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A Semantic Layer for Embedded Sensor Networks

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ABSTRACT

Sensor Networks progressively assumed the critical role of bridges between the real world and information systems, through always more consolidated and efficient sensor technologies that enable advanced heterogeneous sensor grids. Sensor data is commonly used by advanced systems and intelligent applications in order to archive complex goals. Processes that build high-level knowledge from sensor data are commonly considered as the key core concept. This paper proposes a semantic layer that would optimally support the knowledge building in sensor systems as well as it enables semantic interaction model at different levels (module, subsystem, system). The semantic layer proposed in the paper is currently used by several architectures and applications in the context of different domains.

Keywords: *Semantic Technologies, OWL, Ontology Engineering, Sensor Network, Embedded Systems*.

1. INTRODUCTION

During the last years, sensors have been increasingly adopted in the context of several disciplines and applications (military, industrial, medical, homeland security, etc.) with the aim of collecting and distributing observations of our world in everyday life. Sensors progressively assumed the critical role of technological bridges between the real world and information systems [1], through always more consolidated and efficient solutions that enable advanced heterogeneous sensor grids [16][19].

Sensors are currently disseminated everywhere and the relevance of their role is growly increasing in the everyday life. They can work as independent stand-alone objects or as part of complex networks, performing cooperative tasks in order to reach common goals [19]. Current sensor networks are able to detect and identify simple phenomena or measurements as well as complex events and situations [19].

Most modern sensor systems have two main "semantic" requirements:

- Complex systems build their own knowledge on the base of sensor data and, eventually, considering other available data. Due to the specificity of the knowledge for each system, also the process for building is commonly considered a domain specific task that requires ad-hoc infrastructures. Semantic Technologies [5][8][14] could allow an innovative approach for the problem [19].
- On the other hand, Semantic Technologies are able to improve the machine-to-machine interaction through an innovative model of interoperability (Semantic Interoperability [12]) that assumes rich schemas for knowledge representation. Semantic Interoperability integrates the common Functional Interoperability model introducing the interpretation of means of data [12]. This model allows a new perspective and an innovative approach for the systems because the "intelligence" is no longer implemented by actors (that are similar to interpreters) but it is implicit in the information (Ontology-driven computation [12]). Any knowledge represented using Ontology is potentially available in high-level logic contexts (e.g. Semantic Sensor Web [4]).

Semantic Knowledge implicitly needs rich schemas that include structured concepts, related properties as well as complex relationships among them [11]. Standardized methodologies for knowledge (semantic knowledge in this case) building are a current open research issue. Mapping real knowledge on semantic schemas is, probably, the most creative task for the concrete engineering of Semantic Systems [12].

The semantic layer proposed in the paper has the double goal of providing a full support for semantic interaction and for semantic data processing. The paper is structured in two main parts that respectively propose a short overview the different logic environments for sensor systems (section 3) and an exhaustive description of the semantic layer (section 4).

2. RELATED WORK

Semantic technologies are currently applied in several sensor architectures in order to reach different goals.

Common applications have the aim of providing advanced support to information description and processing [2], data management [6], interoperable networking [5], dynamic representation of situations and system states [7], advanced analysis of data [9] and classification [10].

Semantic Sensor Web [4] would be a generalized approach in which semantic technologies allow interoperable interchanging of semantic data [12].

Also semantic environments for data processing are not an absolute novelty [19]: the convergence of semantic technologies enables the development of advanced semantic interoperable environments in which

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abstract knowledge is directly built on the top of sensor data with a completely transparent approach for higher layers of systems [19].

The semantic layer proposed in the paper addresses a full semantic support that provides a semantic approach to knowledge building (on the model of [19]) and, at the same time, it enables embedded resources and related data within semantic environments.

3. LOGIC ENVIRONMENTS FOR SENSOR NETWORKS

The goal of the section is providing a short but exhaustive view on the logic environment in which a sensor networks can be defined or work.

As showed in Figure 1, a perspective with an increasing level of abstraction and interoperability is adopted for the analysis.

Four different logic environments are considered in the model (Figure 1):

- ***Physical Resource***: This is an environment that assumes limited interaction between considered resource and external systems. This is really common in sensor systems if they are autonomous or embedded without any relationship with the external world.

- ***Logic/Virtual Resource***: The Physical Resource model is conceptually limited if resources are shared or, more generally, they are working in the context of Virtual Organizations [20]. In this last case, resources are understood as virtual or logic resources and they usually to work in an higher technologic contexts (e.g. Grid Computing [20]).

- ***Sensor Web:*** It is a global concept (Figure 1) that assumes web-accesible sensor networks and archived sensor data that can be discovered and accessed using standard protocols and application interfaces. At the moment, the Sensor Web is conceptually modelled on web-services even if it is mainly limited by the fundamental lack of standards for interfaces and data models.

- ***Semantic Sensor Web*** [4]. It is the realization of the Sensor Web in the context of the Semantic Web. Any information or knowledge related to systems is represented using semantic schemas. The interaction model is so improved according to a semantic interoperable model.

In the context of this work the reference logic environment is a simplified (and realistic) vision of Semantic Sensor Web that is approached on short or contextual scale: the knowledge related to systems is assumed to be represented according to its own semantic schema but vocabularies can be shared and logic links can be established among semantically equivalent concepts reducing ambiguities [12].

The space of semantic concepts (eq.1) is composed by the concepts provided by the internal ontologies (C*ke*) unified concepts provided by external domains (C*ext*). C*ke* is understood as the shared vocabulary of the semantic logic environment.

$$C = C_{ke} \cup C_{ext} \qquad \text{(eq.1)}$$

Independence of computational model [12], one between eq.1.1 and eq.1.2 can be considered. There is no difference in the context of this work.

$$C_{ke} \cap C_{ext} = \emptyset \qquad \text{(eq.1.1)}$$

$$C_{ke} \cap C_{ext} = C_{imp} \qquad \text{(eq.1.2)}$$

Two different semantic concepts are considered as semantically equivalent concepts (eq.2) if there is a semantic link between them or if they are both linked to the same concept.

$$c_1 \equiv c_2 \leftrightarrow \; ((c_1 \rightarrow c_2)\; OR \;(c_2 \rightarrow c_1)\; OR \;(\exists c_3 : c_1 \rightarrow c_3 AN$$

$$c_1, c_2, c_3 \in C_{ke} \qquad \text{(eq.2)}$$

In order to maintain the semantic consistence among heterogeneous schemas, semantic rules are valid rules only in the context in which they are defined.

In other world, dynamic learning and dynamic knowledge building is not allowed.

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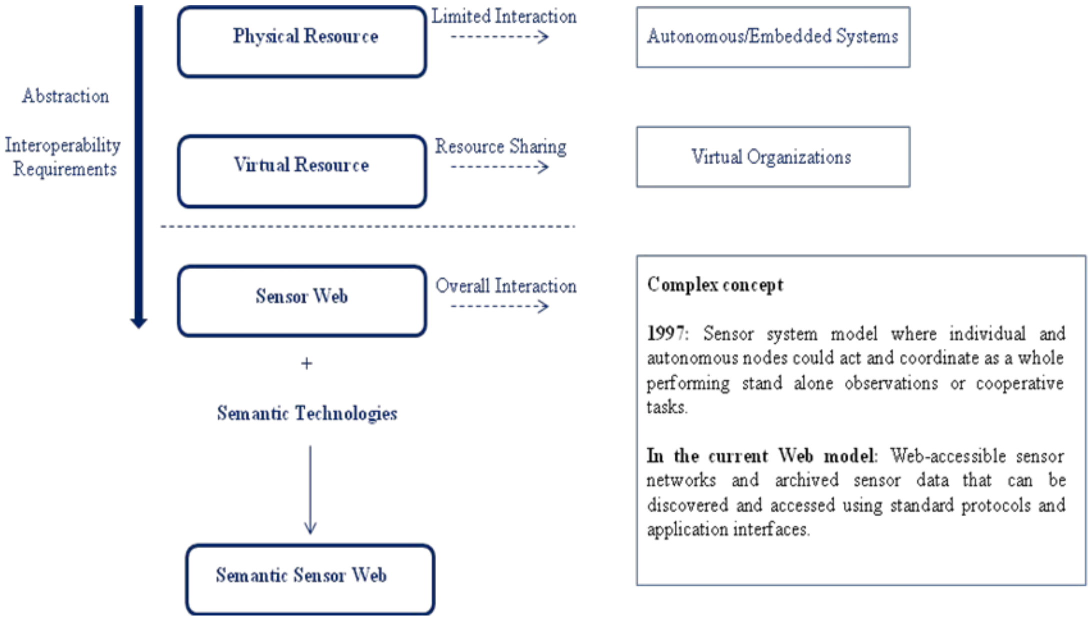

Fig. 1. A schematic view at the logic environments for sensor networks.

4. A SEMANTIC LAYER FOR EMBEDDED SENSOR NETWORKS

In order to provide a full semantic support for sensor networks, the proposed semantic layer is structured and composed of three independent ontologies that can be logically related by reasoners or applications.

More concretely, the following semantic schemas are currently included in the model:

- ***Domain Ontology*** that provides a semantic representation of the sensor network domain.
- ***Process Ontology*** that supports the semantic process of sensor data.
- ***Data Ontology*** that provides a semantic representation of data and a contextualized relationship among them.

A detailled and exhaustive description of the three ontologies is out of paper scope.

In the following sub-sections, an overview on the Domain Ontology and the Process Ontology is proposed. A full description of the ontologies is available, respectively, in [13] and [19].

Conecrning to the Data Ontology, just the considered model is proposed. The implementation is currently a work in progress.

4.1 The Domain Ontology

The Domain Ontology [13] has the key role of providing a contextualized representation of resource according to different perspectives and abstraction levels.

The Ontology is the result of a two-side methodology [13] for knowledge engineering: the top-down side allows knowledge directly built on physical systems; the bottom-up approach allows a high level perspective for systems typical of complex environments.

The overall semantic schema that brings together these two approaches is the core of the proposed Domain Ontology. This is structured in three different semantic layers [13]:

- ***Main Domain.*** It includes the main concepts of the Domain Ontology [13]. The reference implementation assumes *Physical Resources* [13] as central concept (Figure 2, left).
- ***External Domain.*** Set of concepts imported by external domains. Each external concept is defined within its domain and has a semantic mean inside as well as outside the Main Domain. In the current reference implementation [13] the External Domain includes three sub-sets of concepts: *Network*, *Host* and *Supplier* (Figure 2, left). Each one of this subset of concept provides a different perspective for the system.
- ***Extended Domain.*** Extended Domain is conceptually different respect to the External Domain: it is logically built on the Main Domain and its concepts have a mean only in the context of the Main Domain. The current reference implementation [13] assumes two sub-domains each one mapping a relationship with the Main Domain: *Logic Resource* and *Features*. Both are a set of inferred concepts. The first one defines logic resources with the aim of relating them with correspondent physical resources; the

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second one is a set of inferred concepts that would provide alternative perspectives for resource classification as well as a high level view at resources.

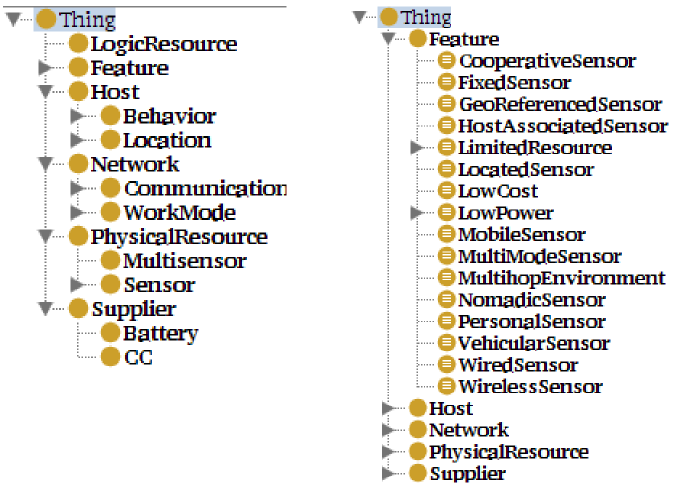

Fig. 2. A view of concept hierarchy of the Domain Ontology (on the left) [13]. The two first levels are represented using Protégé 4.1 [17]. Inferred concepts (on the right) [13].

4.2 The Process Ontology

The problem of semantic data processing of sensor data cannot be approached as the definition of the domain [19].

This is mainly because the data processing is implicitly an ad-hoc task (or set of tasks) that has to be modeled as a local knowledge environment.

As consequence, the Domain Ontology can be defined as a final extensible Ontology (as in the previous sub-section); on the contrary, the Process Ontology should be defined as a meta-ontology that defines a reference schema that has to be particularized considering concrete applications [19].

The key idea of the proposed schema (Figure 3) is the classification of the knowledge in two different classes:

- ***Basic Knowledge***: In the current reference implementation [19], it includes *Data* and *DataSource* (Figure 3). Both concepts provide external potential links respectively to the Data Ontology and the Domain Ontology.

- ***Abstracted Knowledge***: This knowledge layer (Figure 3) includes, at the moment, two concepts (*Event* and *Action*) [19]. This layer is a set of inferred concepts.

The key concept is allowing high-level application to work using just the abstracted knowledge inferred on the basic knowledge.

The semantic rules that build high-level concepts have to be specified in function of specific applications.

4.3 The Data Ontology

The Data Ontology has a key role in the interchange of data among heterogeneous systems.

The current model is designed according to an "open world" vision: each data has its own semantic representation that explicitly specifies its means and data source; on the other hand, data can be contextualized considering semantic links to external concepts.

This model assures a double vision for sensor data: local and contextualized view.

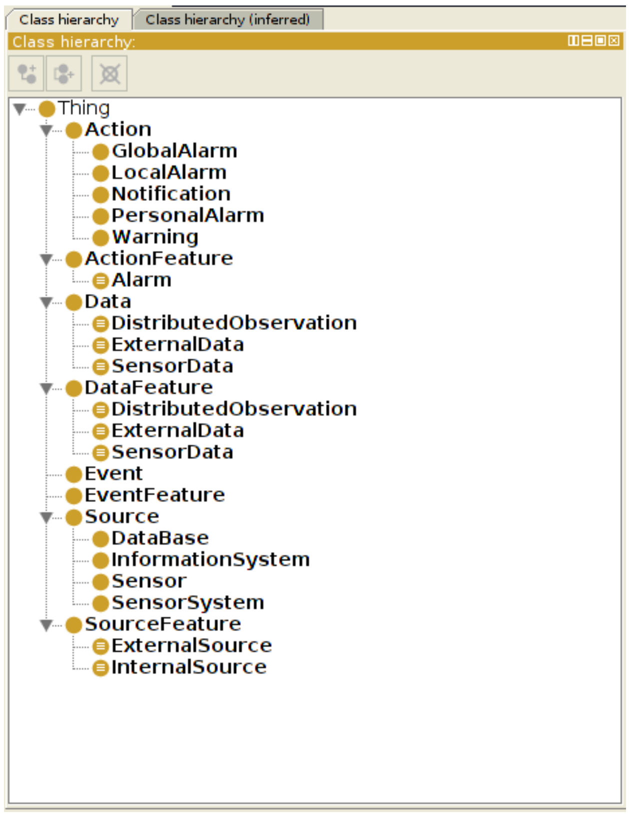

Fig. 3. Implementation of the Process Ontology (class hierarchy) [19] in Protégé 4.1 [17].

5. VALIDATION AND EXPERIMENTATION

The Domain Ontology was validated using *OWLSight* [19] (Figure 4) and it is actually used by advanced architectures for pro-active environmental monitoring (Figure 6) and for health and wellness care.

The Process Ontology was particularized in order to be used within the same systems actually using the Domain Ontology (Figure 5). Each final process ontology was validated using the same methodology adopted for the Domain Ontology (Figure 5).

The current experimentation within heterogeneous domains should provide in the next future a

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vital feedback for the consolidation of the semantic framework.

At the moment, the semantic support provided is able to bring together multiples sensor sources and data in a unique knowledge environment.

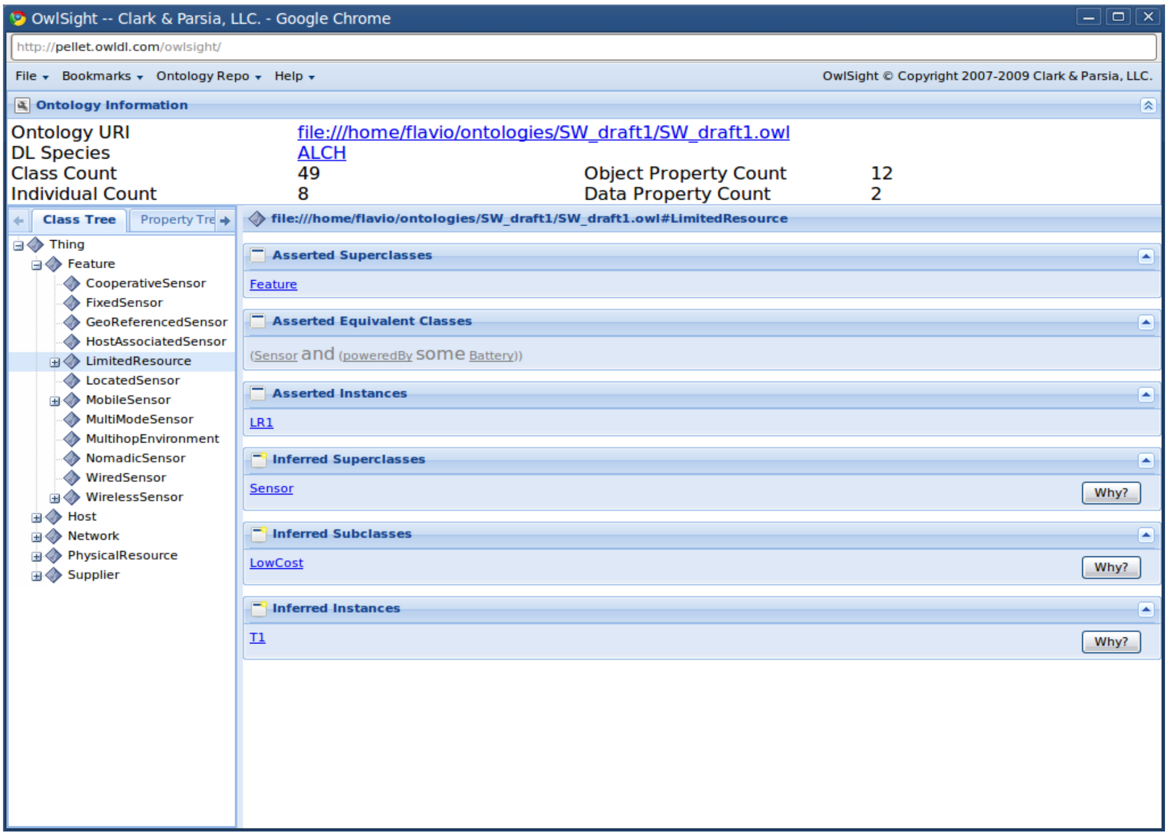

Fig. 4. Validation of the Domain Ontology using OWLSight [18].

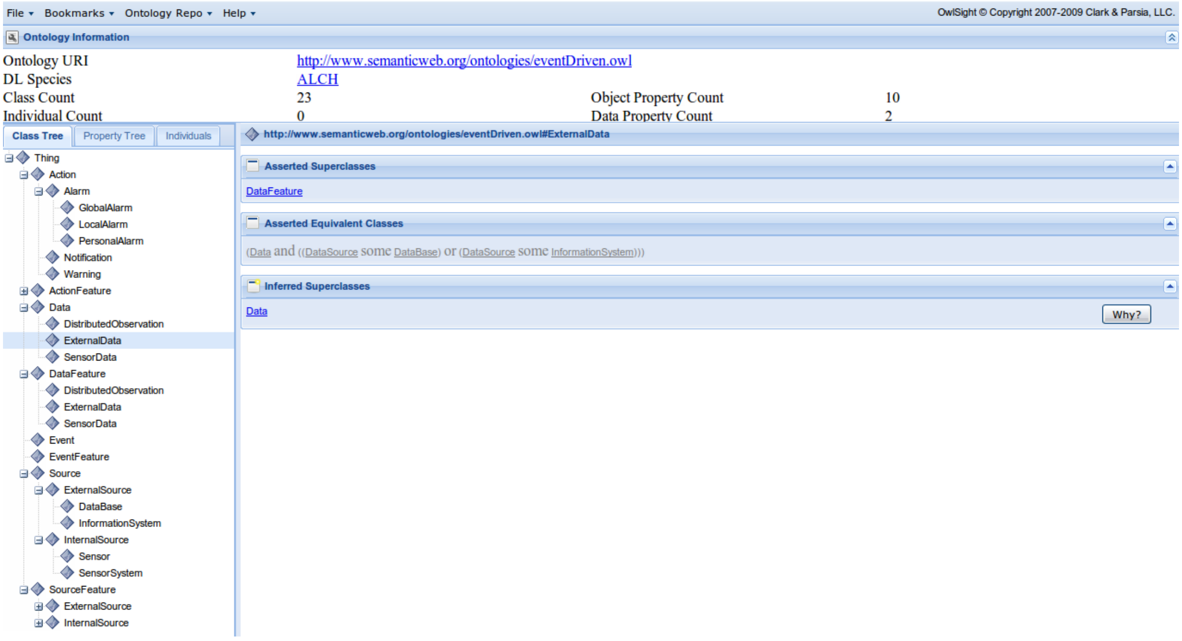

Fig. 5. Validation of the Process Ontology using OWLSight [18].

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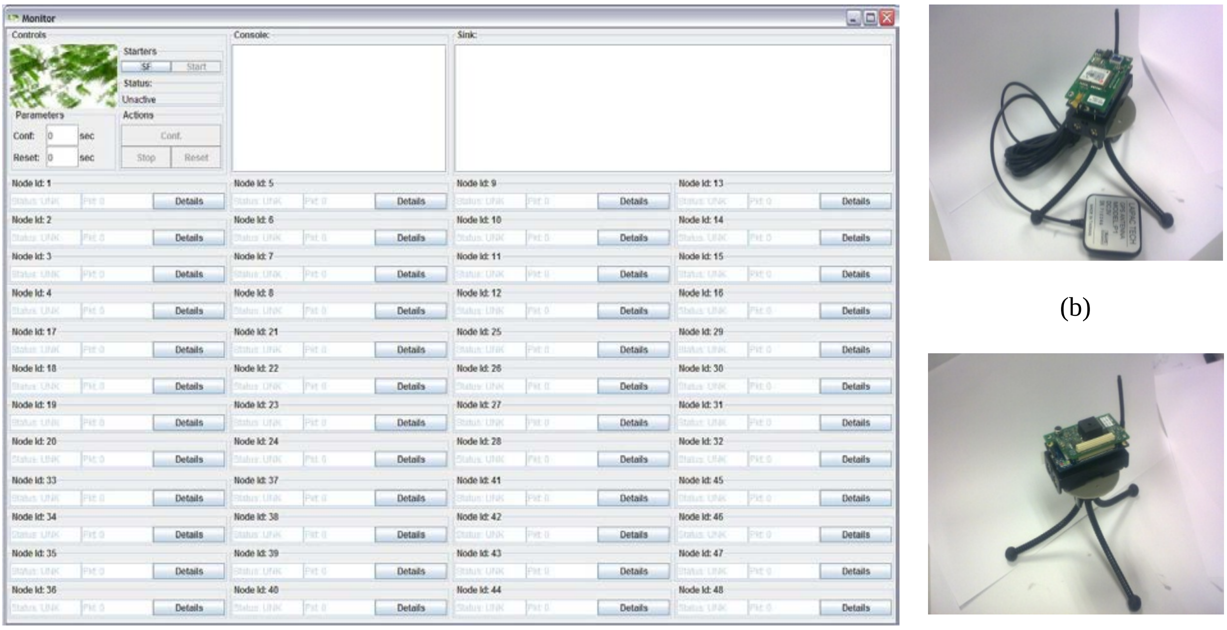

(a) (b) (c)

Fig. 6. Architecture for pro-active environmental monitoring. Control GUI (a). Geo-referenced sensor node (b). Basic sensor node (c).

CONCLUSIONS AND FUTURE WORK

A semantic layer has a critical role for embedded sensor network that could be easily contextualized within complex systems and environments. Furthermore, semantic technologies could assure a certain flexibility as well as an improved level of interoperability that could be one of the key issues for applying advanced approaches in the engineering of complex systems.

The proposed semantic layer is composed of several potentially related ontologies that assure:

- A semantic representation for resource according to several perspectives and abstraction levels (Domain Ontology).
- Semantic support for intelligent data processing and knowledge building (Process Ontology) through a set of abstracted inferred concepts.

The semantic layer proposed in the paper is currently used by several architectures and applications in the context of several domains.

In the next future, a full Data Ontology will be proposed according to the model described in the previous section. Furthermore, the overall semantic layer will be object of a deeper experimentation in the context of additional sensor systems. The results should provide a vital feedback for the refination and consolidation of the proposed reference models.

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