environment includes all what is necessary for the evolution of a Being, in terms of habitation, food, travel, leisure, care, etc. In our ontology, the concept of Environment is subdivided into two main subconcepts. The first subconcept is *Tangible*, which refers to all things that can be able to be touched or capable of being given a physical existence,⁸ such as utensils, ingredients, devices, appliances, furniture, etc. and the second subconcept is *Intangible*, which refers to something that cannot have a physical existence like geometric shapes and computational entities. For example, a computer memory has a storage capacity which is intangible, but the memory as an electronic component is tangible. Figure 6 shows the hierarchy of the Environment concept and its related subconcepts.

Location-awareness is highly relevant subject in ubiquitous environments, as many applications exploit location information to provide adequate services or adapt to a changing physical environment (Schuhmann et al., 2008). To deal with the localisation problem in smart environments, and to overcome the limitations of the existing ontologies, we define two types of localisation in smart environments as described in Section 3.

5.2 'Being' ontology concept

The Being plays a vital role in smart environments. In our ontology, the concept of Being is divided into two important components. A *Physical* component that

Figure 6 Environment ontology concept (see online version for colours)

reflects the physical existence of the Being. This component encompassing Animal, Plant, Insect and Person. The second component focuses mainly on the profile of the Being that allows to efficiently characterise the Being's state, in terms of behaviour, preferences, disabilities and so on. The profile which is a *NonPhysical* component, that according to the international classification of functioning, disability and World Health Organization (2001) is composed of three main categories: personal profile, health profile and organic profile.

- The personal profile refers to the particular background of an individual's life and living. It comprises features of the individual that are not part of a health condition or health states. The personal profile may include gender, race, age, other health conditions, fitness, lifestyle, habits, upbringing, coping styles, social relationship, education, profession, past and current experience, etc. World Health Organization (2001).
- The health profile refers to the individual's health state, including information about diseases, prescriptions, allergies and medical histories, etc. World Health Organization (2001).
- The organic profile refers to the body functions and structures and impairments. Body functions are the physiological functions of body systems (including psychological functions). Body structures are anatomical parts of the body such as organs, limbs and their components. Impairments are problems in body function or structure as a significant deviation or loss World Health Organization (2001).

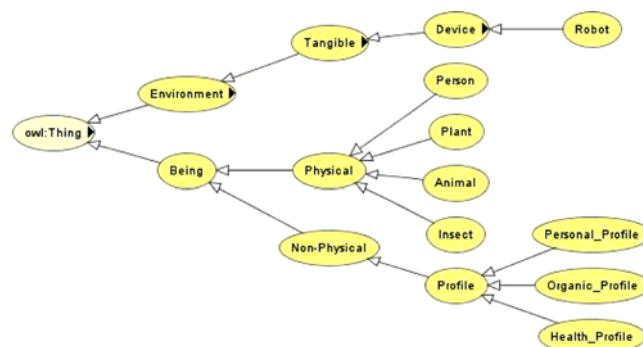
For example, the person named ‘John’ which is an instance of the Physical sub concept of ‘Being’ is linked to the Profile concept using the object property ‘hasProfile’. We note that medical ontologies developed to support human diseases such as the Generic Human Disease Ontology (GenDO) proposed by Hadzic and Chang (2005) can be used to enrich our ontology.

The three profile categories are mainly applied to characterise human being. However, they are implemented to be applied for other beings such as animals and plants.

5.2.1 Robot vs. Being

There have been many questions about the principle of classification of the robot in an ontology. Indeed, is the robot considered as an electronic component that has well defined functionalities, or is it considered as a being that evolves in an environment? It is true that robots can not increase scientific knowledge as much as a human being can. As we are interested to smart environments which are being centred environments, the robot is always considered as a smart and interactive component that is used to serve and assist a person. Therefore, in our ontology the robot is regarded as a device which has well known functionalities. Figure 7 shows the Being concept as well as the derived sub concepts, and how the robot is classified in our ontology.

Figure 7 Being ontology concept (see online version for colours)

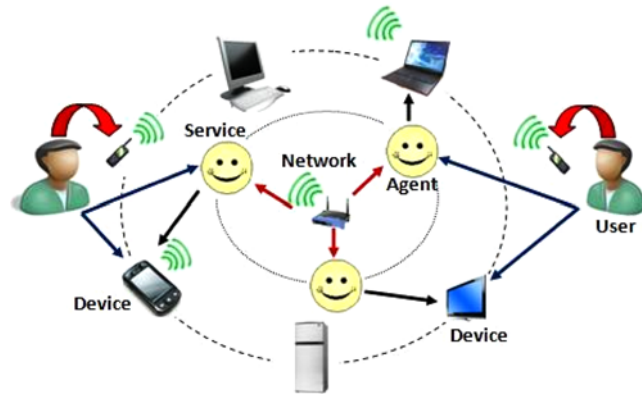


5.3 ‘Dynamic’ ontology concept

The concept of Dynamic refers to all kinds of activities that might exist in an Environment. In our ontology, the concept of Dynamic is not limited only to activities related to a Being like daily living activities (preparing, eating, cleaning, etc.) or entertainment, but rather, it may expand to include other kinds of activities such as mechanical activities, and computational activities provided by computational entities disseminated in the environment, in order to help beings and ensure their well being. Therefore, the concept of Dynamic can be broadly classified into two subconcepts such as *Virtual*, which refers to all computational activities, and *Non_Virtual* which refers to all activities that can be achieved by a human being or a machine such as a robot. Figure 8 shows the hierarchy of Dynamic concept and its related subconcepts.

Figure 8 Dynamic ontology concept (see online version for colours)

Computational activities can be generated either by the execution or interaction between computational entities, or either by the interaction of the person or any object in the environment with computational entities such as services, agents and other software applications. Figure 9 shows an example of these interactions.

Figure 9 Types of interaction in smart environment (see online version for colours)

In our ontology, agents and computational entities can communicate, negotiate and take decision in order to provide the appropriate services when and where needed. The work of Bravo et al. (2006) can be easily integrated in our ontology to facilitate the agents communication during the negotiation process.

6 Case study

An important step of our work is to focus on the practical aspects of our ontology. Indeed, several projects are under development that will put into practice our ontology, and demonstrate its usefulness and effectiveness. Our ontology is mainly developed to fulfill the Domus laboratory needs in terms of information management, sharing and reuse. The classification adopted in our ontology allows to study each concept separately by extracting the sub-ontology known as materialised ontology related to that concept using existing methods such as distributed methods introduced in Bhatt et al. (2004a, 2004b, 2006). These ontologies are extracted in order to satisfy certain requirements and user needs. In this section, we will show through a case study how our ontology is used in a software self-organising middleware for smart environments.

6.1 A software self-organising middleware for smart environments

Smart spaces or pervasive environments are made of several devices: computers, sensors, actuators, communication devices, etc.; and software applications: GUI,

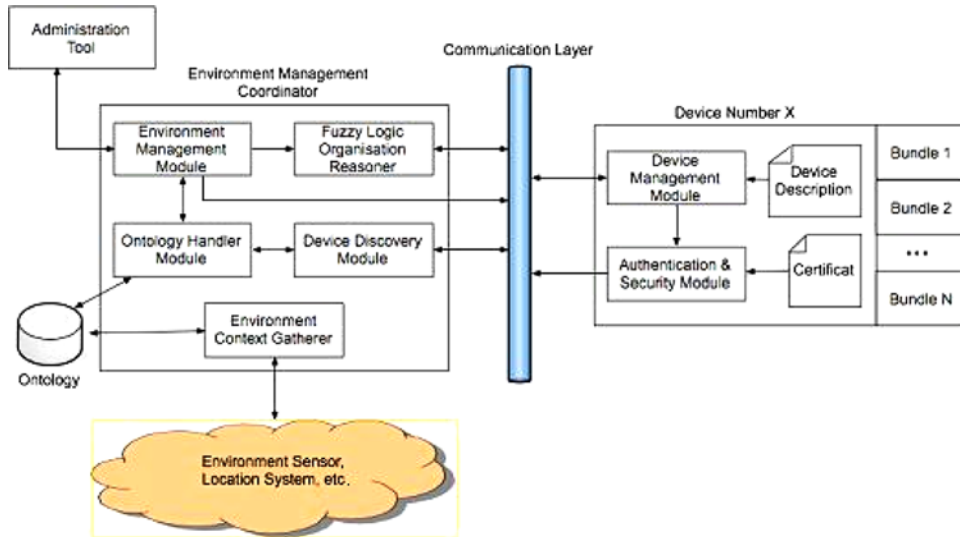
services, embedded processes, etc. The heterogeneity and the high number of environment components made complex and difficult to really understand the environment systems, leading to important difficulties. The high costs in the implementation and maintenance of the pervasive technologies slow the democratisation of the pervasive/smart environments. The heterogeneity of the used devices and applications and often their lack of usability make their utilisation difficult by non-expert people. More specifically, the organisation/configuration, the management and the maintenance of the software applications in the environments are resource and time consuming since the important number of devices and their heterogeneities (Talwar et al., 2005; Weiser, 1993). To organise the environment's software in a suitable configuration, it is required to have a good knowledge of the pervasive environment, which is not the case for most non-expert people such as the health caregivers or the elders.

One solution is to eliminate most of the required manipulations by simplifying the information and feedbacks returned to the users; and by moving the required context reasoning from the users to the environment systems. Therefore, we implement a middleware that is using contextual information to reason about software provision and organisation in smart spaces. This middleware is based on the top of the OSGi framework (Larsson, 2009), which is providing the Service Oriented Architecture (SOA) functionalities to deploy, manage, update and use services in a dynamic way. Thus, this middleware provides the functionalities allowing deploying new applications in smart spaces with few manipulations and little knowledge about the environment components. As contextual information is used during reasoning processes, the middleware is using the above presented OWL environment description to describe environment components. The description is instantiated into the JENA Semantic Framework (Jena, 2009), more details about the JENA utilisation are presented further. The self-organisation middleware is composed of several modules that are working together to provide the autonomous software deployment. These modules are listed below:

- *The Environment Manager Module*: Receiving the deployment and management requests and coordinating the software deployment with the other used modules.
- *The Device Management Module*: Receiving the final deployment request from the Environment Manager Module. Advertise the device and providing the device semantic description.
- *The Authentication & Security Module*: Manages the security around the software deployment and installation.
- *The Device Discovery Module*: Receives the device advertisements, extracting the descriptions from the devices and adding it to the semantic framework/ontology.
- *Ontology Handler Module*: Allows to apply queries on the semantic framework and manipulate it by adding, modifying or removing concepts or instances.
- *Fuzzy Logic Organisation Reasoning Engine (FLORE)*: Matches the software needs with the device resources/context. Find the software's more suitable environment device.

Figure 10 presents the middleware architecture with its organisation, management, ontology and discovery modules.

Figure 10 The self-organisation middleware architecture with its two main components: the environment manager coordinator and the device node (see online version for colours)



We integrated the JENA Semantic Framework to our middleware by embedding it in middleware modules and by providing middleware services to query and manipulate contextual information. The middleware's contextual information contains in JENA, is in either way, provided by the original environment description and by a series of contextual information gatherers that are adding, modifying or removing contextual concepts and instances. These gatherers can be user software, event sources, location systems, etc. The contextual information part related to the device description is provided by the device discovery mechanisms, which is extracting the device descriptions from the devices during the discovery process. The contextual information can be combined to the environment description and user preferences in order to provide high personalisation and assistance system. For example, Izumi et al. (2009) proposed a supervisory system called 'uEyes', that considers actual situations and social aspects of users in a ubiquitous computing environment. This system introduces social context awareness which is a distinguishing component for supervision. The system combines both environmental information gathered from sensors and common-sense knowledge related to human daily life activities. The authors used an ontology to design the social context awareness.

6.2 Environment description utilisation

The presented middleware uses mainly four concepts of the environment description:

- *The OSGiBundle*: Inheriting from the Application concept and describing the software and its needs (resources, peripherals, location, etc.).

- *The NonDedicatedDevice*: Device that is able to support new software and where we are able to manage the existing ones like PCs, PDAs, Servers, Cell phones, etc.
- *The DedicatedDevice*: Device where it is impossible to modify or add new processes/software like peripherals (mouse, keyboard, etc.).
- *Zone*: Simple concept of logical environment zone that can be bonded or not to physical zone. In the middleware implementation, the kitchen is a zone and can include several other zones like the fridge's zone.

The DedicatedDevice and NonDedicatedDevice are subconcepts of the concept Device which stems from the concept of Environment in our ontology.

The software deployment requests include the software descriptions (OSGiBundle) and are used by the Environment Manager Coordinator to find the more suitable device for the software needs. Figure 11 presents an example of an OSGiBundle software.

Figure 11 OWL code snippet of the application description

```
<rdf:RDF
  xmlns="http://www.domus.usherbrooke.ca/Environment.owl#"
  xml:base="http://www.domus.usherbrooke.ca/Environment.owl"
  xmlns:Environment="http://www.domus.usherbrooke.ca/Environment.owl#"
  [ ]
  <OSGiBundle rdf:about="#JUnit">
    <hasDownloadURL rdf:datatype="xsd:string">http://www.knopflerfish.org/
      releases/2.3.2/osgi/jars/junit/junit_all-2.1.0.jar</hasDownloadURL>
    <hasUUID rdf:datatype="xsd:string">JUnitBundle</hasUUID>
    <isMobile rdf:datatype="xsd:boolean">false</isMobile>
    <needPermanentMemory>3</needPermanentMemory>
    <hasName>JUnit</hasName>
    <hasDescription>It is the JUnit Bundle</hasDescription>
    <needRAM>5</needRAM>
    <needCPU>1200</needCPU>
    <neededZone rdf:resource="#Office"/>
    <hasStatus>Uninstalled</hasStatus>
  </OSGiBundle>
</rdf:RDF>
```

The NonDedicatedDevice describes the environment devices. The description includes the resources (CPU, RAM and Permanent memory), their utilisations, its location, etc. It includes also the device's related dedicated devices such as the peripherals, the GUI, etc. Figure 12 presents the RDF/OWL description of an environment device.

Finally, the zone concept describes the logical zone of the environment. For the middleware purpose, we created a new inter zone relation, the adjacent relation. A zone can have several adjacent relations if the adjacent zones are directly accessible from one to another. These zone relations are used by the organisation reasoning engine to evaluate the viability of a device to support a software bonded to a specific zone. Given the high heterogeneity and distribution involved in pervasive environments, such as services, applications, networks, devices and agents, our ontology allows a distributed management of these components by adopting the distributed ontology framework principle inspired from the work (Flahive et al., 2005) in semantic grid environment. This later allows to design and adapt tools for managing these environment (Flahive et al., 2005).

Figure 12 OWL code snippet of the device description

```

<rdf:RDF
  xmlns="http://www.domus.usherbrooke.ca/Environment.owl#"
  xml:base="http://www.domus.usherbrooke.ca/Environment.owl"
  xmlns:Environment="http://www.domus.usherbrooke.ca/Environment.owl#"
  [ ]
  <NonDedicatedDevice rdf:about="#Laptop">
    <inTo rdf:resource="#LivingRoom"/>
    <hasCPUSaturation rdf:datatype="xsd:float">10</hasCPUSaturation>
    <hasRAMSaturation rdf:datatype="xsd:float">40</hasRAMSaturation>
    <hasPermanentMemorySaturation rdf:datatype="xsd:float">50
      </hasPermanentMemorySaturation>
    <hasRAM rdf:datatype="xsd:float">1000</hasRAM>
    <hasCPU rdf:datatype="xsd:float">19142</hasCPU>
    <hasPermanentMemory rdf:datatype="xsd:float">200000
      </hasPermanentMemory>
    <hasStatus>Started</hasStatus>
    <isMobile rdf:datatype="xsd:boolean">true</isMobile>
    <hasServiceAddress>10.41.57.125</hasServiceAddress>
    <hasUUID>uid:0000000000001</hasUUID>
    <hasDescription>Charles s Laptop Computer</hasDescription>
    <haveDedicatedDevice rdf:resource="#TouchScreen"/>
    <haveDedicatedDevice rdf:resource="#KeyboardWithTrackPad"/>
  </NonDedicatedDevice>
  <DedicatedDevice rdf:about="#KeyboardWithTrackPad">
    <inTo rdf:resource="#Laptop"/>
  </DedicatedDevice>
  <DedicatedDevice rdf:about="#TouchScreen">
    <inTo rdf:resource="# Laptop "/>
  </DedicatedDevice>
</rdf:RDF>

```

6.3 Fuzzy logic organisation reasoning engine

To move the organisation/configuration reasoning to the environment's system, the system must have the required information on the environment context to apply the right reasoning. This contextual information covers a large variety of data type, ranging from quantitative information such as the room's temperature to qualitative information such as the user state. The Fuzzy Logic approach (Ross, 1995), based on the fuzzy set theory, allows to easily compare quantitative and qualitative information in a same set of reasoning rules. Moreover, a reasoning algorithm based on the Fuzzy Logic does not need to have an accurate knowledge of the model and can work with a high level of imprecision, which is the case of the pervasive environment, where it can be difficult to describe precisely the model and get accurate data. The contextual information is used by the FLORE, which is matching the needs of the applications to deploy in a pervasive environment (hardware resources, contextual location, peripherals, etc.) with the context and the resources of the environment devices. As some of the data are qualitative and others quantitative, we are using the capabilities of the Fuzzy Logic to work with these kinds of data in the fuzzy (qualitative) perspective. By using fuzzy reasoning rules and fuzzy membership functions, the FLORE qualify the capacity and the viability of environment devices face to software by attributing to them a Device Capability Quotient (DCQ). The DCQ is use during the software deployment to find the more suitable devices face to software; the device with highest DCQ being the more suitable one. The actual FLORE evaluate the device resources, device peripherals and their locations face to the software resource and contextual location needs. For instance, we are evaluating the adjacent relation between the software zone target and the zone where the device are located or the inheritance relation

between the zones. More the relation between the software's needed zone and device's zone is closed, more the device is viable for the software deployment. The zone relation are qualified in singleton membership functions as (in the decreasing order of closed relationship): same zone, directly adjacent zone, have a same parent and dissociated. Moreover, less the device resources are used (or saturated) and more the device is viable. The resource saturations are also qualified through membership functions : resource free, resource used, resource very used and resource saturated. All these reasoning rules are evaluated and processed with the help of the jFuzzyLogic API jFuzzyLogic (2009). Figure 13 presents the Fuzzy rules (in the Fuzzy Control Language) used by the FLORE to compute the DCQ.

Figure 13 The FLORE fuzzy evaluation rules

1. IF CPUSaturation IS free AND RAMSaturation is free AND devicePMSaturation is free AND zoneSimilarity is same THEN deviceViability IS optimal WITH 1;
2. IF (CPUSaturation IS free OR RAMSaturation is free OR PMSaturation is free) AND (CPUSaturation IS used OR RAMSaturation is used OR PMSaturation is used) AND zoneSimilarity is same THEN deviceViability IS optimal;
3. IF (CPUSaturation IS free OR RAMSaturation is free OR PMSaturation is free) AND (CPUSaturation IS used OR RAMSaturation is used OR PMSaturation is used) AND zoneSimilarity is directlyAdjacent THEN deviceViability IS subOptimal;
4. IF (CPUSaturation IS used OR RAMSaturation is used OR PMSaturation is used) AND (CPUSaturation IS veryUsed OR RAMSaturation is veryUsed OR PMSaturation is veryUsed) AND zoneSimilarity is same THEN deviceViabilityIS subOptimal;
5. IF CPUSaturation IS veryUsed AND RAMSaturation is veryUsed AND PMSaturation is veryUsed AND zoneSimilarity is same THEN deviceViabilityIS subOptimal;
6. IF CPUSaturation IS veryUsed OR RAMSaturation is veryUsed OR PMSaturation is veryUsed THEN deviceViabilityIS notOptimal;
7. IF CPUSaturation IS saturated OR RAMSaturation is saturated OR PMSaturation is saturated THEN deviceViabilityIS impossible;
8. IF zoneSimilarity is sameParent THEN deviceViabilityis notOptimal;
9. IF zoneSimilarity is dissociated THEN deviceViabilityis impossible WITH 1;

As we are aiming to reduce the complexity and related processing time for software organisation and configuration in smart spaces, we need to evaluate if the proposed solution is computing in a decent interval time and if it gave results that are matching the targeted behaviours. Concerning the computing time, our first requirement was to get results faster than the time spent for a user to do the task itself. Thus, we ran some tests and benchmarks to verify the FLORE computing times. We ran benchmarks where we sent to FLORE evaluation requests concerning an application deployment, with different quantity of ontology devices. Our initial results are satisfying our goals, by giving computing time of around 0.07 seconds for 50 devices in the ontology and 0.4 seconds with 500 devices. More details on the FLORE tests and benchmarks results will be published in a future paper.

6.4 Future improvements and perspectives of the middleware

The proposed self-organisation middleware implementation and its FLORE is the first version of a middleware that will reduce the complexity and the number of the user required manipulations to deploy new software applications in pervasive environments. We want in our next work, to extend the middleware capabilities

by adding the users and their profiles in organisation/configuration reasoning. We will extend the environment description and the FLORE to evaluate the position and the orientation of the users in the pervasive environment face to the device locations and interaction capabilities. We aim also to use the user restrictions and preferences face to devices and peripherals in the reasoning, to choose the devices with which they will be more comfortable, more usable. Moreover, by taking in account the user profile properties in the FLORE, the DCQ attribution will be more complex, depending on a larger type of data. A second reasoning algorithm will be required, which will include new fuzzy rules and membership functions that will evaluate the user profile properties.

7 Conclusion and perspectives

Ontologies are key requirements for building ubiquitous systems, and describing smart environments. Through ontologies, ubiquitous systems can easily share knowledge and provide relevant services and information to users. In our paper we introduced a universal ontology for smart environments. By using this ontology, three main key issues were resolved namely the referentiality in terms of location and time and the environment change. We illustrate through a case study the usefulness and efficiency of our ontology. The middleware developed in this study uses the most concepts of our ontology such as the Environment, the Being and the Dynamic with more focus principally on the Environment and Dynamic concepts.

Despite the huge efforts provided in the development of ontologies for smart environments, the development of a complete ontology remains a difficult task. However, our objective is to achieve an ontology for smart environment which could then be adopted as a standard by scientific community.

We are working to improve the usability of our ontology by integrating it in several research projects being developed in the Domus laboratory, such as continuity of services, context-management, activity recognition, and other projects.

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Notes

¹<http://domus.usherbrooke.ca/>

²FOAF Ontology: <http://www.foaf-project.org/>

³<http://www.cs.rochester.edu/ferguson/daml/>

⁴<http://www.daml.org/services/owl-s/1.0/owl-s.html>

⁵<http://www.wsmo.org/>

⁶<http://www.w3.org/TR/owl-ref/>

⁷<http://protege.stanford.edu/>

⁸Definition from the encarta online dictionary.