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 lead 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 evolved and have been applied to major Web innovations such as the Web of services or the Social Web. With the advent of sensors, sensor networks, computationally enhanced physical devices, 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. Earlier efforts related to Task Computing allowed users to easily compose services based on semantic descriptions of devices [8] while ontology-based smart environments and devices were investigated by initiatives such as SOCAM and CoBra.

An overall characteristic of the previously mentioned approaches is their centralized nature, where the intelligence of the individual devices is dependent on the processes handled by a central computer. 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 [14]. For example, the SoaM architecture relies on Semantic Web technologies to realize semantic gadgets [4]. The architecture allows both distributed and centralized topologies thus providing a smooth transition from centralized solutions towards autonomous smart objects. The authors’ experiments show that distributed topologies often rival centralized topologies in terms of performance.

In the next section we describe smart objects by summarizing various definitions from fields as diverse as business studies, ambient intelligence and semantic web. Then we discuss a set of research challenges facing the Semantic Web in realizing smart objects.

2. Smart Objects

The notion of objects (products, devices, gadgets) that display some level of intelligence has been proposed in various research fields. For example, Almendinger 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, [7]...
defines smart products as products that are adaptive to situations and users. This adaptivity is enabled by three main technologies: sensing technologies which ensure sensing the global and the local context of a product (using global or local sensors respectively); communication infrastructures and 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 [9], smart products are products (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 behavior, multimodal natural interfaces”.

In the Semantic Web area, Lassila and Adler proposed the notion of semantic gadget, a device capable of performing “discovery and utilization of services without human guidance or intervention, thus enabling formation of device coalitions” [5]. Vaquez et al [14] 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 behavior 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 artifact which sense lighting and temperature conditions and ask the user to move the plant to the most suitable position) or the Aware-Umbrella (umbrella which obtains weather information from local sensors and the Internet and alerts user to take it along if it is likely to rain).

The SmartProducts project1 combines research from the ambient intelligence and semantic web 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 [9] 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 diverse and originating in diverse fields, the above definitions converge towards a set of core characteristics that a smart product should have. These are:

- 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.

In addition to these characteristics, Mühlhäuser and the SmartProducts consortium emphasize the fact that smart products should support their entire life-cycle as well as that special care should be devoted to offering multimodal interaction with the users, in order to increase product simplicity. Maas and colleagues highlight the need for using context information in order to support personalization and adaptiveness. 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. 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 imposed by some products.

3. Challenges for Semantic Technologies

Knowledge technologies play a crucial role in embedding intelligence into physical objects, in particular, for semantically representing context (and other) information and providing reasoning mechanisms that underpin proactivity and product to product interactions. In this section we discuss some of the challenges that such technologies are likely to face in this novel context. These are:

Dealing with hardware resource limitations. In the process of moving from intelligent, centralized 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 to 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 [10] and optimizing 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. Alternatively, W. Tai et al propose an automatically composable OWL reasoner which is customized automatically depending on the semantics of the ontology to be reasoned upon by selecting the required reasoning modules only [12]. They show that the approach reduces memory requirements while maintaining reasoning ability thus being well suited for resource constrained devices.

Providing complex reasoning algorithms Smart objects use reasoning mechanisms on their rich knowledge bases in order to adapt to user needs, to perform personalization and to proactively interact with users and other products. This complex expected behavior 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 [3]).

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 analyzing the performance and scalability of different rule engines and already used for comparing 11 systems [6]. 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. [13] 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.

Dealing with 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. While an important part of research focuses on this translation process, the resulting semantic information is likely to 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 [11]. 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 [8], 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, mech-

\(^2\)http://rulebench.projects.semwebcentral.org/
anisms 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.

4. Summary

As a common denominator of current definitions of smart objects (products, gadgets, devices) and by dismissing variations introduced by particular views, we conclude that smart objects are context-aware (by relying on sensing technology), they have a proactive behavior (ensured by formal reasoning on the represented context data) and are capable of self-organization in terms of networking with other smart objects (by making use of communication technologies).

The characteristics of smart objects raise a set of challenges for semantic technologies. In particular, semantic technologies will need to provide representation support for a wide variety of informations (going well beyond the time, space and thematic ontologies employed in semantic sensor networks) and reasoning mechanisms should allow for a sophisticated proactive behavior while being robust enough to deal with potentially low quality data obtained from sensors. Additionally, the resource limitations associated with physical objects put further constraints on semantic technologies and require their optimization. Challenges also arise in supporting the emergence of new knowledge as a side effect of the product’s interaction with users and peers and in ensuring trust and privacy for the user’s data.

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References