Smart Objects: Challenges for Semantic Web Research

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Abstract. The increased availability and robustness of sensors, the wide-spread use of the internet as a communication environment and the intensified adoption of semantic technologies foster the vision of embedding intelligence in physical objects. The race of realizing this vision is pervasive to a variety of research fields, most notably ambient intelligence and semantic web, and leads to the proliferation of several overlapping definitions and terminologies: smart products, semantic devices, semantic gadgets - to which we collectively refer to as *smart objects*. What exactly are smart objects? And what are the research challenges in realizing them? We hereby explore the answers to these questions.

Keywords: smart objects, semantic web, ambient intelligence, challenges

1. Introduction

While the Semantic Web (SW) started out as an initiative for enhancing a Web of primarily textual documents, the technologies developed by this community have evolved and have been applied to major Web innovations such as the Web of services or the Social Web. With the advent of sensors, computationally enhanced physical devices, ubiquitous connectivity of objects (e.g., Internet of Things), the SW community naturally follows suit and an increased interest is now shown in extending the use of semantic technologies beyond the digital world into the realm of physical things and devices.

This novel orientation of the SW field complements longstanding efforts in AI to embed intelligence in the surrounding environments and physical objects in the context of research areas such as robotics and, more recently, ambient intelligence [21], [15],[14]. Obviously, the intention is not to compete against that large body of work but rather to complement it towards the realisation of a vision that, over the last two decades [21], has become a "melting pot" for various scientific disciplines. In particular, we note those differentiating characteristics of SW techniques which make them well suited in scenarios which involve a high number of heterogeneous devices: (i) they have been designed to work at Web scale; (ii) they foster interoperability between heterogeneous data sources; (iii) they rely on a stack of Web technology standards which allow for easy and large scale adoption.

While the quest for using SW technologies in pervasive computing application is currently intensifying, we can actually trace it back to almost a decade ago, in the area of Task Computing [11] where users can easily compose services based on semantic descriptions of devices. Then, ontology-based smart environments and devices were investigated by initiatives such as SOCAM [6] and CoBra [3]. However, an overall characteristic of these approaches was their centralised nature, where the intelligence of the individual devices depended on the processes handled by a central com-

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puter. The recent proliferation of intelligent devices, advances in sensor and communication technologies, all support a trend towards making devices more autonomous by embedding intelligence into them [19]. For example, the SoaM architecture relies on SW technologies to realise semantic gadgets [20]. The architecture allows both distributed and centralised topologies thus providing a smooth transition from centralised solutions towards autonomous smart objects. Indeed, the authors' experiments show that distributed topologies often rival centralised ones in terms of performance, thus providing an early proof for the feasibility of the distributed approaches.

In the next section we describe smart objects by summarising various, complementary definitions from fields as diverse as business studies, ambient intelligence and Semantic Web. Based on these definitions and on our experiences within the SmartProducts project[1], we discuss a set of research challenges in realising smart objects as well as current efforts towards solving those challenges. Our analysis complements a similar study in the area of the semantic sensor web published in this issue [4]: although smart objects rely on sensors and sensor networks, they provide a more focused application domain with its own challenges.

2. Defining Smart Objects

The notion of objects (products, devices, gadgets) that display some level of intelligence has been proposed in various research fields. Allmendinger and Lombreglia investigate the notion of smartness in a product from a business perspective [2]. They regard "smartness" as the product's capability to be *preemptive*, i.e., to be able to predict errors and faults thus "removing unpleasant surprises from [the users'] lives".

A recent notion introduced in the area of ambient intelligence is that of *smart products*. In 2008, Maas et al [10] define smart products as *adaptive* to situations and users. This adaptivity is enabled by three main technologies: (i) sensing technologies which identify the global and the local context of a product (using global or local sensors respectively); (ii) communication infrastructures and (iii) IT services, in particular, "rich context representations, representations about product capabilities and domain knowledge" used "to infer how to learn from and adapt to users and situations". For Mühlhäuser [12], smart products are objects, software or services that have improved *simplicity* (in terms of user interaction) and *openness* (in terms of connecting to and communicating with other devices). These characteristics are achieved through *"context-awareness, semantic self-description, proactive behaviour, multimodal natural interfaces"* [12].

In the Semantic Web area, Lassila and Adler proposed the notion of *semantic gadget*, a device capable of performing *"discovery and utilisation of services without human guidance or intervention, thus enabling formation of device coalitions"* [8]. Vaquez et al [19] extend this definition to that of a *semantic device*, a system that is *"spontaneously aware of surrounding context information, capable of reasoning and interpreting this information at a semantic level, and finally able to develop a reactive behaviour accordingly"*. Additionally, a semantic device is able to *"spontaneously discover, exchange and share context information with other fellow semantic devices"*. Some prototype semantic devices include SmartPlants (house plants paired with an intelligent artefact which sense lighting and temperature conditions and ask to be moved to the most suitable position) or the AwareUmbrella (umbrella which obtains weather information from local sensors and the Internet and alerts the owner to take it along when it is likely to rain).

The SmartProducts project combines research from the ambient intelligence and SW fields to provide an industry-applicable, lifecycle-spanning methodology with tools and platforms to support the construction of smart products. While using Mühlhäuser's definition [12] as a starting point, the project focuses on tangible objects (i.e., physical products) as smart products and not virtual products like software or services. Proactivity is a core characteristic of these products and is ensured by them being *"self-, situational-, and context-aware"*. Finally, the knowledge and functionalities of smart products can be shared with other products and evolve over time as a side effect of their interactions with users and other products.

While originating from diverse fields, the above definitions converge towards a set of core characteristics that a smart object (product, gadget, device):

- *context-awareness* - the ability to sense context;
- *proactivity* - the ability to reason upon and make use of this context and other information in order to proactively approach users and peers;
- *self-organization* - the ability to form and join networks with other products.

[1] `http://www.smartproducts-project.eu/`

In addition to these characteristics, smart products should support their entire life-cycle and should offer multimodal interaction with the users, in order to increase product simplicity [12]. Maas and colleagues highlight the need for using context information in order to support personalisation and adaptiveness [10]. They also see products as being aware of concrete business and legal constraints. The SmartProducts consortium identified some additional characteristics to those provided by Maas and colleagues in [10]. Most importantly, products are seen as capable of acting autonomously (by themselves) without the need of central control. The rest of the characteristics refer to aspects of the knowledge component that enables the smartness of the products. This knowledge has an important procedural component, it should evolve during the life-cycle of the product as a side effect of its interaction with users and products and, finally, it might need to be stored in a distributed fashion in order to overcome the resource limitations of some objects.

3. Challenges for Semantic Technologies

Knowledge technologies play a crucial role in embedding intelligence into physical objects, in particular, for semantically representing context information and providing reasoning mechanisms that underpin proactivity and product-to-product interactions. We hereby discuss some of the challenges that such technologies are likely to face:

Hardware resource limitations. In the process of moving from intelligent, centralised architectures towards autonomous objects with on-board intelligence, the hardware limitations of these objects present an important challenge. Although physical objects are heterogeneous in terms of their hardware resources for information storage and processing, even the most powerful objects will lag behind the resources characteristic of the computer machinery for which semantic technologies are currently built.

An important objective for the Semantic Web community is to adapt its technologies for use on objects with limited computational resources. Strategies in this area include reducing the storage space needed for semantic data [13] and optimising semantic tools in terms of resource consumption. For example, Ali and Kiefer [1] describe the μOR query answering and reasoning system for resource-constrained (mobile) devices which improves on the performance of two earlier reasoners specifically built for mobile devices, i.e., Bossam and Pocket KRHyper [7]. Alternatively, W. Tai et. al propose an automatically composable OWL reasoner which is customised automatically depending on the semantics of the ontology to be reasoned upon by selecting the required reasoning modules only [17]. They show that the approach reduces memory requirements while maintaining reasoning ability thus being well suited fore resource constrained devices.

Complex reasoning algorithms. Smart objects use reasoning mechanisms on their rich knowledge bases in order to adapt to user needs, to perform personalisation and to proactively interact with users and other objects. This complex expected behaviour requires sophisticated reasoning mechanisms such as diagnosis or planning. Such reasoning is much more ambitious than current work in the area of sensor networks which primarily relies on subsumption matching (e.g., for matching between available resources and tasks [5]).

We expect that, given the proactive nature of smart objects, they will mostly rely on production rule-engines rather than DL reasoners. As a response to the increased interest in rule engines, the OpenRuleBench[2] benchmark has been established for analysing the performance and scalability of different rule engines and already used for comparing 11 systems [9]. While a good step towards understanding the capabilities of various rule-engines, this benchmark is not suited towards evaluating rule-engine performance on resource-constrained devices.

Tokmakoff et al. [18] argue that, in order to deal with ambiguities and uncertainties inherent in environments involving human beings, the reasoning mechanisms of smart products should not rely on two-valued logics but rather combine fuzzy, rough or probabilistic deduction methods. However, combing these methods is not trivial and still requires extensive research.

Suboptimal data quality. A fundamental characteristic of smart objects is that they rely on context information obtained from associated sensors which is then translated into higher level semantic information. However, as pointed out by Corcho and Garcia-Castro, ensuring sensor data quality is an important challenge and has to account for issues such as data unavailability or lack of accuracy [4]. Although they also describe a set of research efforts towards improving sensor data quality, it is reasonable to assume that sensor

[2] http://rulebench.projects.semwebcentral.org/

data will have a lower quality than manually authored and checked semantic information. For example, the derived data could be incomplete or, on the contrary, contain redundant elements. Therefore it is important a) to further develop fusion techniques that combine data from multiple sensors into meaningful semantic data and b) to build semantic techniques that are *robust* enough to be able to process such data.

Representing a variety of information. Researchers investigating semantic sensor webs generally agree that semantic models are needed for representing information about time, space and the domain relevant for the sensors [16]. From our analysis of smart objects and their characteristics, we can conclude that their representation needs are much richer and more diverse. Indeed, at a minimum, knowledge associated with smart objects should contain user models, task models (procedural knowledge), models to represent life-cycle stages and the main users (or communities of practice) involved in each stage, interaction models. Therefore, the employed semantic technologies should be able to cover all these representation needs.

Earlier studies from using semantic techniques in pervasive computing applications suggest new representational requirements for ontologies. For example, in [11], the authors report on using ontologies to enable task computing, i.e., easy composition of services provided by various devices in a room. The authors acknowledge that ontologies were not so much used for formal reasoning, but rather for making service composition easier for users. As such, ontology comments and labels played an important role.

Further challenges. It is envisioned that smart objects will continuously update their knowledge bases by deriving knowledge as a side effect of their interaction with users and other objects. Therefore, mechanisms for supporting the derivation and evolution of *emergent knowledge* need to be built. Further, given their close interaction with users, smart objects need to maintain a considerable amount of information about users including their likes, dislikes, their usage patterns, their personal information etc. It is therefore crucial to implement access rights mechanisms that can ensure the desired level of *trust and privacy* for user data distributed across multiple objects.

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