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An Ontological Approach for Domain Knowledge Modeling and Querying in Wireless Sensor Networks

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Abstract—Wireless sensor networks (WSNs) generate large volumes of raw data which increases the difficulty for applications to manage and query sensor data. WSNs are normally application specific with no sharing or reusability of sensor data among applications. In order for applications to be developed independently of particular WSNs, sensor data need to be enriched with semantic information. Ontologies are widely used as a means for solving the information heterogeneity problems because of their capability to provide explicit meaning to the information. This paper presents our work towards the development of a wireless sensor network ontology. Based on the proposed ontology we use the SPARQL query language to enable querying of sensor data. We present the description of the development of the proposed ontology, partial evaluation of the early prototype ontology, a discussion of design and implementation issues, and directions for future research works.

Keywords—sensor networks; knowledge representation; ontology; OWL; SPARQL

I. INTRODUCTION

Wireless sensor networks (WSNs) have gained a significant research attention in recent years. A Wireless sensor network in its simplest form can be defined as network of autonomous devices known as sensor nodes. In a Wireless Sensor Network, the individual nodes are capable of sensing the environments, processing the information locally, or sending it to one or more collection points through a wireless link [1]. The development of WSNs is motivated by several systems such as military monitoring system, smart home system, etc.

WSNs are largely used to collect data of various domains. They deploy large number of heterogeneous sensing nodes and generate large volumes of raw data which increases the difficulty for applications to manage and query sensor data. WSNs are normally application specific with no sharing or reusability of sensor data among applications. In order for applications to be developed independently of particular WSNs, sensor data need to be enriched with semantic information.

Semantics can play a role in assisting users to manage and query sensors and data. Indeed as the scale and complexity of sensing networks increases, machine interpretable semantics may allow autonomous or semi autonomous agents to assist in collecting, processing, reasoning about and acting on sensors and data. For their own part, users generally want to operate at

levels above the technical details of format and integration, and rather work with domain concepts and restrictions on quality, allowing technology to handle the details.

The problem dealing with heterogeneity, even semantic has been deeply investigated in the field of ontology. Ontologies describe a shared and common understanding of a domain that can be communicated between people and heterogeneous software tools.

One of the most important projects based on ontologies use is the Semantic Web, which consists of adding to the Web a layer of knowledge, allowing in a first time, a information research at the semantic level and not at a syntactic one [2]. This led to the proposal of various XML-based languages whose objective is to facilitate the contents representation of electronic documents and the ontology exchange on the Web. Among them, is OWL language. The latter, offers the primitives of a frame-based representation, and adding the formal rigor of a Description Logic [3].

This paper focuses on the semantics of the wireless sensor network. Semantics will be attached to the data to make the sensory data be understood more easily. It enables information exchange between sensors in multiple wireless sensor networks. So, our main goal is to propose the development of a wireless sensor network ontology for facilitating sensor data processing, interpretation and sharing between heterogeneous devices in WSNs.

In the development ontology process, the conceptualization step is based on the work results realized in knowledge engineering which seeks to determine how to find the good concepts and the good concepts interrelations. In addition, the step of formalization and checking are based on the research works in AI. These works give importance to the formal representation and reasoning aspect, and use in particular the description logics which have a clear semantics and provide powerful inferences.

The proposed ontology is implemented using Protege APIs [4] which the famous ontology editor. In addition, based on the proposed ontology we use the SPARQL query language [5] to enable querying of sensor data. Equipped with term representations and relationships definitions defined by the ontology, the SPARQL query engine will have information about the meaning of terms. Moreover, these relationships can

be used to capture synonyms of a term to retrieve all information available for particular concept.

The remainder of this paper is organized as follows. Section 2 covers background information on sensor networks, ontologies design and the semantic Web technologies. Section 3 highlights some related work. In section 4 and 5 we present our approach for building and querying a sensor network ontology. Section 6 concludes this paper and talks about further work.

II. BACKGROUND

A. Sensor Network

A wireless sensor network is a group of specialized transducers with a communication infrastructure intended to monitor physical phenomena like temperature, sound, light intensity, location, motion of objects and so on. Each sensor network is deployed to serve a specific purpose and uses its own protocols. This heterogeneity in sensor networks makes it impossible to communicate with each other or to reuse and share their data with different applications.

The term WSN is used since most sensors are connected using wireless technologies such as Zigbee, Bluetooth and Wibree. The typical architecture of WSN consists of several nodes communicating with the outside world through a gateway. Sensor nodes are responsible for detecting and monitoring of certain phenomena and sending the raw measurement data to an end user. Further analysis and processing of sensor data is application dependent.

Sensor networks are characterized by two main features [6]:

- First, they are highly dense so that hundreds or thousands nodes may be deployed in limited geographical areas. These nodes return huge amount of data that must be efficiently searched to answer user queries. Unfortunately, classical information retrieval techniques showed poor performance in searching sensor networks data as they return many false positives/negatives.
- Second, many of the captured data are analogous in nature making the chance of finding a specific term quite good. Most sensors are characterized by similar calibration mechanisms that can be described using different terms. String matching search techniques may not retrieve all relevant data because different words/terms were used that did not match directly the term. For example temperature measurement is specified with the name temp or min temp and max temp or low temp and high temp. Relative Humidity is a name used in some domains and Humidity in other domains. This compromises the performance of the search engine. A big improvement in search engine performance could be achieved if these relationships are captured and utilized, and this is exactly what an *ontology* can do.

B. Ontology Building

Ontologies have been developed to capture the knowledge of a real world domain. "Ontology is defined as a formal and explicit specification of a shared conceptualization of a domain" [7]. An ontology comprises three components: (1) classes or concepts that may have subclasses to represent more specific concepts than in super-classes, (2) properties or relationships that describe various features and properties of the concepts, also named slots or roles, and (3) restrictions on slots (facets) that are superimposed on the defined classes and/or properties to define allowed values (domain and range). Individuals can be defined simply as instances of the classes and properties. The ontology together with a set of instances of classes and slots constitute the knowledge base.

Many advantages of ontology building are explained in [8], including: (1) sharing common understanding of the structure of information among people or software agents, (2) enabling reuse of domain knowledge, (3) making domain assumptions explicit, (4) separating the domain knowledge from the operational knowledge, and (5) analyzing domain knowledge. On the other hand, there exist several arguments and challenges, among which are the lack of an agreed-upon taxonomy and quantitative evaluation procedures.

Building a well-developed and usable ontology represents a significant challenge. A range of methods and techniques have been reported in the literature regarding ontology construction methodologies [9]. Mike Uschold's methodology [10], Michael Grüninger and Mark Fox's methodology [11], and Methontology [12] are the most representative. These methodologies have in common that they start from the identification of the ontology's purpose and the need for domain knowledge acquisition. However, having acquired a significant amount of knowledge, Uschold's methodology and Grüninger and Fox's methodology propose coding in a formal language and Methontology proposes expressing the idea as a set of intermediate representations. These representations bridge the gap between how people think about a domain and the languages in which ontologies are formalized. Thus, Methontology enables experts and ontology makers unfamiliar with implementation environments to build ontologies.

For our purpose, we have chosen the Methontology for the application ontology building. Methontology enables the construction of ontologies at the knowledge level. It includes the identification of the ontology development process and a life cycle based on evolving prototypes.

C. The Semantic Web Technologies

Semantic Web is an extension to the current Web in which the meaningful relationships between resources is represented in machine processable formats [2]. The main idea in the semantic Web is to provide well defined and machine accessible representation of the resources and their relationships rather than simple links as they are offered by the link structure on the current Web (i.e. href links in HTML). Ontologies are utilised by the semantic Web applications to offer conceptualised representation of domains and to specify meaningful relationships between the resources. The World Wide Web Consortium (W3C) has defined different standards for representing the semantic Web data in machine accessible and processable formats.

Semantic technologies can improve interoperability and integration, as well as facilitate reasoning, classification and other types of assurance and automation. Semantic interoperability supports high-level, context-sensitive information requests over heterogeneous information resources, hiding systems, syntax, and structural heterogeneity [13]. Integration and fusion of data into higher-level abstractions is aided by a data representation intended for machine reasoning.

The primary technologies for the semantic Web include the Resource Description Framework (RDF)¹ and the Web Ontology Language (OWL)². OWL is based on description logic [14] and facilitates construction of ontologies for different domains. An OWL ontology contains descriptions of classes (or concepts in DL terminology), properties (roles in DL terminology) and individuals. There are two types of properties: object properties (properties for which the value is an individual) and datatype properties (properties for which the value is a data literal).

The OWL data can be accessed by software agents for reasoning and inferencing purposes and to enable systems to derive additional knowledge from the represented data. There are common query languages such as SPARQL³, namely SPARQL Protocol and RDF Query Language. It is developed as a query language and a protocol for accessing RDF graphs.

There are categories of tools allow for editing ontologies. The most widely used OWL editor is Protege⁴, a free open-source editing framework developed at Stanford University. By virtue of its open plugin structure, it allows for the easy integration of special-purpose ontology editing components. There are also widely used software systems such as Jena [15] to deploy and manage the constructed ontologies.

Creating a semantic sensor data model for sensor data related to the nature of sensors, their observations and locations is important aspect in designing highly scalable and advanced heterogeneous sensor network applications.

III. RELATED WORK

Ontologies provide a formal, usable and extensible model that is suitable for representing information, in our case sensor data, at different levels of abstraction and with rich semantic descriptions that can be used for searching and reasoning [16]. Moreover in a highly heterogeneous setting, using standards and widely adopted vocabularies facilitates the tasks of publishing, searching and sharing the data.

Many researchers have realized the problem of semantic integration of sensor data and try to address it using semantic web technologies. A theoretical discussion has been done by Lionel et al. [17], who proposed a concept of Semantic Sensor Net (SSN). They have identified the same associated problems for heterogeneous sensor networks and sensor data. A SSN is a heterogeneous sensor network which enables dynamic

tagging of semantic information to sensor data so that it can be integrated and reused across various applications.

The ontologies exploitation in the context of wireless sensor networks, requires a good comprehension semantic, a good design and a good definition of concepts that will be represented. Several sensor ontologies have been proposed in the past, some of them focused on sensor descriptions, and others in observations [18]. The work in [19] presents an attempt to capture the most important features of a sensor node that describes its functionality and its current state. The ontology describes the main components of a sensor node such as processor CPU and memory, power supply, and radio and sensor modules.

A step further in ontology-based sensor nodes is presented in [20] and [21]. The researchers in [21] define an ontology that integrates high level features that characterizes sensor networks for customizing routing behavior. The proposed ontology describes the network topology and settings, sensor description, and data flow. Again, there is no mention of sensor data. Subsequent work like [22] is an effort in the direction of facilitating semantic-service oriented sensor information systems. The notion of ontology used in this research is to capture the information about physical entities that sensors sense and their relationships.

Most of these proposals are, however, often specific to a project, or discontinued, which do not cover many important areas of the sensor and observation domain. Moreover many of these ontologies did not follow a solid modeling process or did not reuse existing standards.

The following sections, present our development process of wireless Sensor Network Ontology (WSNO). In this process, RDF language will be used to specify the requirements specification, results of the first step. METHONTOLOGY methodology is the basic support, for the conceptualization of the Sensor Network ontology to be created. Descriptions logic is the type of formalism which will be adopted for the representation of semi-formal ontology, result of the conceptualization step. Based on this formalization, OWL language will be chosen to implement the ontology. The Protégé editor will be used to design the class and property structure of the proposed semantic data model and also to define the constraint rules for the associations and attributes. Through the use of SPARQL query languages, a semantic sensor network database can be queried to retrieve information about the structure and the nature of sensors, their observations and locations.

IV. THE PROPOSED WSNO BUILDING PROCESS

Our goal is to propose a method for building a wireless sensor network ontology. Thus, we had to face (i) the discovery of relevant concepts, (ii) their organization in taxonomy, and (iii) the non-taxonomic relationships between concepts.

The method that we propose is complete, insofar as, starting from brut data it allows to arrive at an operational ontology represented in OWL language. To do this, four main

¹ <http://www.w3.org/RDF/>

² <http://www.w3.org/TR/owl-features/>

³ <http://www.w3.org/TR/rdf-sparql-query/>

⁴ <http://protege.stanford.edu/>

steps are followed in order to explain and to guide the building of the SN ontology.

A. Requirements Specification Step

The proposed process begins with the ontology specification step. The purpose of this step is to establish requirements specification document. This latter, allows to describe the WSNO, to build, through the following four aspects:

- 1) Domain Knowledge: This aspect consists of delimiting as precisely as possible the domain that the ontology going to cover.
- 2) Users: This aspect consists of identifying the intended users of the ontology to be created.
- 3) Operational goal: This aspect precises the purpose of the ontology to be created for the considered domain.
- 4) Ontology scope: This aspect consists of determining the most important global terms referring entities of domain knowledge to represent. In the context of sensor network we can determine the following global terms: {System, Sensor, Sensing, Data}.

The result of this step is a document of requirements specification represented by the RDF language. The later, associates three types of objects (Cf. TABLE I): A *resource* (corresponding to the document of requirements specification) defined by *properties* (corresponding to the four aspects) and the association of a resource to a property by a *value of property* (corresponding to the result of each aspect). For that, we propose the following two phases:

TABLE I

REQUIREMENTS SPECIFICATION DOCUMENT AS AN RDF DECLARATION

Subject (resource)	<i>Needs specification document identified by a URI</i>
Predicate (property)	<i>Aspect</i>
Object (value)	<i>Result of an aspect</i>

1) Representation by the RDF graph: This phase consists of representing the result of each aspect by a RDF graph (diagram). For example, Figure.1 illustrates the diagram allowing to represent the following assertion: "the domain knowledge of the ontology to be created is: 'WSN' "

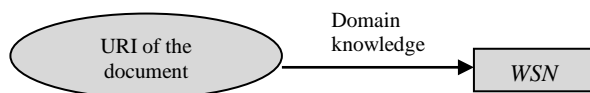


Figure 1. RDF graph concerning the first aspect

2) Representation by the RDF syntax : RDF also proposes a XML syntax. This phase consists of encoding, in RDF syntax, the various graphs presented in the preceding phase. For example, the serialization in XML/RDF of the graph given in Figure 1 is as follows:

```

<rdf:Description about=" URI of document" >
    < Domain-knowledge>WSN </ Domain-knowledge >
</rdf:Description>
  
```

B. Conceptualization Step

Conceptualization deserves particular attention because it determines the rest of the ontology construction. The objective is to organize and structure knowledge, using semi formal representations (tables and graphs) that are independent of the paradigms of knowledge representation in which the ontology will be formalized.

During this step, we construct a set of semi-formal representations, that we call "conceptual ontology". The latter identifies and define the domain vocabulary, independently of any implementation language. We were inspired of the conceptualization phases proposed by METHONTOLOGY methodology. To do so, we distinguish the following main activities:

1) Building a Glossary of Local Terms:

A term may be a relevant representation of a domain entity called, concept or a binary relationship between two concepts. This activity consists in building a glossary of local terms. This last collects terms of the domain and associates to each term identified a natural language description, see TABLE 2.

TABLE II
GLOSSARY OF TERMS

Term	Description
System	System is a unit of abstraction for pieces of infrastructure for sensing. May be: Device, Sensor and Wireless Sensor Network that can be mounted on platforms.
Wireless Sensor Network	A WSN is a communication system consisting of a large number of sensors.
Sensor	A sensor is an entity that can follow a Sensing method for observing a property with Measurement Capability
Humidity Sensor	A device which used to assess the humidity in a specific field.
Wind Sensor	A device used to evaluate wind speed.
Sensing	A process that results in the estimation, or calculation of the value of a phenomenon, describes the principle behind a sensor and how the observations were made.
Deployment	A process that encompasses all phases of the cycle of a deployed system such as installation, maintenance in a WSN.
Transforming	A process that can describe how the transformations of the data were made.
Communicating	A process that can describe how communications were made. Its inputs are the outputs of Transformation or Sensor Output.
.....

2) Building a Hierarchy of concepts:

The hierarchy of concepts shows the organization of the ontology concepts in a hierarchical order which expresses the relations sub-class and super-class.

We use the relation Sub-Class-Of between the classes to define their classification. C1 class is sub-class of C2 class if any instance of C1 class is an instance of C2 class. We follow a development process from top to bottom. We start with a definition of the general concepts of domain and then continue by the specialization of concepts. For example, we can start by creating classes for the general concepts: System, Process, Property, State, Event, Outputs and Situation . For example, figure 2 shows the hierarchy of Process concept.

3) Building a binary relations diagram:

We will build our diagram in two principal steps; initially, we determine the organization of concepts, then we will connect the concepts by relations so necessary.

We represent the binary relations between classes by a diagram in figure 3. In this diagram the classes are represented by rectangles and the relations by arrows (domain towards codomain) labelled by the name of the relation.

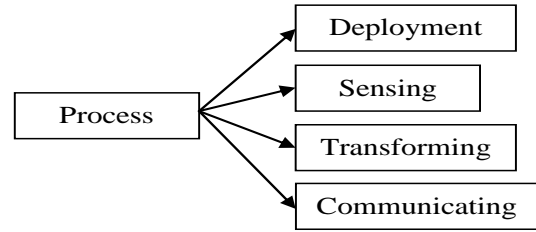


Figure 2. Hierarchy of Process Concept.

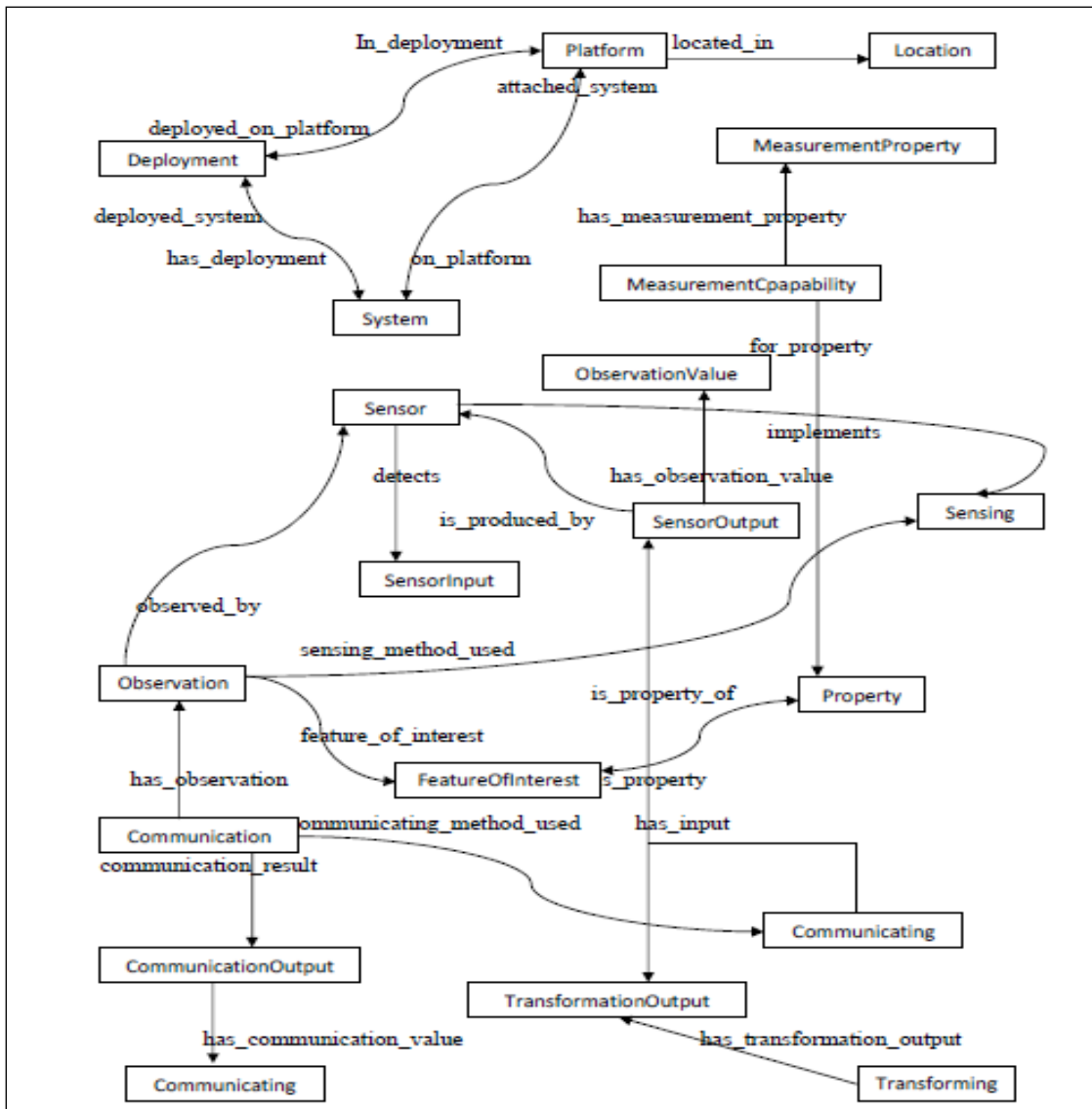


Figure 3. Binary relations diagram

4) Building a Dictionary of Concepts:

The dictionary of concepts consists of describing all concepts represented in the hierarchy of concepts, by representing instances of such concepts, attributes of the concepts and, optionally, concept synonyms (see TABLE 3).

TABLE III
TABLE OF CONCEPTS DICTIONARY

Name concept	Synonym concepts	attributes	instances
Sensor	SensingDevice	serial_number creation_date identification	-

5) Building a table of binary relations tables:

The binary relations are represented in the form of properties which attach a concept to another. For each relation whose source is in the tree of concepts classification, we define: its name, the name of the source concept, the name of the target concept, cardinality and the name of the inverse relation if it exist (see TABLE 4).

TABLE IV
TABLE OF BINARY-RELATIONS

Relation	Source Concept	Source Card	Target Concept	Target Card	Inverse relation
detects	Sensor	(1.n)	SensorInput	(1.n)	detected_by

6) Building the logical axioms table:

We will define the ontology concepts by using the logical expressions which are always true. In the table below, we define for each axiom, its description in natural language, the name of the concept to which the axiom refers, attributes used in the axiom and the logical expression (see TABLE 5).

TABLE V
LOGICAL AXIOMS TABLE

Concept name	Description	Logical expression
Value	Can be Communication Value or Observation Value.	(X), Value (X) Communication Value (X) v Observation Value (X)

7) Building the instances table:

In this table, we describe the instances, which are identified in the concepts dictionary. For each instance, it is necessary to specify the instance name, the concept name to belong to it, the attributes and their values.

TABLE VI

INSTANCES TABLE

Instance	Attributes	Values
wind_sensor_1	serial_number creation_date identification	111 2016-02-12T14:24:16 W1

C. Formalization Step

In this phase, we use the DL (Description Logic) formalism to formalize the conceptual model that we obtained it at the conceptualization phase.

DL forms a language family of knowledge representation; it represents knowledge relating to a specific area using "descriptions" which can be concepts, relations and instances. The relation of subsumption (\sqsubseteq) allows organizing concepts and relations in hierarchy; classification and instantiation are the basic operations of the reasoning on description logic, or terminological reasoning. Classification permits to determine the position of a concept and a relation in their respective hierarchies.

The result of this step is a formal ontology made of two parts: terminological part TBOX in which we define concepts and relations; and an assertion part ABOX in which we introduce the instances (see Table 7).

-TBOX construction: We define here concepts and relations relating to our domain, by using the constructors provided by description logic to give structured descriptions at concepts and relations.

- ABOX construction: The assertion language is dedicated to the description of facts, by specifying the instances (with their classes) and the relations between them.

TABLE VII
EXAMPLE OF DL EXPRESSIONS

TBOX
Sensor \sqsubseteq Device
Detecting_Sensor \equiv Sensor \sqcap \exists Detect.Event
ABOX
Detecting_Sensor (s1)
Detect (s1, e1)

D. Implementation Step

The implementation deals with building a computable model. To implement the formal ontology Protege tool is used. The knowledge representation language for modeling the various ontological knowledge of sensor network is OWL DL. The constructed class hierarchy is shown in Figure 4.

For checking, we need to use the inference services provided by many systems such as RACER [23]. It can work well with large ontologies. The use of the RACER system can make possible to read OWL file and to convert it in the form of a DL knowledge bases.

References

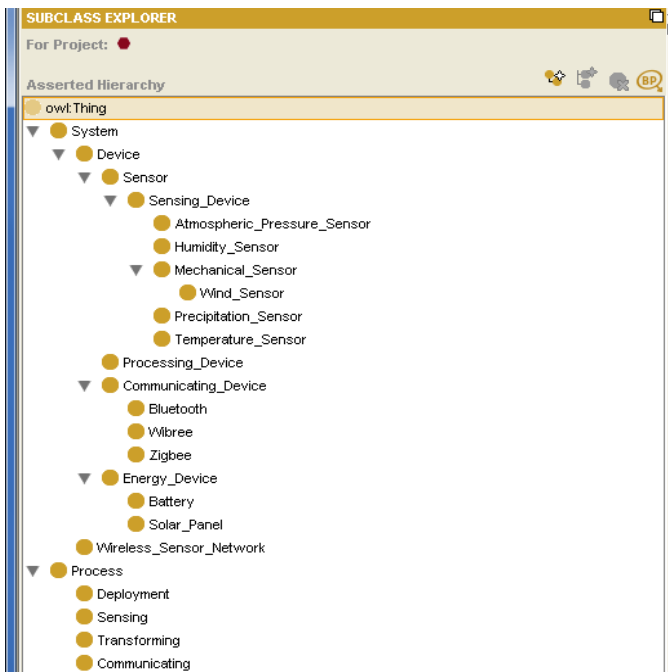


Figure 4. Hierarchy of the proposed ontology

Once the constructed ontology is validated, it is ready to be invoked by users' requests. As a query language, we used SPARQL query language which is provided and plugged-in to Protege. For example, Figure 5 shows a SPARQL query allowing to find the URIs and locations of temperature sensors.

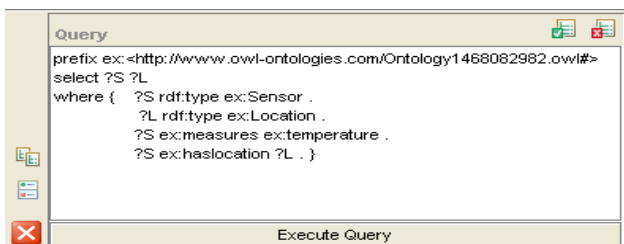


Figure 4. SPARQL Query Statements

V. CONCLUSION

The semantic representation of wireless sensor networks data is an exciting vision that enables structured information to be interpreted unambiguously. Precise interpretation is a necessary prerequisite for automatic search, retrieval, and processing of sensor data.

In this paper, we have proposed a process for building an wireless sensor networks ontology. The proposed process is complete, insofar as, starting from brut data it allows to arrive at an operational ontology represented in OWL language. For the future work, we need to concentrate on the ontology enrichment with new concepts to be more meaning and thus really reflects the modelled domain.

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