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Metamodeling of Smart Environments: from design to implementation

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ABSTRACT

A smart environment is a physical environment enriched with sensing, actuation, communication and computation capabilities aiming at acquiring and exploiting knowledge about the environment so as to adapt itself to its inhabitants' preferences and requirements. In this domain, there is the need of tools supporting the design and analysis of applications. In this paper, the Smart Environment Metamodel (SEM) framework is proposed. The framework allows to model applications by exploiting concepts specific to the smart environment domain. SEM approaches the modeling from two different points of view, namely the *functional* and *data* perspectives. The application of the framework is supported by a set of general guidelines to drive the analysis, the design and the implementation of smart environments. The effectiveness of the framework is shown by applying it to the modeling of a real smart office scenario that has been developed, deployed and analyzed.

1. Introduction

A Smart Cyber-Physical Environment, or Smart Environment (SE), is an environment where devices work continuously and collaboratively acquiring and applying knowledge about the environment and adapting to its inhabitants' needs [1]. SEs are integral part of the Internet of Things (IoT) [2], which in the last decade is opening new scenarios in the everyday life, where every object, every people, and every environment can be addressed and accessed from everywhere for countless purposes.

Several works in the literature have already been devoted to the design and prototyping of such SEs [3,4] but there is a lack in the definition of high-level abstractions devoted to the metamodeling of smart cyber-physical environments. An SE metamodel allows the representation of smart cyber-physical environments through concepts (classes), attributes (or properties) of concepts, and relations between concepts, which are specific to the smart-environment application domain. The use of metamodels is of paramount importance as it provides SE modelers with a versatile and effective tool to support the modeling through the use of a widely-understandable, shared, and reusable common vocabulary [5].

The main contribution of this work consists in providing a Smart Environment Metamodel framework, called SEM,[1] that offers two metamodels, namely the *functional metamodel* and the *data metamodel*. The former focuses on the functionalities that an SE has to offer and specifically describes the offered services, the functional components in the system and the interactions existing among them. The latter supplies the description of properties and relationships of the data sources involved in the SEs.

In the paper, a set of general guidelines are also provided in order to support the proposed framework so as to drive the modeler through the phases of (i) analysis, (ii) design, and (iii) implementation of a specific SE.

This paper highlights the effectiveness of SEM by proposing a case study referring to a smart office scenario devoted to the monitoring and control of ambient parameters and energy wasting. As a practical use of the provided guidelines, the modeled smart office has been also implemented, deployed, and run at the premises of the ICAR-CNR in Rende, Italy. An analysis of part of the gathered data is also provided.

The reminder of the paper is organized as follows: Section 2 introduces the related work, Section 3 describes the proposed framework including the functional and the data metamodels and also discusses the set of guidelines for SE development. Section 4 presents the case study showing a concrete instantiation of the proposed metamodels for a smart office and detailing its

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[1] A preliminary version of the framework here proposed has been presented in [6].

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realization and analysis. Finally, conclusions are drawn and future work is briefly delineated.

2. Background and related work

The realization of Smart Environments (SEs) is an on-going hot topic since their inception. In this field, several works in literature have already tackled the problem of analysis, design and realization of SEs [7–10]. Moreover, many research efforts have been devoted to the modeling of SEs [11,12].

With reference to the latter category, in [13] authors present the *Syndesi* framework for creating personalized smart environments using wireless sensor networks. *Syndesi* has been designed to identify people in an environment and to realize personalized actions based on this recognition, such as control of electrical devices based on people preferences and needs. In [14] the architectural design of a smart-home context-aware middleware is proposed. Such middleware has been conceived to both realize smart home environments and facilitate the sharing of contextual information via diverse entities available in the environment itself. Authors of [15,16] realized *iSapiens* which is a distributed platform based on agent computing for the realization of SEs. Such platform allows to hide the heterogeneity of both hardware devices and communication protocols, and to distribute computation all over an SE in a smart way.

The works introduced above tackle the issue of modeling specific smart environments, without taking in consideration a top-down approach that starts from an high-level metamodeling perspective.

In order to metamodel specific systems, some languages have been introduced so far. SensorML [17], for example, is an important tool that has been designed to provide a generic framework for the high-level description of processes. It is particularly appropriate to describe sensors, systems and observations of the processes related to sensors. As introduced in [5], the UML language [18] and the Entity-Relationship Diagram (ERD) language [19] can be used as metamodel languages due to their capacity to depict concepts, attributes of concepts, and relationships among them.

In [5] several (meta) levels of abstraction for modeling various kinds of systems have been described. This leads to create a high-level model that abstracts from all kinds of platform issues. The work remains theoretical but gives good hints on how ontologies fit for the modeling and metamodeling of systems. The authors of [20] provide an overview on how to formalize workflows within cyber-physical environments so as to create a metamodel of the environment. To do this, they developed a metamodel for processes (or "process metamodels"), which is mainly based on object-oriented concepts and component-based systems. However, they do not give a generic metamodel framework, but only guidelines suitable for developing SE applications.

The authors of [21] present a three layer architecture for modeling of smart environments. Their approach enables to describe and configure a smart home environment at design time and empowers the applications to access contextual information, reason about it, detect situation changes and even influence the environment at runtime. An implementation of the proposed three layer architecture relies on the use of executable models and exploits the Model Driven Architecture [22] concepts for the implementation of the final system. Such approach does not introduce specific concepts and vocabulary that can be used/re-used to define a specific model.

In [23,24] authors provide a framework to support the systematic development of systems based on smart objects. The proposed approach is based on metamodels implemented by using the UML meta-language. Such metamodels have been defined at different levels of abstraction to support the phases of analysis, design and implementation. Since such work has been conceived to model ecosystems of smart objects, it does not provide domain-specific abstractions to model smart cyber-physical environments. In [25], the BOnSAI smart building ontology for ambient intelligence is provided, which benefits from the use of other pre-existing ones, like OWL-S. BOnSAI features a taxonomy for the smart building domain which can be exploited in the context of service-oriented computing, but it was not defined with the purpose of designing new applications.

A distinguishing feature of our work is the proposal of a generic metamodel framework for the modeling of SEs from two different points of view, namely the *functional* and *data* perspectives. Such framework also offers a set of general guidelines to drive the modeler through the analysis, the design and the implementation of SEs.

3. SEM: a Smart Environment Metamodel framework

In this section we propose the domain-specific Smart Environment Metamodel (SEM) framework for the modeling of SEs. The aim of SEM is to provide modelers with a useful tool for the development and analysis of new SEs as well as the reverse engineering of existing ones. The framework includes a functional perspective, namely the *functional metamodel*, and a data perspective, namely the *data metamodel*. The functional metamodel allows the modeling of even complex custom SEs by focusing on the smart services provided to the final users. The data metamodel complements the previous one and allows to describe properties and relationships of the data sources involved in the SE under-modeling. The proposed perspectives introduce a set of entities permitting the modeling of SEs by using concepts which are specific to the SE domain. The basic introduced entities, in fact, can easily be specialized in order to meet precise needs arising when modeling specific SEs.

The metamodels are described in Sections 3.1 and 3.2 by using UML class-diagrams [26]. The diagrams exploit UML stereotypes [18], which are one of the mechanisms offered by the language for extending the UML vocabulary in order to create new model elements having specific properties and being suitable for a particular problem domain. The use of the UML language, which is a commonly used standard language for the design of computer applications, makes also the metamodel (and therefore the realized models) understandable to a large audience.

This section concludes by providing some guidelines for the exploitation of the proposed SEM framework in the development process of SEs.

3.1. The functional metamodel

The functional metamodel relies on two key concepts: *smart environment* and *smart functionality*. An environment can be considered as "smart" only if it is able to provide cyber-physical functionalities to the final users. Fig. 1 shows the proposed functional metamodel, and its relevant features are described in the following.

A generic smart environment is identified by the *SmartEnvironment* stereotype. A *SmartEnvironment* is recursively defined by the composition of other nested *SmartEnvironments*. This highlights the fact that an environment usually contains other (sub) environments. For example, a smart apartment can be seen as a composition of its component smart rooms. Besides its functionalities, a *SmartEnvironment* is characterized by:

- A *PhysicalEnvironment*, which is the physical counterpart of a cyber environment.