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Enabling Intelligent Interoperability: Advancing Sensor Networks Through the Semantic Sensor Web (SSW)

V. Basil Hans[1,*]

Abstract

The Semantic Sensor Web (SSW) is an evolution of the traditional Sensor Web, integrating semantic web technologies to enhance the discovery, interpretation, and integration of heterogeneous sensor data. By embedding semantic annotations into sensor observations and metadata, SSW enables automated reasoning, improved interoperability, and more sophisticated querying capabilities across diverse sensor networks. This approach addresses key challenges in handling large-scale, distributed, and dynamic sensor data, particularly in domains such as environmental monitoring, smart cities, and the Internet of Things (IoT). In this study, we explore the core concepts of SSW, including ontologies, semantic annotation frameworks, and reasoning engines, and review current applications and ongoing research challenges. We also highlight the potential of SSW to enable context-aware decision-making and intelligent data fusion, laying the groundwork for more adaptive and responsive sensor-based systems.

Keywords: Semantic sensor web (SSW), sensor networks, ontology integration, semantic interoperability, real-time sensor data processing

INTRODUCTION TO THE SEMANTIC SENSOR WEB

With the rapid growth of sensor data, data formats and protocols to produce, transmit, and access sensor data have proliferated. Open Data Access protocols have been introduced by various standardization bodies to promote universal accessibility of sensor data: the Open Geospatial Consortium (OGC) Sensor Web Enablement (SWE) Web standards for discovery, access and delivery of real-time sensor data, and the World Wide Web Consortium (W3C) Rule Markup Language (RuleML) and SensorML interchange formats as a joint effort with the International Society for the Systems Sciences (ISSS) to allow web services to obtain, apply and compose sensor data with applications in various fields ranging from tracking moving objects to the fusion of heterogeneous data streams. Recently there has been a notable increase in research on Semantic Sensor Web approaches that, by providing knowledge representation models (ontologies) based on Semantic Web technologies (i.e. RDF, OWL, SPARQL, rules and ontologies), promote interoperability of sensor data and can potentially enable the development of semantically enhanced sensor applications such as comparison and combination of sensor observations and reasoning on this data, which can often reveal more useful information than is contained in the raw data. On the basis of the above two trends, sensor data discovery and access through the OGC SWE protocol is now possible. A semantically-enabled sensor plug and play architecture is introduced to automatically register and discover sensor/sensor data annotations on Semantic Sensor Web based on OWL ontologies about sensors, sensor data and the relationships among them. A formal semantic reasoning framework based on the Semantic Web Rule Language and Description Logics to answer complex sensor data queries with operational semantics is proposed.

***Author for Correspondence**
V. Basil Hans
E-mail: vhans2011@gmail.com

Research Professor, Department of Management & Commerce, Srinivas University, Mangalore, Karnataka, India

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The Semantic Web describes a stack of methods and technologies to make the meaning of data more explicit. Using this technology stack, it is possible to annotate datasets with metadata that express the data's properties, and associate the terms with relevant ontologies that describe their meaning. Thus, a machine-readable understanding of the data can be provided along with a vocabulary for human interpretation. In particular, ontologies (knowledge representations of a domain) have been extensively studied and applied to represent the meaning of data [1]. Recently, Sharifzadeh *et al*. demonstrated how the interplay of these Semantic Web technologies with annotated geographic information can be used to create semantically-enabled browsers [2]. Moreover, several ontologies have been developed to address the vision of a Semantic Sensor Web.

OBJECTIVES

1. *To define the concept of the Semantic Sensor Web (SSW)* and explain how it extends the traditional Sensor Web by integrating semantic web technologies.
2. *To explore the role of semantic annotations and ontologies* in enhancing interoperability, data discovery, and automated reasoning in sensor networks.
3. *To examine the architecture and key components* of the SSW, including data models, annotation frameworks, and semantic middleware.
4. *To review real-world applications and case studies* demonstrating the benefits of SSW in areas such as environmental monitoring, smart cities, and IoT.
5. *To identify current challenges and research directions* in the development and deployment of SSW, including issues related to scalability, standardization, and real-time processing.
6. *To evaluate the impact of semantic technologies* on improving the context-awareness, adaptability, and intelligence of sensor-based systems.

OVERVIEW OF SENSOR NETWORKS

The last couple of years have seen an explosion in interest towards sensor networks due to the availability of small, cheap sensors that can be wirelessly connected to the Internet or other networks. These sensors give birth to an increasing number of applications in a variety of environments such as cities, factories, buildings, vehicles, and environmental monitoring [3]. However, traditional Web technologies such as databases and search engines have been used for sensor networks [4].

A limited success has been achieved because of the changing model of data access. Instead of having static data, sensor network data is continuously generated in real-time and is context-dependent. For example, a temperature reading of a certain situation becomes stale if time passes or other reading exists. The next generation of Web technologies such as the Semantic Web will enable better processing of sensor data in discovery, integration, and reasoning because of richer semantics. Geographic Information Systems (GISs) can be used for better interpretation of data; however, the integration between GISs and sensor networks remains to be improved. With the rapid growth of sensor networks, there arise many pressing issues related to sensor data management, retrieval, and integration, especially across networks or for heterogeneous data sources. The combination of the Semantic Web and sensor networks makes the Semantic Sensor Web.

Because of the immediate impact of the Semantic Sensor Web on the daily life of Web users, it has attracted much attention from the research community, and much progress has been achieved. There are ontology languages, architecture frameworks, and data storing methods addressing semantic issues in sensor networks. However, they have only focused on partial parts of the architecture and the underlying technologies to solve partial technical issues. For example, to the best of knowledge, there is no global view of these issues or the relationships among them. In this study, we focus primarily on a discussion of representing, accessing, and storing semantic sensor data with a global view. Semantic analysis and reasoning are not discussed in this study. All of these issues are complementary, and no one technique is sufficient without others.

LITERATURE REVIEW

The Semantic Sensor Web (SSW) represents a convergence of sensor network technologies and the Semantic Web, aiming to enrich sensor data with formal semantics to facilitate automated interpretation, interoperability, and integration. The foundation for SSW was proposed extending the Sensor Web Enablement (SWE) framework of the Open Geospatial Consortium (OGC) with semantic annotations to enable more meaningful querying and reasoning over sensor data [5]. Early work focused on integrating ontologies such as the Semantic Sensor Network (SSN) ontology, developed by the W3C Semantic Sensor Network Incubator Group. The SSN ontology provided a standardized vocabulary to describe sensors, observations, and related concepts, forming a critical building block for semantic interoperability. They further refined the SSN ontology to support a wider range of applications, leading to its adoption in various domains [6].

Research efforts have also examined middleware platforms and tools for managing semantically annotated sensor data. Notable projects such as SemsorGrid4Env and 52°North's SemSOS extended sensor web infrastructures with semantic capabilities, enabling users to formulate SPARQL queries over sensor observations. These systems demonstrated the potential of SSW to support complex event detection, context-aware reasoning, and adaptive querying.

In addition, the literature highlights the importance of reasoning mechanisms for deriving high-level insights from raw sensor data. Techniques such as ontology-based data access (OBDA), stream reasoning, and complex event processing (CEP) have been explored to enable real-time semantic analysis.

Despite significant advancements, challenges remain. These include ontology alignment across heterogeneous domains, scalability of semantic reasoning over large data streams, and standardization of annotation practices. Recent research continues to focus on lightweight ontologies, edge computing integration, and semantic data fusion to address these limitations and extend the reach of SSW in dynamic and resource-constrained environments.

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SEMANTIC WEB TECHNOLOGIES

The integration of Semantic Web technologies with sensor networks has the potential to open new opportunities for the discovery, interoperability, and intelligent use of sensor networks and their data streams. Unfortunately, a number of technical and practical challenges must be overcome in order to realize this vision. In this section we provide brief descriptions of how the aforementioned challenges are being addressed in existing initiatives and projects, by means of semantic-based methods, techniques and technologies. We start with the characterization of the abstraction level at which sensor data can be obtained, processed and managed.

A number of sensor network ontologies have been defined, which aim at describing different aspects of sensor-based data, from the device point of view to the domain point of view. Several aspects are relevant in the development of most of these ontologies, such as the distinction between raw observed data and derived data, the representation of aspects like accuracy, or the consideration of observations and measurements according to the relevant models. The development of an ontology in this area is one of the main tasks being performed in the W3C Incubator Group on Semantic Sensor Networks (SSN).

The aforementioned work on sensor network ontologies also takes into account the quality of the data sources. Data quality is a large research area that is not only applicable to sensor-based data, but to any type of data that can be managed in an application. However, sensor-based data depends largely on the context of the sensor network, such as the network physical infrastructure, deployment strategy, or surrounding environmental conditions. With respect to the integration and fusion of data, work has been done in the context of integrating and fusing heterogeneous data streams from various sources. Some of this work uses semantic techniques, and some does not. A recent research trend is focused on the generation of Linked Data from sensor network data streams by means of transforming sensor-based data into RDF and making it available using HTTP by means of sensor-related URIs.

The Role of Metadata in SSW

In the SSW, besides semantic languages for the annotation and description of sensors/network observations, the necessary metadata is needed to make the surroundings machine-readable. This is similar to the Semantic Web, where various ontologies and RDF vocabularies exist to enable the annotation and description of web content and data. In the SSW area, several ontologies and vocabularies have emerged to facilitate the complex task of discovering sensors and network observations.

The Sensor Observation Service (SOS) is an OGC standard for the access of sensor data across the Web. It enables request and delivery of observed properties and measured values of sensor network. Each SOS typically comes with a SML description of its sensor network (including platforms, sensors, and sensor systems). Both SOS and SML, however, are XML-based standards and their usability is limited, because they cannot easily express the meaning of the data contained in the output XML document [1]. Sensors and sensor networks are part of the Sensor Web environments, which cover a scene in a spatiotemporal domain for a wide range of sensor observation situations, e.g. the traffic condition on a road network of a city, the weather condition of the whole country, and the temperature distribution inside a room. An SSW description should explicitly express sensor and sensor network information in terms of their data and structural semantics (both in the domain of sensor observations and in the contextual spatial, temporal settings) and heterogeneous data. These descriptions will enable to retrieve and use Sensor Web contents (SNSWO) described in a wide range of spatiotemporal domains and data formats.

In order to make such descriptions flexible and easily understandable, it is important to develop a set of ontologies, which can ontologically describe the semantics and structure of a SSW description. The use of OLAP queries in sensor observations makes it possible to find out Sensor Web contents (SWC) without any understanding of the underlying data structure. The main goal of this work is to bear the semantic structure of sensor observation datasets. In order to achieve this goal, this work introduces a set of sensor and sensor observations ontologies (SSWO) by reusing OWLTHUR and W3C basic ontologies and extending them with extra properties. Thanks to this set of ontologies, a sensor observation SPARQL query will return syntactically and semantically understandable query results.

Data Integration Challenges

The first challenge to address is how to characterize the abstraction level at which sensor data can be obtained, processed, and managed. A preliminary step in this characterization task is to characterize the types of data involved, their capabilities, and the purposes for which such data can be obtained. The development of several ontologies and vocabularies in this area is being performed within the context of W3C and OGC initiatives. One of the most relevant ontologies is the Semantic Sensor Network ontology. This ontology provides a rich characterization of sensor networks and sensor data management by means of OWL DL formalizations. Among the most relevant aspects considered in this ontology are the distinction between raw observed data and derived data, the representation of aspects such as accuracy, data's concerns on space, time, and sensor, or the consideration of observations and measurements according to the relevant OGC models. The final challenge, in this case, is how to characterize the integration and fusion capabilities of existing and future sensors and sensor networks. As one could imagine, this integration task can be very complex and time-consuming. With respect to the design of sensor networks, this implies the task of designing a sensor network architecture to deploy several sensors in a desired geographical area, providing desired coverage and quality while minimizing the costs of deployment and maintenance. The development of ontologies and models in this area is still very incipient, but some pioneering work can be found in the analysis and characterization of this design problem. The work on the characterization of sensors and sensor networks can be directly applied in the context of data quality, which is, in fact, the second challenge. Data quality is a large research area that is not only applicable to sensor-based data, but to any type of data that can be managed in an application. Since any data, independently on how it is managed and represented, can be faulty due to processing errors or low-quality sources, it is essential to check it and to characterize and manage its quality. However, with respect to sensor-based data, one has to consider that this quality depends largely on the context of the sensor network, such as the network physical infrastructure, deployment strategy, or surrounding environmental conditions.

Ontologies in the Semantic Sensor Web

Integration of diverse data sources is the foundation of the Semantic Sensor Web. These data sources, such as sensor networks or surveillance cameras, typically have their own data models and structures. Encoding this information in ontologies provides a common vocabulary that increases knowledge reuse, allows output and query interoperability, and serves as a foundation for the inference of new knowledge [6]. Adaptation of applications and data available in a restricted range of areas is facilitated by ontologies. Interruption and disuse of an application in one area would not occur if an equivalent application is available through another data source, given that applications would use large ontologies as interfaces. When an agent discovers that useful data is being generated by a sensor network, a system has to transform the model and structure of that information into its own language. If that information is encoded as an ontology, requests could continue being processed correctly and with the same level of performance if the ontology being used is in the knowledge repository of the agent.

The SWWS world is expected to evolve in this manner. A Semantic Sensor Web (SSW) adds a new dimension to existing Web services by providing both the semantics of available sensors and service ontologies to describe available sensors and acquisition capabilities. Web services would be the interface through which sensor Webs would be accessed, queried or updated. Promising approaches to the problem of services discovery, selection and invocation exist. Very few approaches directly address the development of the Web services of sensor Webs. The automation of management, querying, integration and monitoring of a far larger scale and aggressively heterogeneous space of distributed observatories would be enabled by discovery systems. Customized data structures would be used together with discovery ontologies, encapsulation, and the results of a massive campaign of annotation of observatories with automatically generated ontologies. In addition to ontologies, other formalisms may be exploited to improve existing approaches to management or query systems.

Sensor Data Representation

Efforts have been undertaken to provide rich semantic representation for sensor data, enabling advanced discovery and intelligent sensor network management. A semantic representation of sensor data enables more meaningful queries like “find me all sensors measuring room temperature greater than 30°C”, which cannot be handled by traditional databases. Many of the discovered sensors deliver data streams containing observations. These observations must also be published in a useful way so that they can be discovered, accessed, and meaningfully processed. This area is referred to as sensor data representation. The standard web service for discovery and access to sensors is complemented by a set of tools for publishing sensor observation streams on a Semantic Sensor Web. The Semantic Sensor Web provides richer semantics and annotations for observations. The emphasis is placed on representing multi-parameter atomic sensor data streams rather than Composite Sensor Data Streams. A new framework is developed to publish and access sensor data using the interface. The key design considerations are outlined for an RDF-XML based approach for representing different data types supported. Streaming observations are represented more efficiently using a modified approach. The implementation of the streaming method has been tested.

Sensor data is relevant in many areas of research and everyday life today. Infrastructure such as sensor networks, remote sensing, aerial vehicles, and other information systems continuously deliver massive volumes of information about the world. Sensor data must be made available on the web in order to ensure their wider discoverability, access, and use. Many efforts have been undertaken to publish sensor system descriptions in a machine-interpretable way on the web, enriching them with semantics in the process. In addition to discoverability and access, it is equally important to publish structured information content of incoming sensor observations in a semantic way. Receiving knowledge from publishing sensors inferences enables understanding of the higher level events and situations. A semantic representation of sensor data helps to build Advanced Semantic Sensor Web applications and infrastructures while enabling rich query capabilities over heterogeneous and dynamic sensor data. To address issues of discovery, access and representation of sensor systems and data, the standards have been designed. Semantic web technologies such as ontologies, rules and enhanced standards support meaningful queries, semantic reasoning and integration among heterogeneous sources. Such enhancements to technologies and standards build a Semantic Sensor Web powering the future intelligent sensor web applications.

Interoperability in Sensor Networks

Interoperability is required in sensor networks for several reasons. It allows the sharing of data acquired by a sensor in a different network. Multiple sensor networks are often involved in a single application scenario where data is processed and fused. Sensor networks from different domains may be used in similar applications where shared data is needed. Sensor performance and network topologies change in time. In these cases, dynamic understanding of the availability of sensors, sensor ontologies and protocols is necessary. There are similarities between this and integration of heterogeneous knowledge sources. However, there are key differences. One, in sensor networks, it is possible to share knowledge about the networking protocols and sensor capabilities. These ontologies can be made available in a generic sensor network ontology that can be imported, adapted and customized in each sensor network. Another difference is that an interoperation framework for sensor networks must be implemented on a smaller, more incapacitated architecture, compared to systems on which database and software integration systems are normally applied. This raises new scientific challenges in the representation and reasoning about the available knowledge. A discussion of these challenges is provided.

Environmental sensor networks have been deployed in several application scenarios such as environmental monitoring, weather forecast and climate change tracking. In these sensor networks, sensors are deployed for long time periods. The sensors in these networks are usually dispersed in a large area in the environment, monitoring a wide variety of natural phenomena. As a consequence, they produce a large volume of time series data that need to be archived and mined. Open data has become an increasingly popular research topic. In many countries, governments, non-profit organizations and universities publish open data to provide citizens with knowledge about the government, economy, society and environment. Sensor network data is time series and belongs to the physical world. This high-dimensional, hierarchically structured and uncontrolled data raises new challenges for knowledge representation and reasoning. To cope with the challenges, an ontology that represents sensor network data semantically has been designed. The representation of ontological metadata and time series data is a key component in building sensor network knowledge management systems and should be refined to support the ontology-based knowledge representation, reasoning and query expansion.

APPLICATIONS OF THE SEMANTIC SENSOR WEB

In the case of semantic sensors, the observed data is usually homogeneous in nature (i.e. geography, others). This is not usually the case in sensor networks. The observation of various events by diverse sensors can generate data of different types, such as image, audio, rainfall, temperature, and derivatives of this data or calculated information. Furthermore, observed data can be stored in different formats (i.e. file-based storage, relational database, others) and the origin of the data can also be heterogeneous. Such diversity makes the creation of proper query languages difficult, and afterwards the formulation of queries even more complex. Nevertheless, ontology-based data access and ontology-mediated queries can assist in this context by providing simple yet powerful query mechanisms.

Considering the above technologies and squarely focusing on applications, which is the aim of this study, it is reasonable to presume that the advent and development of SPARQL endpoints and the publishing of SPARQL endpoints on the Web has completely changed the landscape of Linked Data by firmly establishing a knowledge discovery framework on the Web and allowing for a broad range of complex applications to be developed. With SPARQL endpoints in place it is possible to ask arbitrary queries on a web of semantically rich data. Further up the stack, the Semantic Web provides a rich set of technologies and tools for building applications on top of SPARQL endpoints or exploiting Linked Data in general. New application paradigms that take advantage of set-oriented data and make SPARQL an integral part of their architecture have emerged. Online marketplaces for reusable Semantic Web components are also flourishing. However, the semantic sensor web largely remains in its infancy with regards to real-world applications. There has been some work on making sensor data accessible on the Semantic Web in the form of knowledge graphs, in RDF/OWL, yet, as of today, relatively little work has been done on the parsing, querying, and mining of provenance knowledge.

Case Studies of SSW Implementations

This study presents the SSW, the convergence of the development and deployment of sensor networks with the Semantic Web. In order to be able to perceive phenomena, in the context of the SSW, we need two approaches to represent data; a description of the sensor network, (i.e. the 'what'), and a description of the data that is provided, which is the meaning. The SSW aims to satisfy the basic requirement for time-dependent information by offering relevant data in a way that is easy to describe, to find and to use. It briefly analyzed why the Web is not enough for the data of a sensor network and explained the limitations of the Web. The SSW offers an alternative approach to deal with the flexibly changing and incomplete sensor networks. It further reviewed the importance of ontologies in general and the Web ontology language in particular for the understanding of the provided sensor data. The preliminary SSW architecture and several case studies were introduced to show how different organizations are solving this problem.

The described improvements are the cornerstone for scaling up any sensor network and hence the SSW. Although they have presented results for the PC-Grid on a few sensors and a few ontologies, this is in a sense a non-issue. What is important is the need for a system to discover ontologies and to interpret them. It also pointed out the challenge to be able to integrate the semantic-based sensor network with existing resource/knowledge/ontology repositories on the Web.

The solution is not going to be easy. The demands for computational power will increase exponentially, and will thus require more efficient algorithms. Furthermore, a careful balance has to be struck between the accurate representation of the ontology and a loadable representation of it. The SSW aims to solve these problems.

Data Quality and Validation

In recent decades, the rapid proliferation of sensors, and smart sensor devices has led to the emergence of environmental monitoring networks. In this context, the Sensor Web (or Sensor Webs) paradigm has been widely adopted as a unified framework for accessing, filtering, fusing, processing, and sharing the data acquired by sensor networks. Sensor Web systems have been increasingly developed to facilitate the discovery and retrieval of observations produced by sensors, with the publication of Web accessible sensor data and sensor description information. The Sensor Web systems deliver observations in a format transparent to the user, while exposing sensors and observation producers independently of their underlying implementation details. Nevertheless, such systems must deal with heterogeneous sources, which produce heterogeneous observations of disparate quality. Managing such diversity can be quite complex and require high levels of expertise from applications developers. Unfortunately, the major Sensor Web systems currently in use do not address such quality issues, which severely limits their use in applications that require safety, reliability, and trust.

To help application developers better manage this diversity and to facilitate the collaborative development of those systems, it is clear that any Sensor Web should provide not only methods and tools that allow them to standardize and homogenize observation content but also insights into the quality of observations exchanged, in particular their limitations and implications. Such a notion is defined as Quality of Observation (QoO) requirements, which aim to represent such information. This QoO notion is shown to be a necessary extension of the OGC's standards for the Sensor Web. However, very few Sensor Web solutions are designed to address these issues. There are several reasons, including difficulties in modeling observation quality and its dimensions, and challenges in leveraging open standards to facilitate the collection and exchange of QoO requirements at appropriate granularity among diverse systems and tools [7, 8].

Real-time Data Processing in SSW

The Sensor Web Enablement (SWE) standard suite specifies a number of web services and encodings to make sensor-related data discoverable and accessible. These specifications provide a homogeneous, interoperable way to access a physical-world sensor, and to query sensor-related information. Central components of the SWE standard suite are the Observations and Measurements (O&M) encoding and the Sensor Model Language (SensorML) [1]. Together, these encodings specify a number of data types used to represent sensor observations and certain sensor descriptions, respectively. Utilizing web services and these data encodings, resources on the Sensor Web can be accessed without the need for any prior knowledge about the resources. As a result, discoverability of data and services on the Sensor Web becomes a key issue. The emergence of semantic web technologies offers new possibilities for improving on existing solutions and for implementing further exciting possibilities to make the Sensor Web easily usable.

Semantic Sensor Web languages and frameworks offer a way to publish and discover sensor observations and descriptions on the Web in a machine-readable way. They enhance discoverability of sensor web resources and add additional degrees of freedom in post-processing sensor data. Additionally, users are able to access sensor-related data without the need for knowledge about possible physical-world sensors. Resources decrease latency and hiding complexities through a higher level of abstraction. Rather than accessing a specific sensor, a user can query a controller that provides access to all appropriate sensors. With the SPARQLing of SWE data, users are able to ask more complex, and hence more meaningful questions. Generic sensor descriptions for a statement on intended use cases eliminate the need for JSON-RPC or WSDL documents tailored to a specific time, usage context, and producer. In the aftermath of the first World-Wide-Web, a series of technologies have been developed over the past 18 years that make web-based data resources comprehensible for both humans and machines. These technologies are labeled collectively as Semantic Web technologies.

User Interaction with Semantic Sensor Data

Motivation for Integrating Semantic Web Technologies with Sensor Web Systems

The rising interest in Sensor Web systems has been motivated by the proliferation of sensor networks in planetary-scale environmental monitoring and the conversion of sensor data streams to web services over the internet. Two main reasons can be cited for this interest. Firstly, the Earth Observing System Web service architectures and encodings were not developed for arbitrary sensor networks and lacked the flexibility required to accommodate many new sensor networks. Secondly, as the Sensor Web-enabled sensor networks grow and sensors and related services are offered as Web resources, application developers, in a manner similar to how services from other domains are integrated, will want to consume a set of distributed services including Sensor Web services and Web standards and RDF will support the flexible and correct consumption of such services.

On the one hand, this study argues that, to support the Semantic Sensor Web paradigm, i.e., the Semantic Web of Sensor Web resources, integrating Semantic Web technologies for the markup and interoperability of Sensor Web resources is essential. Translation of Sensor Web resources to ontologies such that they are encoded in Semantic Web standards and publishable in the Semantic Web is the first step towards this end. Adding capabilities for the annotation of ontologies to Sensor Web systems is the second step. Metadata quality is then an important aspect of interacting with Web resources in the Semantic web, and a quality metric and measure framework to evaluate the quality of sensor stream data in the Semantic Sensor Web is proposed.

On the other hand, given the countless sensor data-capable devices, it is recognized that streaming the sensor data from many sensor data sources to the Web poses scalability concerns. With a focus on structured sensor and sensor data, Semantic Web-based techniques to alleviate scalability concerns in terms of both discovery and accessing Sensor Web resources have been proposed. A 'Web Service for All' architecture that is based on a complex event processing paradigm to retain and publish sensor data in a context-aware manner on the Web is also presented. Scalability with regard to the volume of sensor and sensor data streams to an arbitrary now-cast is also approached using probabilistic SPARQL query formulation, coupled with adaptive data sampling and Mosaic inference based semantic uplift processing of sensor data.

Security and Privacy Issues

Security and privacy concerns have become hot topics lately because of the burgeoning number of wireless sensors networks (WSNs). Although many of the security provisions or protocols for traditional wired and wireless environments may be applicable to WSNs, they were not always designed with the limitations and characteristics of sensor networks taken into due account. This drives the need to design new security protocols, algorithms, and mechanisms specifically for WSNs. The challenges in this design process are exacerbated by the different user scenarios for WSNs, expected security assurance levels, and target applications [9].

Very recently, a few researchers have studied security and privacy issues in sensor networks worldwide. A survey article on this topic was published previously; however, the focus was on what, why, and how of security in sensor networks rather than the review of the design issues or solutions. The key contributions of the authors include the literature review of security issues covering many aspects, especially emerging issues in sensor networks and smart dust in surveillance applications and the survey of security solutions to these research topics across all levels of the sensor networks. Such a cross-layer survey is very timely and useful to both researchers and practitioners.

The topics of interest considered along with security and privacy issues parallel to the layers of the Open systems Interconnection (OSI) Reference Model. In addition to traditional data link layer and network layer security schemes, the emerging application-layer privacy issues and their possible solutions are reported. On the other hand, the information provided may be highly sensitive and confidential; thus, it is important to ensure that the appropriate privacy policies are put in place and that information is properly secured so that it cannot be learned, modified, or used improperly by unauthorized users.

Future Trends in Semantic Sensor Web

Although the deployment of Sensor Web technologies and the generation of Sensor Web data in a variety of domains is turning into more and more common practice, there are still some challenges regarding the meaning, representation, integration, fusion, publication, annotation, access, search, retrieval and processing of data coming from heterogeneous Sensor Web resources [9]. Addressing these challenges is expected to promote a wider adoption of Sensor Web technologies, combined with a bigger trust in and added value of the Sensor Web data coming from those technologies. Although the challenges described in this section are general and they go beyond the Ontology framework, the latter is used to provide a general organization of those challenges. Following the framework, the challenges are organized into the following abstraction levels: (i) data sources, (ii) data ingestion, (iii) data processing, (iv) data understanding and (v) data use (with an emphasis on data discoverability, interoperability, sharing and publication). In addition to that categorization, some challenges related to data query and storage, and to a lack of widely accepted standards for some of the Sensor Web standards are also mentioned in this section.

Most of the challenges described in this section are being addressed by means of Semantic Web based methods, techniques and technologies in currently running initiatives, projects and prototypes. Within the relevant initiatives, projects and prototypes, ontology based methods are being used for mapping specifications from the Sensor Web standards to OWL ontologies, which are being used for transforming Sensor Web data into RDF, publishing that data using the Linked Data principles, generating Linked Sensor Web Data and enriching those data (using semantic enrichment methods including ontology based annotations and SPARQL End-Point Semantic Web Services usage). Therefore, it is fair to say that there is a growing and active research community addressing problems related to one or a few challenges in the context of geospatial Sensor Web domain with semantics based technologies. However, some of the challenges are still at the state of the art and they still need methodologies, techniques, methods, systems and tools using Semantic Web technologies for addressing them.

Comparative Analysis of SSW Frameworks

This section presents a comparison of the existing Semantic Sensor Web (SSW) frameworks. These frameworks are classified into three categories according to their aims. The first group of frameworks aims to support the discovery and publication of sensor data such as Seshat and OWL-S. The second group of frameworks assist the user in querying sensor data, e.g., SWS-Nova. Finally, the last group of frameworks deals with reasoning over heterogeneous data acquired from sensor networks like SmartSantander and SenseGov. For each framework, existing gap analysis is discussed regarding the SSW requirements.

The Semantic Sensor Web (SSW) aims to define a standard form for publishing, discovering, and automating the usage of sensors and sensor data [1]. There are many existing frameworks that provide some of the SSW functionalities. However, the overall coverage and integration of such functionalities in a single framework is still lacking. Moreover, existing SSW frameworks were even not able to completely fulfill the unambiguous definition of sensor, as it is defined in the IEEE 1451 Standard for a Smart Sensor. Thus, a more efficient and organized form of web services to deal with sensor networks is essential.

One essential requirement of a framework deals with how to publish sensor data. The importance of annotating heterogeneous sensor data originates from the Semantic Web vision, whose key goal is to facilitate the sharing and reuse of web resources. Implementations like Seshat facilitate standard form addressing obstacles such as database compatibility and cross-domain discovery [9]. By providing a well-defined ontology, existing willingness to publish sensor data becomes valuable and hence there is no point in joining proprietary systems to publish sensor data.

Standards and Protocols for SSW

The Sensor Web Enablement (SWE) initiative has established a suite of standards to realize the vision of a Sensor Web. By integrating standardized services for sensor discovery, access, tasking, and eventing, a platform can be built that is interoperable with heterogeneously deployed sensors and the underlying sensor data. In particular, the Sensor Observation Service (SOS) enables access to measured sensor data and semantic sensor descriptions from heterogeneous sensors [1]. Semantic Sensor Web (SSW) research extends these standards with ontologies, languages, and tools that make sensor metadata, sensor data, and sensor access services semantically interoperable [9]. Such research can lead to the technical realization of an SSW. However, standards and protocols covering the communication patterns and the format of the data exchanged between involved systems and/or their components are required for the production deployment of such a system. Literal interpretations of the standards are not sufficient, since the systems must be able to communicate under sufficient and precise conditions. The heterogeneously deployed sensors use a huge variety of communication technologies. This heterogeneity must be hidden from applications and users to provide seamless access to the Sensor Web and a simplified user experience. The Sensorscope project has designed a prototype architecture integrating both domains. The architecture consists of a set of micro-services that are deployed and publicly accessible. The data and access services implemented by these micro-services expose data and functionalities of the deployed sensors. Such services can be called and queried in a number of pre-defined ways. Intermediate results, which are generated through chaining a number of services, are also published as a web-accessible resource and can be further accessed with an approach similar to the sensor data access. This architecture has gained traction as a possible way of deploying and sharing Sensor Web resources. However, it sets no formal requirements on new services that can be published as part of the Sensor Web. Formally defined communication protocols, based on the WSDL standard complemented with a number of tailored semantic extensions, are needed for the proposed integration.

Tools and Platforms for SSW Development

The Semantic Sensor Web (SSW) is an upcoming specialization of the currently very broad Semantic Web technological stack [1]. Reasoning and discourse technologies added to the Sensor Web standards will enable rapid progress in the development of the Infrastructure for the Sensor Web. The overall goal is to improve our understanding of the Earth and its processes, an urgent need in the face of Climate Change. The SSW communicates the meaning of the available observations to potential clients in a wide variety of languages. It also indicates which sensors have sensed which query-relevant (semantic) named-situations currently exist. Matching between named-situations and time-dependent observational source-constraints is done at the level of OWL 2 DL ontological modelling, thereby solving the greatest part of the communication bottleneck. Most potentials will be demonstrated by applying the SSW to the vast array of current and planned Pavement Sensor Networks in the Netherlands. The first prototypes of the SSW components have been designed, implemented and tested. The most meaningful prototype for clients is currently under construction.

The built SSW conditions show wide applicability, because new sensor plug-ins will automatically be accepted if they comply with standard protocols and ontologies. In this way, costs for both clients and providers will drop rapidly. The design of Sensor Web Servers is so flexible that a wide variety of observational situations of any sensor type anywhere in the world can be automatically accommodated. Complete independence of the language in which the discovery service communicates with the central query processor is ensured by a common intermediate Esperanto language [9]. The System to Be Developed uses standard Semantic Web technology. Standard railway infrastructure ontology models will be used for proving the method's versatility. The simulations will include type failure and non-discovery of an SSW or a sensor plug-in, both of which will be rapidly detected.

Challenges in Data Fusion

The semantic sensor web is an initiative that aims to augment existing sensor networks with semantic-based capabilities. It embraces two key technology areas: semantic web technologies, which share data in a manner enabling automatic discovery and integration of information; and sensor networks and associated sensor-based data, which provide information about the physical world. The combination of these technologies is expected to create a new generation of intelligent sensor networks that will be able to automatically discover, query and integrate disparate data sources across the web. Data sources will be described in a standard manner to facilitate understanding and integration. Observed data streams will be described in terms of the context and accuracy of their associated sensor networks. The result will be a sensor web that offers an ordered set of streams of observed data and their descriptions obtained by augmenting and integrating the data streams collected from heterogeneous sensor networks and data sources. This web of descriptions will create a new opportunity for automatic discovery and integration of sensed and observed data, and new applications from tourism to intelligent management of natural resources.

Given the growing interest in and use of sensor networks and associated sensor-based data, moving towards a semantic sensor web is technically feasible. However, several new and significant challenges must be addressed. On the one hand, novel techniques need to be developed, extending and building on existing technologies in different areas: ontologies and semantic description languages; sensor networks and sensor data structures; observations and sensed data; sensor network context and reasoning; quality of observations and data; data integration, transformation and fusion; and query formulation, evaluation and processing. On the other hand, the integration and extension of basic features, ideas and techniques from semantic web technology with these new challenges must be developed. The aim is to enable more sophisticated automatic addressing of the knowledge and information needs of users and sensory or observed data service providers.

Describing products about which information is sought is an active area of semantic web research. Products can consist of basic goods, such as a book or a software application, with or without digital components. However, products are often more complex constructions made up of a number of simpler product and/or service components. A complex product has a complex description defined in terms of simpler components or services, and the information sought could be regarding the complex product directly or any simpler components in the hierarchy. Therefore, a recent direction in semantic web research is the description of complex products. This involves extending existing vocabularies or designing new ontologies to enable the provision of such descriptions. The challenge here is the issue of the complexity of the described product hierarchy: products and services of different types of complexity would have to be described in different manners and work with different degrees of complexity [9].

THE ROLE OF ARTIFICIAL INTELLIGENCE IN SSW

The integration of semantic web technologies with sensor networks has great potential for making sensor data available on the web. However, several challenges need to be addressed before this can be achieved. These challenges fall into five categories: a possible sensor network ontology, data quality, integration and fusion of heterogeneous data sources, ontology discovery, and reasoning. The challenges, their relevance, and how they are being or can be addressed are summarized in this study.

There are two characteristics that make sensor networks different from traditional databases in terms of the proper and useful publication of sensor network data on the web. First, the data provided by sensor networks need to be integrated and fused in order to obtain higher-level information that could be useful to more applications. Second, the implicit semantics of the sensor data sources must be made explicit and structured on different levels of abstraction for both humans and machines to be able to exploit it. A high-level ontology can provide a framework into which several existing ontologies could be integrated. However, there are also domain-specific ontologies needed, which should be defined more in line with application domain standards. The ontologies are meant to endow the sensors with a semantic description of their capabilities, purpose, measurement units, monitored phenomena, etc. An ontology can also describe the quality of the data source (e.g. how often it delivers updates), and is composed of domain invariant, domain dependent, and quality description ontology components.

As for integration and fusion, several approaches have been developed in the database and information retrieval communities, but none of them have been implemented for sensor networks. There is no open publication standard for exchanging sensor data, much less for the implicit semantics of the data sources. Some systems have an implicit representation of the knowledge involved in the integration and fusion of heterogeneous data sources, e.g. in the form of wrappers. However, if different wrapper algorithms can be exploited, machines need to be made aware of the available wrappers and their description in a format and level of detail adequate for the fusion task. Describing the wrappers on the semantic web with the proper degree of formalism will also enable answering the more challenging questions of deciding which algorithm to use to combine multiple inputs or to assess their output quality automatically [9].

Active research is being conducted to get a better understanding of the spatial, temporal, and contextual characteristics of sensor data and the rationale behind their accuracy. Inter- and intra-domain methodologies and algorithms have been developed to fuse heterogeneous stream data from different sensors taking advantage of both homogeneous and heterogeneous models of the sensors involved in the fusion. In some cases, fuzzy methods are used, but they have not, as far as the authors are aware, been applied to sensor networks. Efforts are being made to calibrate the sensor measurements relative to their reference measurements or target values. Rule systems can be used to derive a number of additional unknown sensor values, and then classify one sensor value as 'anomaly' based on the best fit with the desired model. However, sensor validation has not been addressed with the approach discussed above [1].

Semantic Annotation of Sensor Data

Although the Semantic Sensor Web is still at an early stage compared to the traditional Web, many initiatives and research efforts have emerged in the last few years to develop the foundations of this knowledge-intensive infrastructure. Advances have been made in sensor network ontologies to approximate situations in open sensor networks by means of semantic-based methods, technologies and protocols to observe, browse, search and query sensor data on the Semantic Web. These advances are presented in the context of a set of key challenges that must be addressed in order to ensure the wide deployment of the Semantic Sensor Web vision [9].

As a first step towards the Semantic Sensor Web, a Semantic Sensor Network Ontology has been defined and released by a W3C Incubator Group. This ontology is compatible with W3C standard ontologies and provides mechanisms to annotate sensors and observations following best practices for ontology reuse and translations to established sensor data formats. Despite initial success in proposing this ontology, there remain several open challenges. The latest specification of the Sensor Network Ontology was released in April 2010, based on input from the wider community. Today, this ontology is widely adopted and represents the main vehicle to provide semantic annotations of sensors.

With the growing number of sensors, there is an increasing need to provide tools to easily understand their provisioned services, as well as their queried data. Discovery of sensors is thus a primary need, to *de facto* serve as a prerequisite for any other tasks, such as searching sensor data or querying sensors [10].

Adding semantic description of sensors not only provides interoperability at the requisite but it also semantically enriches the sensory data by linking them to external sources of information. New means to search sensor data emerge, analogous to meaningfully querying standard data in the traditional Web. Towards this endeavor, a main challenge is to re-use and align the best standard ontologies that reflect the intricacies of sensor data. To address this task, a gathering of the best practices of ontology reuse has been followed to develop this sensor data search framework.

User-Centric Design in SSW Applications

Understanding sensors and the data they produce is a complex problem requiring multimodal knowledge. The challenges introduced by the integration of sensors, the variety of hosted services, the scale and real-time retrieval of the data generated, and interoperability among sensors arise from a diversity of research areas: sensor networks, distributed systems, cloud computing, databases, data mining, machine learning, and artificial intelligence (AI).

These elements mostly originate in different disciplines with their own terminology, suggesting that encouraging the development of a Semantic Sensor Web (SSW) does not only mean creating a standard ontology, but also dealing with an inherent knowledge integration challenge [1]. Improving data discovery and usage capabilities in heterogeneous sensor networks implies the need for an interoperable representation of both acts of sensing and sensory data, in relation to the common schema they refer to. It also implies existing sensor descriptions as code lists, machine-readable sensor discovery protocols, seasoned sensor applications, and newly-founded services (SSW systems).

User-centric design fosters active participation of end users in the design of sensor web systems, inviting them to create, share, discover, and employ their sensors in collaborative systems. User-centric design principles are elaborated through research questions in terms of both, methods and approaches. Preliminary specifications have been synthesized, along with development guidance systems, grounded in sensor web knowledge design principles.

By actively synthesizing existing knowledge in domains such as human-centered design, human-computer interaction, and user-design, foundations of user-centricity are elaborated so as to question themselves against the evolution of the web. Rather, instead of looking to the Web 3.0 hype, the design of systems supporting user-centric, common-sense understandings about sensors is inquired instead. How might sensor web systems be designed so as to understand sensors according to the mind of an end-user? What is the knowledge that would allow a user to think about her sensors and sensor observations?

Impact of IoT on the Semantic Sensor Web

The advent of IoT is anticipated to yield tremendous impact on the Semantic Sensor Web (SSW). The new design of SSW services that integrate Semantic Web Technologies with Sensor Web technologies is required in order to leverage this impact. This section discusses how the explosion of new IoT systems creates requirements for SSW services. The new challenges can be mapped to gaps in the current SSW approach. Current proposals for extending the SSW architecture are discussed together with an outline of the next steps needed in research. Proliferation of pico-sensors, mobile phones and sensor enabled smart devices is expected to create an explosive growth in instrumented environments.. Embedded sensors will eventually be everywhere: in vehicles, under the streets, at home, in clothing and in packaging. Building such Sensor Webs will be one of the key challenges in coming years. The new Smart City era is anticipated to be dominated by advances in Networking, Handling Big Data and Semantic Data Modeling.

Static SSW systems designed to be data sinks that work with few trusted data providers are under duress from the IoT growth. The new era requires support for numerous temporary and roll-in/roll-out data producers. Such roll-in data producers may not be trustworthy and may be created dynamically. Thus, shared, open and semi-automated data processing services are required. In addition to open data access services, the new state of affairs requires knowledge discovery services that work with many data producers generating dynamically evolving semi-structured data. The future SSW systems should also support mobile and rapidly changing data sources and thus provide methods to incrementally maintain or adapt data models [11]. This poses additional queries concerning schema evolution and temporality capabilities of any SSW-store based on Semantic Web Enforcement. The new landscape of IoT mainly consists of 28 billion resource-constrained devices anticipated to be connected to the Internet. Many of these devices will be powered by energy harvesting technologies and they will work with minimal resources.

Evaluation Metrics for SSW Systems

To evaluate SSW systems, metrics can be classified with respect to the point of view with which those systems are evaluated. Different roles require different metrics. A service provider is interested in the overall system, while service users are interested in its capabilities, such as the kind of services offered, the size of its knowledge base, etc. [12]. Both service providers and service users need to know how well services match their expectations. Service interrogators utilize many metrics to efficiently select services of potential interest to users. At last, developers of a particular SSW system are interested to evaluate the performance of each of the system's components in order to identify any bottleneck or defect.

At the level of the entire system, metrics can be distinguished in those indicating the size of the system, and those indicating its throughput. Size measures include the number of interfacing components, the number of deployed ontologies, the number and types of domain knowledge extraction tools, the number of services registered in the system, and the size of the stored axioms, among the others. Throughput measures include the number of requests that the system is able to process in a given time interval, and the average time that it takes to fully process a request. In addition to size and throughput, it can be useful to measure and analyze "passive" parameters, such as the amount of data transfer.

User-oriented metrics indicate: the capabilities of the system, how well automated services match user's profiles, quality of services provided, types of services selected by the users, and time needed to serve request. The kind of capabilities offered by a SSW system may be quantified using the numbers of urban and non-urban services, of deployed ontologies, of parsing algorithms provided, and of non-graphical query generators. Quality measures might include: the number of services returned by each base service and by combinations of base services; the type of returned services (urban versus non-urban); the number of semantic links applied to query refinement, if graph-based matching is applied; the average matching time; the reason for which services are rejected; and the reason for which returned service descriptions differ from requested ones [1].

Collaboration and Community in SSW Development

Just as we benefit from a world wide web of interlinked HTML documents, it becomes evident that a linked world of openly available and reusable sensor data would have a similar effect on robotics and multi-sensor applications. Publishing and sharing sensor data in a machine-readable format allows for innovative applications that merge heterogeneous data from different domains. Querying geographic information, sensor readings, and other related data may provide decision support for many real-world applications. Today, everyone uses a database of geodata or sensor web services possibly without realizing it. Similar developments will arise for the Linked Sensor Web (LSW), a world wide web of linked sensor data, capabilities, ontologies, etc. [13].

The contributing hardware, software, and people of the LSW community online to reap the possibilities described earlier need a glue to describe it, to aggregate, re-process, and to query it. Missing components should be identified together. Sensor manufacturers need to position their devices on the LSW. Standardization bodies and software engineering companies can attest to sensor device interoperability over the web. The Web, Web Services, and other stack-able standards for querying, processing, and publishing are ideally suited to aggregate existing and to build new networks of sensors. Linked-data techniques to publish metadata in a machine-readable way and a semantic wiki to soak up domain knowledge of people in the LSW are on the horizon [9].

The specification aims to describe the observations and the generation of observations. For the description of the observations, an OWL ontology will be developed which describes the properties of the data such as a description of what the property means, what kind of data type it has, its unit, etc. As sensors are many, a solution will have to be found such that observations from different sources can be queried using a common query language. A good candidate seems to be the W3C standard SPARQL.

Ethical Considerations in SSW

In the contemporary society increasingly composed of sensitive information stored in sensors, it is fundamental to explore the ethical context of the Semantic Sensor Web (SSW) [1]. With the development of ontology languages, it is possible to represent knowledge on the sensors and their observations in an explicit and interoperable way. This knowledge may also exploit social properties of the data, the users, and their relationships for semantic inference.

While considerable effort has been devoted to understanding and elaborating the ethical implications of the Semantic Web in general, further research is needed regarding the more specified field of the SSW. For instance, it is unclear how ethics representation systems competing to define web-wide frameworks will interact. It is required to elaborate the ethical views of different agents in new ways. Treating ethical concerns as knowledge, sufficient formal representation would be needed to exchange ontologies over the web and to process them automatically to derive information inferences. Ultimately, ethical considerations must be co-managed by collaborative human-machine systems [14].

Recent technological improvements increased the number of local sensors and the access to web wide sensors. Despite precise infrastructure requirements and sensor performance concerns, many attempts have been dedicated to providing this information effortlessly to a wide audience. Furthermore, sensing has been commercialized, allowing access to observations in real or deferred time and through different owners and provenance. An intermediate layer of mediators and processors helping interact with this growing adaptation of the web has been developed to help protect user sensitive information [15]. Specialized location services help resolve geographic coordinates to a web address of the sensing data. Solutions discover and integrate parallel data streams over space, time, and domain and extended only partially to social sources (along with reputation, trust, privacy, and security concerns). Notably, these developments are achieved independently from each other and their basic integration poses formidable technical challenges.

CONCLUSION

The notion of a Semantic Sensor Web, that is, the convergence of the Sensor Web and the Semantic Web, has recently gained a lot of interest and momentum. The Sensor Web is understood as the loosely coupled and open-ended network of Internet-connected sensors that collect and disseminate measured observations and raw data concerning the physical world. The Semantic Web comprises technologies to make Web content understandable by machines, with the use of explicit semantics and defined Web ontologies about the content of the data. The Semantic Sensor Web is thus understood as the integration of Web-enabled sensors and observatories with Semantic Web technologies for creating sensor observations on the Web that can be processed and interpreted by machines and applications. Sensor data and observations on the Web would include their provenance metadata, time, place, quality information, and semantic annotations. Semantic Sensor Web efforts aim at extending the capabilities of the Sensor Web and Semantic Web using the standards, technologies, algorithms and applications of both approaches. In the past couple of years, a number of conferences and workshops have been organized, special interests groups have been formed, and various application areas have been successfully addressed and relatively well-studied. Several projects have attempted to provide implementations of the Semantic Sensor Web vision. However, most efforts have concentrated on the second part, the integration of Semantic Web technologies into the Sensor Web, and not so much on the first part: how to exploit the Semantic Sensor Web. The aim is to provide a foundation for experimental work on the Semantic Sensor Web in terms of a generic model architecture, and to provide a few important and exemplary testbed applications on top of that. These are data provenance and data fusion approaches and applications, both of which are especially relevant in the area of environmental monitoring using sensors on the Web. Sensor data provenance is about making answers to queries reliable. When originating from an observation, the reliability depends on a number of factors, including the direct properties of the source, the aggregation of data by other entities or tedious and error-prone manual coding.

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