An Ambient Assisted Living Framework with Automatic Self-Diagnosis

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***Abstract*—As the population in many countries is steadily aging, allowing elderly people to stay longer at home is a growing concern. Ambient Assisted Living (AAL) proposes new techniques to help people remain autonomous, based on ambient intelligence. We present an ontology-based framework in which ontologies enable the expression of users' preferences in order to personalize the system behavior. They are also used for the discovery and interconnection of devices, the storage and retrieval of collected data and the transmission of actions. Basing everything on ontologies allows the designer to express the behavior of the system using high-level logic rules. To render AAL systems as autonomous as possible, devices that fail should be detected at runtime. For this reason, the framework offers a diagnosis service that builds a prediction model of the values detected by sensors. It is based on information discovered *opportunistically* at run-time and knowledge about physical laws. The framework monitors the run-time behavior of the AAL system and uses the prediction model to detect inconsistencies and hence faults. Therefore, fault detection is totally dynamic and opportunistic; there are no pre-defined control loops. This paper describes an actual implementation, with precise technological details, in order to prove the feasibility of the technical choices, and provide implementation ideas for future projects.**

Keywords-Ambient Assisted Living (AAL); ambient intelligence; ontologies; diagnosis; fault detection; reasoning.

I. Introduction

Due to the demographic change towards an aging population, society must find ways to assist elderly people to stay active at home longer. Currently, this support is mainly provided by human caregivers, but in the future technology is expected to play a more and more important role both for elderly persons and caregivers. In Europe, a roadmap has been defined in the last years called Ambient Assisting Living (AAL). A software platform for AAL was described in our previous paper entitled *An Ambient Assisted Living Framework Supporting Personalization Based on Ontologies* [1]. This paper is an extended version of the latter, which introduces improvements to the self-diagnostic features of the framework.

AAL [2] is part of the larger *ambient intelligence* vision [3], in which information technology supports everyday tasks in an unobtrusive way. The business context of AAL is rich in terms of technology (from tele-health systems to robotics) but also in terms of stakeholders (from service providers to policy makers, including core technology or platform developers).

The work presented here has been carried out within the CBDP project (Context-Based Digital Personality) [4], which aims at creating a framework for building various kinds of ambient-intelligent applications, based around the concept of Digital Personality for representing the preferences of users. Aside from AAL, several application domains were considered, such as digital TV guides, assistants for workers at a construction site, or marketing application on mobile phones. Therefore, the CBDP framework addresses a wide variety of requirements. However, in this paper, we focus exclusively on the parts of the CBDP framework relevant to AAL.

Our approach is entirely based on ontologies. Not only are ontologies used to capture domain knowledge, but more importantly they serve as the runtime mechanism that allows the interconnection of devices, the exchange of data and the execution of actions. The Digital Personality of the users is stored in the ontology.

On top of that, a diagnosis process is able to construct a model predicting the expected sensor readings at runtime, as a function of requested actuator commands. Using this and by observing actual sensor values found in the ontology, it is able to monitor the run-time behavior of the system and to detect unexpected patterns, that are probably caused by failed devices (sensors and actuators).

The ontology is presented in Section II. Section III describes the CBDP framework and gives implementation details. Section IV focuses on diagnosis: it explains what models are used, and how they are exploited. Section V describes a typical AAL use case, and goes through its complete realization. Section VI introduces some related work, and compares our approach with published results. Finally, Section VII gives directions for future work.

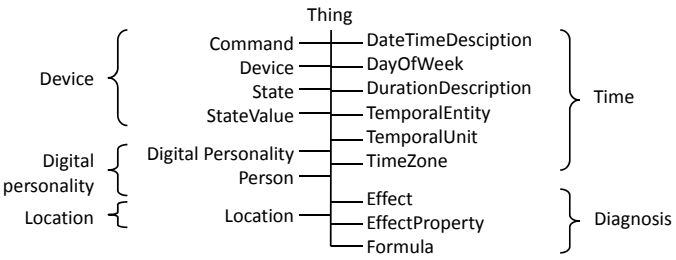

Figure 1. First level of the CBDP ontology.

II. An Ontology for AAL Applications

CBDP is built around an ontology: this section justifies this choice and describes the ontology used.

A. Why use ontologies?

AAL applications are trans-disciplinary by essence (for instance, they can mix automatic control with modeling of user behavior), therefore, the ability to reuse knowledge and integrate several knowledge domains is particularly important for them. Furthermore, the field of AAL is very open and changing, so it is not possible to base an AAL platform on a fixed set of features, on a fixed set of data models: extensibility is key. In addition, an AAL environment may require the interoperation of software and hardware devices from a variety of suppliers: there must be a standard way of exchanging knowledge.

Ontologies are well-adapted to all these needs [5]: an ontology framework provides a standard infrastructure for sharing knowledge. In addition, semantic relationships such as equivalence may be expressed between various knowledge sources, thus permitting the easy integration of several sources or domains. In addition, one can easily extend an ontology to take into account new applications or new devices. For these reasons, leading AAL projects such as OASIS (Open architecture for Accessible Services Integration and Standardisation) have put a strong emphasis on ontologies [6]. Being oriented toward personalization, CBDP explicitly introduces an ontology module for modeling the "Digital Personality" of the user.

B. Ontology used by CBDP

The ontology defined for CBDP is built around the OWL language [7], which is based on the Resource Description Framework (RDF). RDF represents knowledge as a set of *triples* or *statements* of the form {subject, predicate, object}. It models different interrelated domains in a modular way, so as to enable its easy adaptation to new applications. In order to put into practice the aforementioned notion of reusability, two of the domains are based on existing ontologies. Figure 1 depicts the first level of the ontology; the main domains are as follows:

- *Device:* this part is based on the DogOnt [8] ontology that has been simplified for our purpose, while keeping the modeling axes (typology, functionality and state).
- *Digital Personality:* a class *Person* allows the representation of a human being, and a *Digital Personality* stores the person's preferences in order to personalize the services offered to him/her.
- *Location:* a location model is required because most of the services offered in the AAL domain must know the position of the user (in/out the house, in the bedroom/in the kitchen, etc.) and of the devices (sensors and actuators).
- *Time:* we import W3C's existing Time Ontology [9] without any change.
- *Diagnosis:* we introduce the concept of physical effect (see Section IV below), to compute the expected result of the action of an actuator onto a sensor.

The ontology is loosely coupled with the framework, so to a great extent it may be changed without affecting it. However, the basic feature of sending commands to actuators rely on specific *core classes and properties* that may not be changed; this part is depicted in Figure 2.

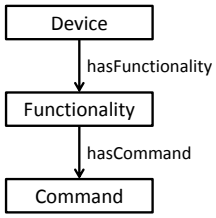

Figure 2. Ontology classes required for proper operation of the framework.

III. CBDP Framework

This section describes the CBDP framework and how it can be used to build AAL applications.

A. Architecture

The main goal of the CBDP Framework is to dynamically handle ontology data and initiate actions when specified conditions in the ontology are achieved. CBDP is written in Java; it is based on OSGi (Open Services Gateway initiative framework) [10], which allows one to build applications flexibly by combining *bundles*. In CBDP, an application is composed of CBDP's core bundles (the Context Reasoner and the Sensor/Actuator Layer, described in Sections III-B and III-C, respectively) and application-specific bundles (see Figure 3). In our case:

- AAL-specific application bundle: contains the rules that define the intended application behavior, meant to assist the user according to his/her needs.
- Zigbee Driver bundle: allows the exchange of data between the physical devices (connected via a wireless Zigbee network) and the CBDP Framework.

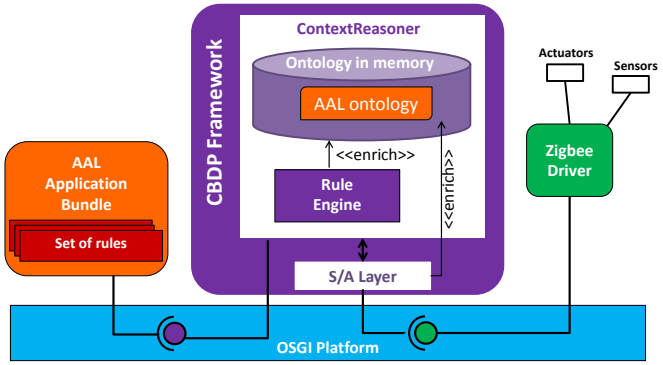

Figure 3. Architecture of the CBDP framework.

Table I
OSGi PROPERTY NAMES USED TO SPECIFY OWL TREES.

Sensor information

instance.id	URI identifying the sensor (String)

1) When referencing a dataProperty present in the ontology

data.property	Name of the "simple data" property (String)
data.property.value	Value (depends on property: Boolean, Double, Integer, String...)

2) When referencing an objectProperty present in the ontology

object.property	Name of the "object" property (String)
object.property.range	Name of the class referenced by the property (String)

B. Context Reasoner and Rules

The Context Reasoner is in charge of managing the information coming from external components (AAL Application or Zigbee Driver) by structuring them according to the AAL ontology. Therefore, it provides methods to add new information, retrieve stored information, and perform queries about that information. Manipulation of the ontology is done using the Jena library [11].

Another feature of the Context Reasoner is its rule engine. Its purpose is to perform actions to help the user and facilitate common tasks, based on a set of application-specific rules (hence the rules are provided by the AAL Application bundle). The rules are Horn clauses [12]: a rule is composed of premises that determine the situations in which the rule applies, and a conclusion, that basically adds a new "fact" into the ontology, such as a new property value. An example of such a rule is given in Section V-A below. Rules are applied by Jena's basic reasoning engine, using forward chaining.

For performance reasons, the rule engine does not apply all rules at each instant. The rules are applied only when a change in the ontology matches a *filter* (i.e., happens in a specific part of the class hierarchy). The filters are application-specific; here they are defined by the AAL Application bundle. At first one may use a "catch-all" filter; performance can be improved later by refining the filters.

C. Sensor/Actuator Layer

The Sensor/Actuator layer (S/A layer) connects the sensors and actuators to the ontology. The communication is two-way:

- Sensor data (sent through Zigbee) is stored in the ontology. This allows one to perform semantic queries and semantic reasoning over sensor data.
- A command request inserted in the ontology (using a property called *hasCommand*) triggers the actual emission of a command to the actuator.

All exchanges are deterministic. They are are triggered in response to events. The module responsible for connecting the sensors to the Context Reasoner is based on the use of a specific OSGi service called *EventAdmin*. A communication protocol through OSGi events has been defined in order to allow the communication between the drivers and the S/A layer. Section III-D describes this protocol.

D. Communication between sensors/actuators and the ontology

This section deals with the protocol used to exchange ontology knowledge using OSGi events. An event is composed of a *topic* and of a list of *properties* ({propertyName; propertyValue} pairs). We have defined two kinds of events: 1) to report sensor data, 2) to send commands to actuators. For both kinds of events, the OSGi *topic* string is built according to the pattern `CBDP/AAL/deviceClass`. `CBDP` and `AAL` are invariant: they reference the general framework and our application-specific ontology; `deviceClass` is the name of the sensor class that sends data, or actuator class that is to receive data. The remainder of this section gives details on the actual *contents* (list of properties) of the events in both cases.

1) Reporting sensor data: When sensor data is reported, a sub-graph (actually a tree) must be created in the ontology. An edge in this tree may be of two kinds: connecting an object to a simple value such as an number ("dataProperty"), or connecting an object to another object ("objectProperty"). A convention using OSGi's properties allows us to completely describe the tree. At each node in the tree to be created, a set of datatype and object properties may be specified. Each edge of the tree is numbered using a simple convention: from the top of the tree, each time an edge is followed, a dot and the index of the edge under its parent node are appended to the OSGi property name (see the examples in Figure 4). This permits the description of each edge and each node to be created. The basic property names (without trailing dots) are given in Table I, and a complete example is given in Figure 4. It represents an event stating that the light level is 500 lux in the kitchen at the date {Calendar value}.

2) Sending actuator commands: Sending a command to an actuator is done using the following convention: a new

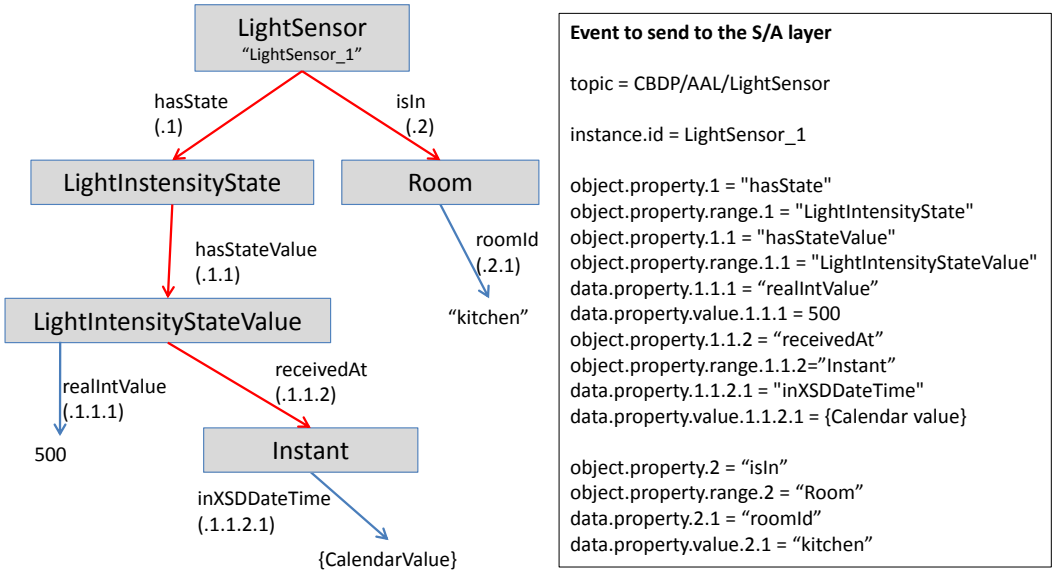

Figure 4. Example of an event containing sensor data.

statement must be added in the ontology, with a relation named "hasCommand" (see Figure 2 above). Such a statement may be added by a reasoning rule, or by application code calling the context manager.

When the S/A layer detects a new "hasCommand" statement, it serializes the corresponding sub-tree of the ontology graph into an OSGi event (using the same convention as above) and sends it to the driver of the target actuator. Figure 5 depicts the "turn light on" event graphically.

E. Deployment

The OSGi implementation used by CBDP is Apache Felix. The use of Java and OSGi permits to deploy the framework on a variety of platforms. We have conducted tests on desktop PCs (under Windows and MacOS) and on embedded systems (on a set-top-box running Linux and on Aonix Perc) [13]. Perc is a Java virtual machine for embedded systems that can be deployed on resource-constrained targets while providing real-time and safety guaranties. This demonstrates the adequacy of CBDP for its target applications, user assistance in ambient environments, i.e., in non computer-centric settings.

IV. Diagnosis

Ultimately, the goal of any AAL application is to activate some actuators, based on data provided by some sensors. However, sensors and actuators may suffer failures. Therefore, the system should check autonomously whether the intended actions are performed correctly. This need for self-diagnosis capabilities of ambient environments was outlined as early as 2001 [3]. Here we focus only on the diagnosis of hardware devices; we do not consider software bugs or runtime failures.

A. Rationale

In software, mechanisms such as exceptions and error codes report whether a procedure executes successfully or not. Likewise, an actuator can provide a return code, but generally this reflects only the way the orders are transmitted to the actuator, not their actual execution. For instance, when the system activates a light bulb, it receives an acknowledgement that confirms the switch-on of the electrical circuit, but this does not necessarily mean that the bulb is really on (the bulb may be damaged for instance). Therefore, a reliable AAL application needs a way to assess at run-time the status of its sensors and actuators.

To address the issue, the designer could apply classical control theory to pre-determine closed control loops using designated sensors. However, the particularity of ambient systems is that physical resources, mainly sensors and actuators, are not necessarily known at design time, but are dynamically discovered at run-time. In consequence, such control loops cannot be pre-determined; the diagnosis strategy needs to be automatically determined at run-time.

We propose an approach in which the system relies only on sensors already available, thereby not requiring the addition of specific devices for diagnosis purposes. The sensors that may be used to perform diagnosis are discovered at run-time. When a sensor measures a physical parameter, the system may deduce sensor/actuator "health" status by comparing actual values with *expected* sensor values.

To achieve this, we propose a diagnosis framework in which the characteristics of actuators and sensors, as well as the *physical effects* involved, are precisely described. The following paragraphs provide a high-level description of this approach; refer to [14] for more details.

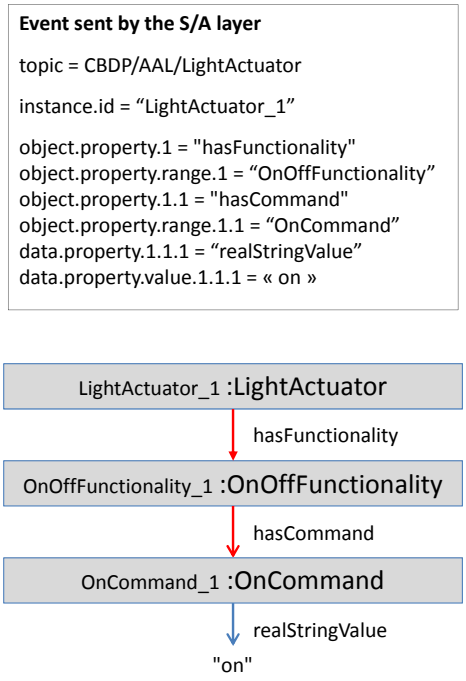

Figure 5. Example of an event containing a command, to be transmitted to an actuator.

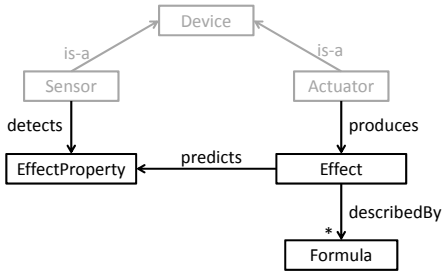

Figure 6. The diagnosis framework adds to the general-purpose ontology (gray part at the top) a few concepts to describe the effects and their detectable properties.

B. Modeling physical effects

Effects are modeled in order to predict the physical consequences of actions in an ambient environment. Each effect is characterized by a set of properties: some *define* the effect (at the source actuator, e.g., the light intensity *emitted by a light bulb*), some are *observable* by a sensor (e.g., the light intensity *received by a light sensor*).

Depending on the application's needs, an effect can be defined at various levels of granularity. For instance, the light emitted by a light bulb could be modeled either using classical laws of physics for light propagation, or using a simple boolean law ("if a light bulb is on in a room then the light sensors that are in that room should detect light"). The choice of the right level of granularity depends, among other things, on the context of use, for instance assisted living homes for blind persons may require a very detailed definition of the model for the propagation of sound waves.

We consider that an effect can be described by some mathematical formula, or set of formulae. For instance, the propagation of light within a room may be modeled by the following functions:

$$\texttt{distance}(A,B) = \sqrt{(A.\texttt{x}-B.\texttt{x})^2+(A.\texttt{y}-B.\texttt{y})^2} \quad (1)$$

$$\texttt{illum}(A,B) = \frac{A.\texttt{flux}}{(\texttt{distance}(A,B))^2} \quad (2)$$

$$B.\texttt{illuminance} = \sum_{A \in \texttt{LightActuators}} \texttt{illum}(A,B) \quad (3)$$

The notation $Obj.\texttt{prop}$ refers to property *prop* of object *Obj*. In the formulae above, A and B stand for any ambient objects modeled by the system. `LightActuators` is the set of light actuators. Formula (1) defines a function, called `distance`, that computes the planar distance between two ambient objects A and B. In formula (2), $\texttt{illum}(A,B)$ is the luminous illuminance contributed by object A onto object B. Formula (3) states that the total illuminance of object B is the sum of the individual contributions of every light actuator onto object B.

C. Using effects for linking actuators to sensors

As ambient systems are highly dynamic, one cannot explicitly link related sensors and actuators. The concept of effect allows for easy decoupling of devices, as illustrated by Figure 6. An actuator class is linked to the effects it may potentially produce. Similarly, a sensor class is linked to at least one effect property. At a generic level, there is a link between a given effect (e.g., emission of light) and the corresponding detectable properties (e.g., illuminance) through the *predicts* relation. A specialization of the abstract level of Figure 6 is presented in Figure 7.

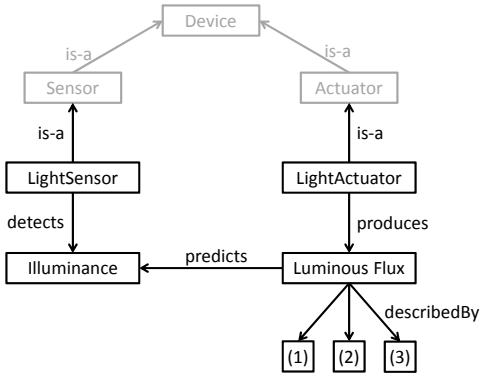

Figure 7. Specialization of the abstract ontology level to account for a specific effect: the emission of light. (1), (2) and (3) refer to the corresponding formulae defined in the text.

Knowing the effects produced by any actuator in the system, and knowing the effect properties sensed by any sensor in the system, it is therefore possible to determine and update at run-time the links between actual sensors and actuators.

We construct a *prediction model* that constitutes an instantiation of the effects for a given set of actuators and sensors, in a given configuration. The formulae are applied to actual objects; the "iterative" expressions (such as the *capital-sigma* notation used in formula (3)) are expanded in accordance to existing objects. The prediction model is updated each time a new object is introduced in the ambient environment, and each time an object is removed. However, for mere variations of property values, it is not necessary to update the model; one only needs to compute the predicted values again with the new property values.

D. Example: light sensors and actuators

Let us suppose that two light actuators `la1` and `la2`, and a light sensor `ls1`, are introduced in a room. The types of devices and the instances are presented in Figure 8. Note that initially there is absolutely no link between the actuator and the sensors. The links will be deduced automatically using available information.

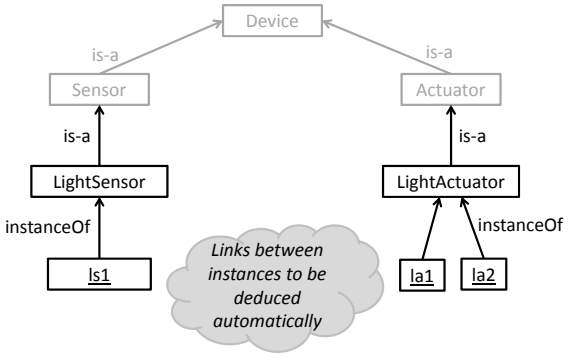

Figure 8. Instances of sensors and actuators created for the example situation, in which two light actuators and a light sensor are placed in a room.

Using formula (3), and by simple rewriting rules, we can successively deduce that:

$$\texttt{ls1.illuminance} = \texttt{illum}(\texttt{la1}, \texttt{ls1}) + \texttt{illum}(\texttt{la2}, \texttt{ls2}) \quad (4)$$

Then:

$$\texttt{ls1.illuminance} = \frac{\texttt{la1.flux}}{(\texttt{distance}(\texttt{la1}, \texttt{ls1}))^2} + \frac{\texttt{la2.flux}}{(\texttt{distance}(\texttt{la2}, \texttt{ls1}))^2} \quad (5)$$

And finally:

$$\texttt{ls1.illuminance} = \frac{\texttt{la1.flux}}{(\texttt{la1.x} - \texttt{ls1.x})^2 + (\texttt{la1.y} - \texttt{ls1.y})^2} + \frac{\texttt{la2.flux}}{(\texttt{la2.x} - \texttt{ls1.x})^2 + (\texttt{la2.y} - \texttt{ls1.y})^2} \quad (6)$$

We obtain what we call a *prediction model*, here a formula that depends only on object properties, and that can be used at any time to predict the expected sensor readings. Once the expected results have been determined, the system checks if they are consistent with the actual readings.

V. Experimentation

This section introduces a complete AAL scenario in which the CBDP framework is able to automate tasks, it shows how diagnosis is performed, and it describes the experiments.

A. Use case: automatic light switch

We propose an experimental scenario that takes place in a bedroom. There is a controlled lamp, a light sensor and a presence sensor. There is also a human-operated lamp on a table, whose light level can be adjusted manually. The system may not control the latter, but the position of the adjustment knob, and hence the expected light level, is known.

The purpose of the scenario is to help elderly people avoid finding themselves lost in the dark. The expected system behavior may be summarized by this rule: "if the ambient light level is under a threshold (specified in the Digital Personality of the user) and if the user is present in the room, then the light must be turned on". Although simple, this scenario demonstrates all the aspects of the system: sensor data gathering, reasoning, command of actuators and diagnosis.

Figure 9 shows what input and output devices are used for this experimentation. They are all Zigbee devices controlled by the aforementioned Zigbee driver, which connects to the CBDP platform through OSGi. Note that the light sensor detects light emitted by both lamps, the controlled one and the human-operated one.

Let us suppose that the illuminance in the room is 80 lux (due to the human-operated lamp being dimmed for instance). Then, the user comes in. His Digital Personality states that he does not like to be in a room where the illuminance is under 100 lux. The system takes the following steps:

1) The current illuminance (80 lux) has already been detected and updated in the ontology. When the user enters the bedroom, the presence sensor sends a notification to the driver through the Zigbee network. The driver sends then an event to the framework and the ontology is updated accordingly.

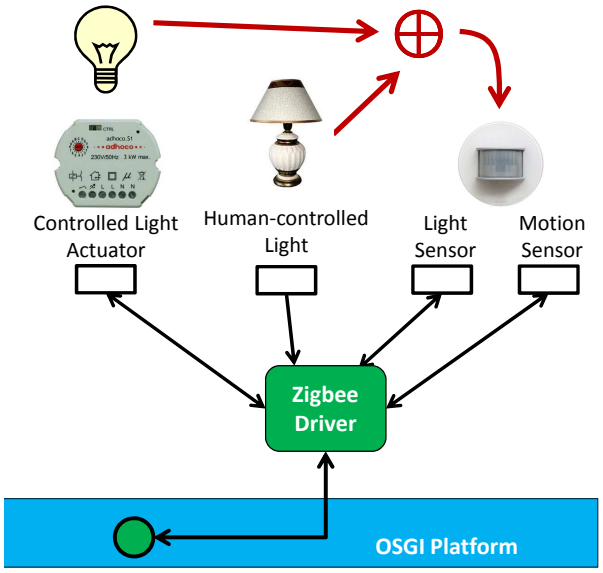

Figure 9. Input/output configuration of the experimentation.

2) The framework detects that the value of a PresenceSensor has changed in the ontology, so the rule outlined in Figure 10 must be evaluated (cf. III-B). Pseudo-natural language is used in Figure 10 for the sake of simplicity; in practice, it is expressed in the formal syntax specific to the Jena reasoning engine as shown in Figure 11.
The reasoning engine reads the current light level, the current presence status and the user preferences in the ontology. The premises of the rule are true, so the conclusion must be executed. To determine which rules to apply, Jena uses a classical *forward chaining* reasoning algorithm.
3) The rule causes a new statement to be added in the ontology: {LightActuator, hasCommand, "on"} (cf. III-C and III-D). The *hasCommand* predicate is detected by the Sensor/Actuator layer, and in consequence, the framework sends an event to the driver asking for the LightActuator to be turned on.
4) The driver commands the light actuator through the Zigbee network. This actually turns the light on.

B. Diagnosis

At this point, the framework performs diagnosis so as to determine if the action has been executed correctly. Both LightActuators are "light effect" producers; the LightSensor measures the "illuminance" value of "light effect". They are all described independently, The system deduces automatically a *prediction model* that links them (see Section IV-C). Here, the prediction model was built at system startup since the objects did not move afterwards. The procedure followed to obtain the prediction model and the eventual

```
IF a LightSensor value is <
   {userPreference in the Digital Personality}

   AND a PresenceSensor detects somebody

   AND the LightSensor, the PresenceSensor
    and a controllable LightActuator
    are in the same room

THEN Turn the LightActuator on
```

Figure 10. Example of rule ("turn the light on") expressed in pseudo-natural language.

```
[CMD_LIGHT_ON:
    (?MS RDF:type AMI:PresenceSensor),
    (?LS RDF:type AMI:LightSensor),
    (?LA RDF:type AMI:ControlledLightActuator),
    (?R RDF:type ?RT),
    (?RT RDFS:subClassOf AMI:Room),
    (?MS AMI:isIn ?R),
    (?LS AMI:isIn ?R),
    (?LA AMI:isIn ?R),
    (?DP RDF:type AMI:AAL_DP),
    (?DP AMI:isCurentDP ?curDP),
    equal(?curDP,'true'),
    (?DP AMI:low_AAL_LightThreshold ?LLT),
    (?MS CORE:realStateStringValue 'personInside'),
    (?LS AMI:realIntValue ?LMV),
    lessThan(?LMV,?LLT),
    (?F RDF:type AMI:OnOffFunctionality),
    (?LA AMI:hasFunctionality ?F),
    (?C RDF:type AMI:OnCommand)
                        -> (?F AMI:hasCommand ?C) ]
```

Figure 11. Example of rule ("turn the light on") expressed in Jena's syntax.

prediction model built have been described in Section IV-D. The prediction model is Formula (6). All the system has to do now is use this formula to calculate the expected illuminance in the room. The steps go on like this:

5) Applying Formula (6) with the current values for all object attribute yields 120 lux, which is the value expected to be read by the light sensor.
6) The illuminance actually measured by the light sensor is still 80 lux, so the system deduces that there is a failure: either the actuator or the sensor is broken. However, it may well be the case that there is another light sensor in the room. In this situation, it will be automatically discovered just like the first one. If the second light sensor reads the same value as the first one, then the faulty component is most probably the light bulb. If conversely the second light sensor detects an illuminance value close to the theoretical expected value, then the first light sensor is most probably faulty.
7) The system finds it most probable that the bulb is burnt out. An error notification is generated so that the user 1) confirms the cause the problem, and 2) possibly to fixes it (often, even an elderly person is capable of replacing a light bulb). Therefore, a "negative"

diagnosis should generate an error notification of some sort asking the user to replace or to check the real state of the light bulb (for a discussion on the acceptability of notifications in a home environment, see for instance [15]). The user's feedback can be added as a statement to the ontology, and can be useful for further reasoning about the light bulb. We can imagine a case in which the user's feedback confirms that the light bulb is properly illuminated even though the system says it is not; in that case, the system deduces that the sensors are not functioning properly.

C. Implementation and Results

This experiment uses the standard CBDP framework, with a bundle containing its specific rules. An interface allows one to choose which user (characterized by their *digital personality*) should be simulated (Figure 12). In a real setting, there would be sensors to detect the particular user: these could be a set of RFID tags and readers, or the Ubisense system [16] for example.

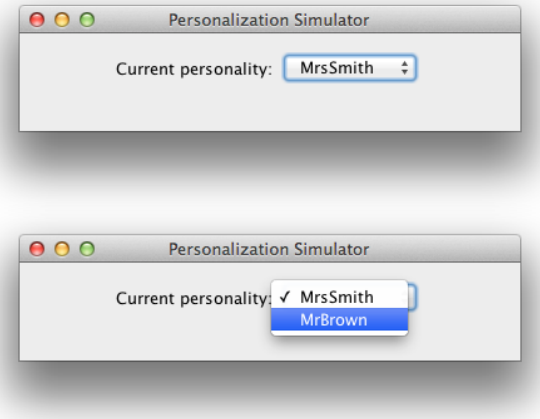

Figure 12. Selection of the digital personality of the user.

The experiment was conducted in two ways:

- using a simulator of the sensors, actuators and physical environment,
- using physical devices in an actual room.

Figure 13 shows the interface of the simulation environment. The experimenters can act on the light level of the human-controlled lamp, on the motion sensor, and they can also introduce a defect in the controlled light bulb. Both in simulation and in real conditions the system displays a message with the current diagnosis (Figure 14). The tests performed showed that the example runs as expected.

VI. Related work

Ontologies are often at the heart of ambient-intelligent systems, and especially AAL systems, such as in OASIS [6]. In 2003, CoBrA (Context Broker Architecture)

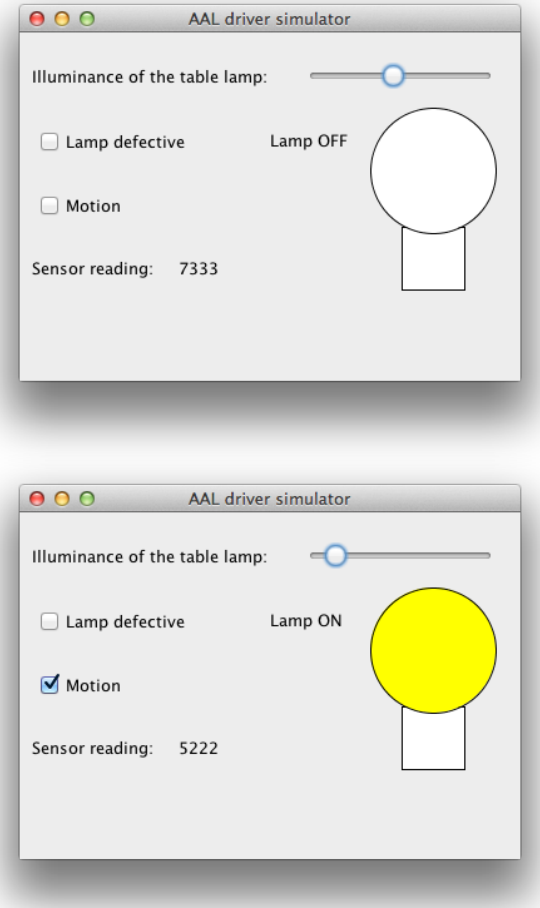

Figure 13. Interface of the simulated environment. The user may act on the human-controlled table lamp, as well as on the presence of motion. The interface displays the current state of the system-controlled lamp.

was an ontology-based framework for ambient settings [17]. In 2004, SOUPA (Standard Ontology for Ubiquitous and Pervasive Applications) [18] was one of the first attempts to define an application-agnostic ontology for ambient systems, but it is specifically aimed at agent-based architectures. More recently, Paganelli et al. [19] introduces a tele-health platform, which is based on an ontology for describing context and medical conditions. The SOPRANO project [20], [21] defines a specific ontology that serves as a unifying vocabulary between software components. In our work, the ontology is specifically used to personalize the system; it stores preferences, and contains application-specific modules. Moreover, we not only reason to infer new facts about context as done in many platforms [22], but also to trigger application-specific behavior, and to actually *trigger actions*, i.e., send commands to actuators. This makes the framework flexible and allows the easy integration of additional services such as the diagnosis framework described in Section IV.

Our choice of using the OSGi middleware was motivated

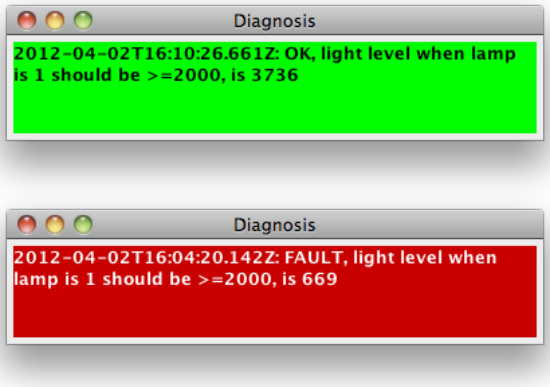

Figure 14. Window showing the results of the diagnosis.

by previous successful attempts in the field of ambient intelligence, such as in the AMIGO IST project [23]. CBDP's generalized reliance on ontologies makes the use of OSGi very consistent with the rest of the framework.

Some works focus on ontologies for specific domains. For instance, Hois [24] describes a well-grounded framework for the description of spatial relationships and spatial reasoning. This kind of contributions could be integrated into the CBDP framework, due to the reusable nature of ontologies.

Sun [25] cites three challenges for AAL systems. Our work is focused on technology, not on social aspects, so we do not address the challenge of having people accept AAL systems. However, we propose solutions to the two other challenges: the dynamic availability of services is handled by relying on an ontology-supported OSGi architecture; the ontology is used for mapping the available services and devices. For instance, relations between a sensor and an actuator may be deduced automatically.

The detection of faults induced by incorrect adaptation patterns in context-aware adaptive application has been studied, and methods based on *static* analysis have been proposed [26]. While it could be interesting to apply these tools AAL systems, we have chosen to focus instead on the detection on *runtime* failures due to unexpected hardware faults. The two approaches are complementary: the former deals with the correctness of adaptation patterns; the latter deals with runtime breakdowns.

The need for self-diagnosis of systems at runtime has been highlighted in the context of autonomic computing [27]. This naturally applies to pervasive systems and ambient environments as well. A vast amount of work has been done to diagnose sensors. For instance, Bourdenas [28] categorizes the classes of faults at sensors, in term of erroneous readings, and explains how to cope with them (self-healing). Indeed, a faulty sensor may be identified by recognizing specific patterns in its readings. Likewise, one can monitor processes or computing devices by analyzing the messages they send and their current state (running threads, memory and power consumption, etc.) [29]. In contrast, realizing that an actuator has become faulty is a different matter, that necessitates to take into account the physical phenomena induced by this actuator. This is where the framework presented here comes into play.

VII. Conclusion and Future work

We have presented a complete framework that supports the creation of AAL applications. This framework is based on the use of an ontology at the core of the system. This ontology contains application-specific knowledge and stores user preferences ("Digital Personality"). Besides, it handles all the run-time information flows: it aggregates sensor data, allows rules to be applied on this data so as to generate commands, stores the commands, and provides the commands to the actuators.

Using an ontology allows one to specify the behavior of an AAL application in terms of easy-to-write logic rules. These rules can rely on any piece of knowledge present in the ontology, therefore, they are not limited in any way by the core ontology that comes with the CBDP framework. Such extensibility is made easy by the use of widespread knowledge engineering standards, namely RDF/OWL.

The other significant contribution of this paper is the diagnosis framework that monitors the run-time behavior of an AAL system by observing changes in the ontology. Currently we take into account only the current state of the system. In reality, the relevant measure might not be the current absolute value of a physical parameter, but rather its *relative evolution*. For instance, when light is switched on, it may be most relevant to consider the *relative increase of the light level*, as the absolute value may vary other time without any action being taken (depending of the intensity of the sun for instance). This prompts us to introduce *dynamics* in the diagnosis framework. Likewise, some physical laws may depend upon quantitative *time* (for instance, the effect of a radiator in an initially chilly room is a slow increase of temperature over time). This is currently being investigated.

We also plan to test such a system in real scale, for example at the homes of elderly people. This will allow us to refine the rules that define the system behavior.

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