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Towards a Web of Sensors built with Linked Data and REST

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***Abstract*— The technological advances in hardware and software communication technologies are speeding up the path towards the actualization of the Internet of Things. Nonetheless, novel requirements are emerging for the effective and efficient usage of the huge amount of available sensor information and functional capabilities. Several approaches have been proposed for leveraging the Web to this purpose (i.e. Web of Things). In this work, we propose an information-centric approach to enable a Web of Sensors. We combine the principles of Linked Data and Representational State Transfer (REST) architectural style to represent sensors as graphs of URI-addressable information nodes, which can be easily combined and reused for developing novel applications and creating software-based sensors (Virtual Sensors). Our approach relies on the adoption of a web-oriented middleware and information model, called InterDataNet.**

Keywords: Internet of Things; Web of Things; Representational State Transfer; Web Services; Linked Data; Sensors; Smart City

I. Introduction

The Internet of Things (IoT) is a promising paradigm in the field of modern communications. The idea behind this concept is the presence of smart devices with collaborative capabilities in the everyday environment [1] [2].

The realization of an efficient IoT requires the definition of a complex architecture that addresses the issues related to data transmission and services development for final applications [3]. Atzori et al. [3] argue that a significant role towards the actualization of the IoT vision should be played by middleware and application functionalities and protocols capable of easing the access and exploitation of real-world objects information and capabilities. While the main purpose of the IoT is to guarantee the connectivity between entities on the network layer (i.e., the Internet), the aim of the Web of Things is to ease the end-user interaction with smart objects and their cooperative behavior by exploiting the Web principles and technologies [4].

The novel Web of Sensor (WoS) paradigm belongs to this context. The WoS is about taking the sensors to the Web and making them available for the applications as end-users services [5]. According to the analysis presented in [5], the WoS can be considered as composed by a stack of three layers: at its bottom there is the *sensor layer*, which includes the actual sensors with their communication standards; the middle layer is the *sensor web layer*, which provides the functionalities for the publication of the sensors' representations on the Web; the top layer is the *application layer*, which enables the interaction between the clients (end-users or agents) and the sensors.

The basic concept of REST [7] is to create loosely coupled services on the Web and this makes REST an ideal candidate to build a uniform API (Application Programming Interface) for web sensors and more generally for smart things [4] [6]. Several approaches have been proposed for implementing the Web of Sensors through REST. Some works [8] [9] [10] combine REST and Linked Data principles in order to enhance sensor representation with semantics. However, poor support is provided to web developers for speeding up the development of web applications for accessing, modifying, reusing and combining sensor information. In this work we propose an approach towards the Web of Sensors based on a graph-based representation of sensors information nodes, that can be accessed and modified at the desired and meaningful level of granularity through REST APIs. This model allows to represent and handle structural and web-oriented relations among information nodes (i.e., containment and reference relations).

This approach has been implemented by exploiting a middleware (called InterDataNet) that supports the REST-based exposure of sensors on the Web.

The remainder of this paper is organized as follows. Section II introduces the main principles of REST and Linked Data paradigms. In Section III we describe the information modeling and management capabilities provided by the InterDataNet framework. In Section IV we describe our information-centric approach realizing a Web of Sensor based on the InterDataNet architecture. In Section V, we present a case study. In Section VI we discuss related work and finally, Section VII concludes the paper with insight for future work.

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II. BACKGROUND

The efficient and effective design and actualization of the Web of Sensors vision should be driven by the Web main principles. Therefore, in this Section we introduce the main principles of Linked Data and REST paradigms and then we motivate our contribution.

A. Linked Data

Linked Data is a new Web concept that promotes a paradigm shift in how the information is conceived. Linked Data principles [11] are best practices for publishing data "*in a way that all published data become part of a single global data space:*

- *use URI as names for things;*
- *use HTTP URIs so that people can look up those names;*
- *when someone looks up a URI, provide useful information, using standards (e.g., RDF* [12], *SPARQL* [13]*);*
- *include links to other URIs, so that they can discover more things".*

The emerging Linked Data paradigm leads towards a global browsable information space where data from different information source are connected and can be aggregated to form new information [11].

B. REST

The main concept in REST [7] concerns the "resource", which is an abstract information entity. Clients and servers exchange information declining resources into concrete representations and interact with them through a uniform interface. REST architectural style is not tightly bound to HTTP, even though HTTP is widely adopted for its implementation. The key principles of REST are the following:

1) Use URIs to identify resources. The resources are exposed by servers using URIs the clients invoke for interaction. URIs belong to a global addressing space and so resources identified with URIs have a global scope.

2) Adopt a uniform interface. The interaction with the resource is fully expressed with four primitives: create, read, update and delete. In HTTP they are mapped on the PUT, GET, POST and DELETE verbs.

3) Adopt self-descriptive messages. Each message contains the information required for its management. Metadata is used for content negotiation (i.e., negotiate the format of the representation), errors notification, etc.

4) Adopt stateless interactions. Each request must contain all the information necessary for its proper management. Session state is kept by the client and no client session data are stored in the server [7]. Instead, the server manages and stores the state of the resources it exposes.

The adoption of REST over HTTP has a very low cost because it leverages well-known W3C/IETF standards and the required infrastructure (HTTP clients and servers) is widespread. Moreover, the statelessness property makes a RESTful web server well scalable with respect to the number of clients.

C. Motivation of our work

Though REST and Linked Data show similarities (e.g., the resource abstraction, the use of URIs for resource identification, and the need of representing relations between resources), they have different scopes: REST defines an API for programming applications based on the Hypermedia as the Engine of Application State (HATEOAS) constraint, while Linked Data focuses on the definition of a distributed data model. We agree with the analysis carried out by Page et al. [14], who highlights how these scopes could complement each other in the design of domain-driven applications. Indeed, on one side Linked Data proposes principles for defining a shared representation of interlinked data (independently on any specific implementation technology, e.g. RDF [15]) in a given application domain, on the other side REST defines a lightweight API for accessing, modifying and publishing data according to the given application domain purposes.

We aim at exploiting the complementary aspects of these Web paradigms in the conception and implementation of the Web of Sensors. To this purpose, we exploit the capabilities provided by the InterDataNet information model and middleware that have been conceived to catch the complementarities of Linked Data and REST principles [16].

Expected benefits of this approach are manifold. The availability of tools allowing the easy access and manipulation of sensors data is crucial to build infrastructures capable of offering smart services to people. Sensors displaced in the territory produce data, and applications consume these data to offer smart services. From this point of view data can be conceived as the information building blocks; the more versatile and disposable the building block, the easier to build useful information.

To expose data in a fruitful way it is important to leverage the Web approach, i.e., to put data in a global space accessible for everyone using standard technologies like HTTP protocol and URIs. If this requirement is met, every researcher, developer or tech-savvy user can retrieve public data and use them to build applications. Even if this scenario is promising, there exist a big improvement to pursue. We argue that data have to be modeled as granular units and have to be individually addressable to support their exploitation, sharing and reuse. Data must also be organized in versatile and expressive information structures like graphs.

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III. InterDataNet

InterDataNet (IDN) is a system offering capabilities for representing and managing information units and their structural and semantic relations on the Web, in a RESTful way. For the sake of conciseness, in this paragraph we provide a brief introduction to the main components of the IDN system: the Information Model, the IDN APIs and the Service Architecture. Further details can be found in [16], [17], [18] and [19].

The main goal of IDN is to enable the easy exploitation and reuse of globally web-addressable information units to support collaboration around data. In IDN, documents represent a structured aggregation of data that conveys some meaningful (and shared) information in a given application domain. In the following, we refer to a document in IDN as IDN-Document.

A. IDN Information Model

The IDN-Information Model (IDN-IM) defines the rules for organizing data in an IDN-Document.

Definition 1: an IDN-Document is a directed graph G=(V,E) where V is the set of vertices and E is the set of edges. The elements of V and E are the nodes containing the granular information (IDN-Nodes) and the relations between IDN-Nodes, respectively. IDN supports two types of relations between IDN-Nodes: aggregation (i.e., containment) and reference.

Definition2: an IDN-Node is a set S={C,P} where C is the set of contents and P is the set of properties related to C.

The enabled properties (collaborative properties) are: integrity, confidentiality, availability, licensing, trust, versioning, provenance, consistency and privacy. A part of them is embedded in the IDN-Node and others are enforced by transversal architectural services.

Let D be an IDN-Document modeled as a graph G. Hence the topology of G expresses the IDN-Information Model used to represent D. Through the IDN-Information Model it is possible to define an IDN-Document as an aggregation of data provided by different information sources. Indeed, an IDN-Node can be referred to by more than one IDN-Document, thus favoring the reuse of information across different applications. This is possible because each IDN-Node is associated to an information provider that is authoritative for the information referred by the IDN-Node. Hence, gathering information from the proper sources enforces an appropriate responsibility distribution across the information providers, who are responsible for the quality of the provided information.

B. IDN-API

IDN-Documents are exposed as resources through the IDN-Service Architecture (IDN-SA) API. The IDN-API is a set of generic REST interfaces for addressing, resolving and handling IDN-Documents.

By exploiting the IDN-API (exposed by the Virtual Resource upper interface), it is possible to develop web-based applications (IDN-Compliant Applications, IDN-CA) that browse and handle graphs of distributed information units (i.e., IDN-Documents), through a uniform REST interface.

By definition, every entity managed through the IDN-API is an IDN-Document which in turns is a collection of related IDN-Nodes. It is important to point out that given an IDN-Document X every sub-graph Y of X is an IDN-Document as well, satisfying the Definition 1. The IDN-API offers the capability of giving a name to an IDN-Document Y representing a sub-graph of an IDN-Document X, as follows.

Let `http://authority/name/` be the name (URI) of a complete IDN-Document X, then:

- `http://authority/name` is the name of the IDN-Document Y containing the root IDN-Node of X only
- `http://authority/name/$rn` where $n \in N^{+}\backslash 0$ is the IDN-Document Y containing the root node and the IDN-Nodes distant n hops form the root IDN-Node.

Given an IDN-Document with the name `http://authority/name` the whole IDN-Document has the name `http://authority/name/` (note the slash character at the end of the URI).

C. IDN Service Architecture

The IDN-Service Architecture (IDN-SA) (Fig. 1) is the middleware that implements the services required to enforce the IDN-Document's properties. IDN-SA has been

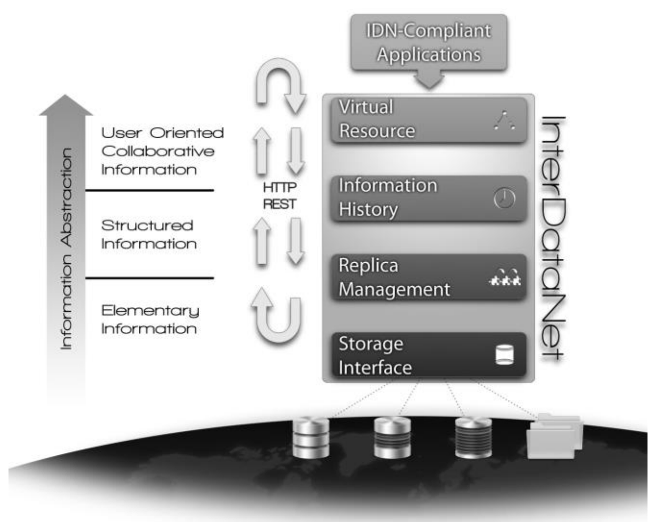

Figure 1. IDN-Service Architecture

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designed with the separation of concern and information hiding principles in mind, and it is organized according to a layered architectural pattern.

The IDN-Service Architecture has four main layers, from the top to the bottom: Virtual Resource (VR), which provides RESTful APIs for accessing creating, and modifying IDN-Documents; Information History (IH), which implements versioning capabilities; Replica Management (RM), which guarantees resources availability through replication across distributed hosts; Storage Interface (SI), which offers persistence capabilities. The SI layer can use its own databases or leverage an adapter towards legacy data sources.

We defined also a set of horizontal services, including names resolution and a discovery service built on top of the Apache Solr [20] service.

In addition, we provide a web-based GUI (IDN Studio), which eases the browsing and management of the IDN-enabled Web of Resources.

IV. Towards a Web of Sensors

Our proposal aims at exploiting IDN for easing the representation and the access to sensors' information. Therefore, the sensor object can be represented as a web resource identified by a URI.

Fig. 2 shows a possible representation of the sensor web resource. The white circle represents the information resources while the black small dots are the attributes of a resource.

Leveraging this graph-based sensor representation it is possible to easily reach many useful resources related to a particular sensor, e.g., measured data, the accuracy of the sensor, the location of the sensor, the hardware and software characteristics and much more.

IDN supports the representation of resources through oriented graphs of information. The model shown in Fig. 2 can be mapped directly to the IDN-IM with very few effort. The only needed operation is the specification of the edges' nature between nodes. As previously asserted, IDN presents two structural types of edges: aggregation links and reference links. When an aggregation link is drawn from a node to another one, a content-container relation is established. The node where the edge starts from aggregates and therefore contains the node the edge points to.

Since the chosen architectural style is REST, interacting with the resources is straightforward: to get the representation of a particular sensor it is sufficient to invoke an HTTP GET on the sensor's name (i.e., the URI). The output of a particular sensor can be retrieved analogously. For example the sensor's output data could be retrieved as follows:

GET `http://authority/sensor/{sensor_id}/data_production/data`

while to get the accuracy could be retrieved using the following request statement:

GET `http://authority/sensor/{sensor_id}/data_production/characteristics/accuracy`

The example of Fig. 2 is an adequate model to depict a context focused on the sensor object. However, in real world scenarios, more complex entities have to be modeled. By adopting the graph-based IDN representation it is easy to enhance the model in Fig. 2 to represent more challenging contexts. For example, we can assume that in a particular location, several sensors of different types are displaced. In this circumstance the IDN-Document flexibility is very handy because the scenario requirements are fulfilled simply drawing an edge from the location vertex to each sensor vertex.

Virtually the sensor model is just a portion of a more complex model graph representing the information available for the whole environment the sensors are installed in and many others.

Following this approach, data are logically interlinked and the graph-based information structure holds the meaning of data structural relations. Moreover it is possible to browse the graph leveraging intuitive operations, such as an HTTP GET on the name of the resource to be retrieved.

A. The Virtual Sensor

The motivations for building a Web representation entity for an actual sensor have been introduced in the previous paragraphs. Briefly, it takes the sensor object from a physical space and put it in a global space where every user can enjoy the information as a common and public asset. The more people are involved, the more brilliant ideas are likely to be presented, and the more interesting applications are envisioned, developed and deployed.

A creative sensor data employment is presented here as the Virtual Sensor (VS) concept. A Virtual Sensor is a software-based sensor whose measured value derives from the values of parameters acquired through other sensors (physical sensors, or virtual sensors as well). A Virtual

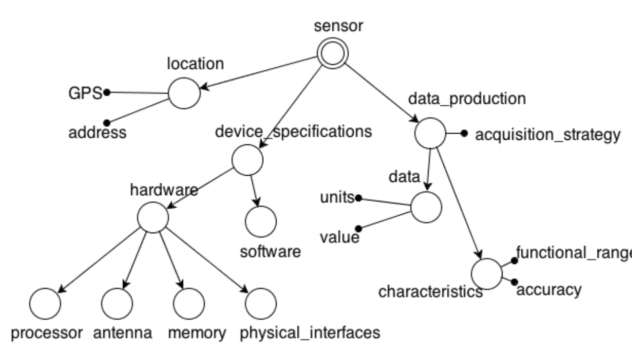

Figure 2. A model for the sensor object

Sensor can be represented exactly as an actual sensor and its data can be consumed leveraging the information model previously discussed. Therefore a Virtual Sensor can has a location assigned, meaning that it is virtually positioned in a real place. The output data are computed as a function of the data taken from the sensors it is connected with. Of course, the function will take in account the physical quantity output by the sensor, the error function depending by position and other factors.

Virtual Sensors may be added to a physical sensing infrastructure to improve the sensor coverage by: increasing the resolution of sensors geographical coverage or adding new sensor types, i.e., software-based sensors whose value derive from the values of parameters acquired through physical sensors. One interesting property of the Virtual Sensor is that it is extremely cheap and easy to deploy. For example, every citizen might have a humidity Virtual Sensor in his own garden leveraging the actual sensors managed by municipality. Moreover, the citizens having a real humidity sensor might enrich the humidity sensors park of the city representing it with the Information Model and connecting it to the global graph.

It is also possible to envisage Virtual Sensors built on top of other Virtual Sensors providing their data to countless new creative applications.

V. Case Study

The Web of Sensor concept, implemented leveraging the IDN capabilities, has been proposed and accepted for experimentation in the SmartSantander [21] European project.

In this section we present a case study concerning the Virtual Sensor concept implemented with the IDN architecture, in SmartSantander real world scenario. SmartSantander aims at enabling smart environments in Santander, Spain. Currently, we are developing an application which leverages the IDN infrastructure and the PM10 sensors displaced all over the urban territory to build PM10 VSs.

A. PM10 Virtual Sensors in Santander

Nowadays, environment care is a very popular topic. Humans health depends widely on the quality of the environment they dwell in. The shared awareness of this subject importance led us to propose a case study about the monitoring of Particulate Matter (PM).

The PM term is used to define material present in the atmosphere in the shape of microscopic particles (with diameter not greater than 10µm). It is made up by dust, smog or floating micro-drops called aerosol.

The PM is harmful for humans and its level of danger is in inverse proportion to its dimension. Small particles have severe implications for health (e.g., asthma, bronchitis, emphysema, allergies, and tumors).

The case study we propose is about the logistic displacement of Web Sensors capable of measuring the PM in strategic locations like schools, public gardens and hospitals. The aim is to leverage the environmental sensors to build a network of VSs capable of monitor the PM level in the territory. The PM-Virtual Sensor is a Virtual Sensor able to detect the PM levels depending on the PM levels detected by other sensors. Given a set of sensors positioned in the space it is possible to derive the PM rate in a different location, leveraging a mathematical model of the distribution of the PM. The PM-Virtual Sensor is designed to accomplish this task.

Of course, the accuracy of the PM-Virtual Sensor outputs depends on two factors: 1) the accuracy of the data taken as inputs and 2) the goodness of the chosen PM analytic model with respect to the reference scenario.

Through the IDN search service the web developer can retrieve the URIs of IDN-Documents representing these sensors and through the IDN Studio he can create a new IDN-Document that models the Virtual Sensor and related sensor-based information.

This new IDN-Document can thus be "created" and inserted into the system through a REST "PUT" operation. Then, the web developer can focus on presentation issues by adopting and customizing basic JavaScript code to allow end users visualizing and navigating the Virtual Sensor information graph.

A PM-Virtual Sensor application for the easy exploitation of data produced by the sensors could be envisaged. The application would display a map of the city with the sensors available for querying (Fig. 3). The citizens could interact with the application in a seamless way and they would learn how to use the data produced by the sensors following a guided procedure. The benefit concerns not only the construction of a rich logical infrastructure of consumable data, but also the promotion of the citizen participation in producing value for the good of the community.

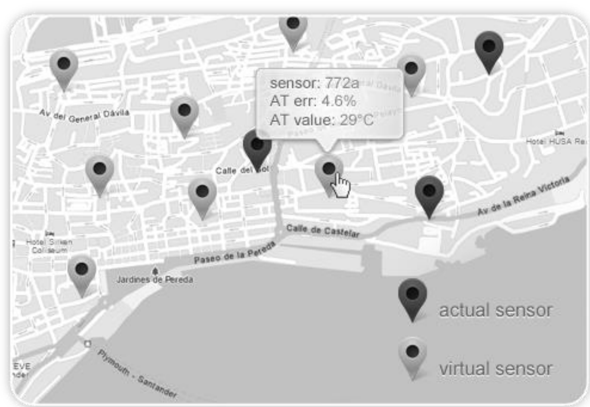

Figure 3. PM-Virtual Sensor conceptual interface

VI. Related Work

The topic of sensors' data integration into a web environment has been addressed by a number of research groups, with different approaches. In this section we selected some of the most relevant works about the topic.

Page et al. [8] [9] argue the utility of representing an actual sensor using a web abstraction suggesting REST and Linked Data paradigms. Barnaghi et al. [10] introduces the Semantic Sensor Web where the sensors are annotated with semantic metadata in order to enrich their description. These works do not address the composition and reuse of the sensors' representation as proposed in this paper through the IDN Information Model and the related Virtual Sensor concept.

Sensor.Network [22] is a data exchange platform that allows the composition of new services incorporating heterogeneous sensors from different sources. Sensor.Network system focuses on the "datastream" concept which is a time-series of sensors value sampled together. The datastream concept can be somehow compared with our Virtual Sensor, still remaining considerably different: first, our Virtual Sensor is a Web resource (represented with a graph) which can be fully accessed in a RESTful way, and second it supports the definition of analytical models to compute the output data.

VII. Conclusions

In this paper we have described an approach for implementing the Web of Sensor vision based on the adoption of Linked Data and REST principles.

As a matter of fact, expected benefits of such principles include the development of scalable applications and easy sharing of data and models across the Web. We discussed the adoption of such principles in the sensing domain, with the objective of improving information sharing and easing the development of web-based applications. These principles have been put into practice through the use of the InterDataNet (IDN) Framework.

As a case study, we discussed the Virtual Sensor (VS) concept and its ongoing implementation in the SmartSantander European project.

Finally, future work will include an improvement of the IDN architecture and the release and testing of the Virtual Sensor application.

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