Earth Observation Sensor Web: An Overview

IN RECENT years, one of the major advances in Earth observation has been the development and realization of the concept of the Earth Observation Sensor Web. This concept has emerged from advances in sensor, communication, and information technologies to meet the demands for timely and pertinent data and information for supporting applications in the societal benefit areas of Earth observation [2]. One consensus view of the sensor web is a coordinated observation infrastructure composed of a distributed collection of resources—e.g., sensors, platforms, models, computing facilities, communications infrastructure—that can collectively behave as a single, autonomous, taskable, dynamically adaptive and reconfigurable observing system that provides raw and processed data, along with associated metadata, via a set of standards-based service-oriented interfaces [1], [3], [5], [6].

The sensor web is an active research field in Earth observation. Many space agencies and international Earth observation programs have an active component that contributes to the Earth Observation Sensor Web. For example, in 2005 the National Aeronautics and Space Administration (NASA) of the United States sponsored more than 30 research projects to evolve and develop the Sensor Web technology through its Advanced Information System Technology (AIST) program. Through those research projects, dozens of applications have been developed in various societal benefit areas of Earth Observation, such as land-use change, ecosystem dynamics, disaster monitoring and assessment, agricultural production and sustainability, biodiversity, weather, climate variability/change, and public health [6]. Through its efforts in CEOS, the National Space Agency Ukraine (NSAU) has also made many contributions to Sensor Web. In addition, the Global Earth Observation System of Systems (GEOSS) implementation task AR-09-02 is incorporating the Sensor Web technology into GEOSS [4].

Standards are one of the keys in realizing the Sensor Web concept as they facilitate the open interoperability of components of the Sensor Web. The Technical Committee 211 of the International Organization for Standardization (ISO TC 211) has been actively developing international standards related to the Sensor Web, such as ISO 19130 and ISO 19130 Part 2: Geographic information—Imagery sensor models for geopositioning, ISO 19115 and ISO 19115-2: Geographic information—Metadata, and ISO 19159 Geographic information—Calibration and validation of remote sensing imagery sensors and data. The Open Geospatial Consortium (OGC) has developed a suite of Sensor Web Enablement (SWE) specifications [7], including Observations and Measurements (O&M), Sensor Model Language (SensorML), Sensor Observation Service (SOS), and Sensor Planning Service (SPS). These standards and specifications have laid the foundation for the implementation of the Earth Observation Sensor Web.

This special issue summarizes the progress made thus far and explores some new horizons in this very active field of research—the Earth Observation Sensor Web. It covers the recent developments in technology, system architecture, implementation of standards, and real-world applications of the Sensor Web concept. This special issue, to our knowledge, is the first of its kind in an academic journal, and represents the "coming of age" of this technical area. The papers in this special issue are grouped into three general categories, as follows, with some overlap among them:

- Sensor Web technologies;
- Sensor Web concept, system architecture and integration;
- Sensor Web applications.

The papers are presented in the following sequence. The first five papers address recent technology advances in the Sensor Web. The first paper, by Chen *et al.*, discusses the interoperable, standard-based technology for automatically feeding multi-source sensor data into Earth system models. The technology has been demonstrated on the AutoChem atmospheric composition model. A Sensor Web system will integrate data from multiple sources. Therefore, making data from those sensors comparable is one of the key enabling technologies of the Earth Observation Sensor Web. The second paper, by Williams *et al.*, presents a method for calibration and validation of Earth-observing sensors using a deployable surface-based sensor network. In a Sensor Web system, the sensors, processing and analysis functions, and models work together to fulfil a specific task. The coordination among those resources is important for a functional Sensor Web system. The third paper, by Yu *et al.*, discusses the resource coordination through the geospatial web service workflows. Autonomy is an important feature of the Sensor Web. In an autonomous Sensor Web, a group of static and mobile sensors can function in a coordinated and self-organizational way to achieve the overall task objectives. The fourth paper, by Talukder *et al.*, discusses novel adaptive control optimization algorithms for dynamic adaptation, coordinated control, and end-to-end resource management. The resulting distributed heterogeneous sensing system, with both static sensors and mobile robots, responds to detected events to achieve overall system goals and objectives. The fifth paper, by Durbha *et al.*, describes the development of standards-based middleware and tools for sharing the data from coastal buoys and stations. The project points to a key aspect of the Sensor Web concept in lowering the barriers to end-users data access.

The next group of four papers covers the Sensor Web concepts, system architecture, and integration. The first one, by Tian *et al.*, discusses a middleware-based, message-driven integration paradigm for enabling multi-way interactions between Earth observing sensors, sensor networks, Earth science models, and decision support systems. The paradigm has been implemented in the Land Information Sensor Web (LISW). The second paper, by Teillet, discusses the advanced concept of Earth Observation Sensor Web and presents the future direction of Sensor Web development. The third paper, by Garay and Burl, describes the Adaptive Sky, an algorithm package to dynamically fuse the observations from multiple sensing

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assets of a monitoring Sensor Web, so as to produce novel data products. Adaptive Sky is a toolbox enabling the Sensor Web to provide a unified perspective of an event or phenomenon under study. A case study on the Bezymianny Volcano on the remote Kamchatka Peninsula on 14 October 2007 demonstrates the capability of the Adaptive Sky. The last paper in this group, by Benedetti *et al.*, discusses the use of wireless sensor networks (WSNs) at the local level as the means for Earth observation, and reviews some innovative implementations of WSN architectures for Earth observation purposes.

The topics covered by the final set of five papers are related to the Sensor Web applications. The first paper, by Bradley *et al.*, describes the integration of images from *in situ* WebCam and satellite remote sensors with diverse spatial scales for the environmental monitoring on Santa Cruz Island in Channel Islands National Park off the California coast. The second paper, by Howe *et al.*, presents an application of Sensor Web in ocean observation. The Sensor Web is composed of both mobile and fixed underwater *in situ* ocean sensing assets and Earth Observing System satellite sensors providing large-scale sensing. The *in situ* sensors communicate through an acoustic communications network, facilitating adaptive sampling and calibration. The third paper, by Moghaddam *et al.*, discusses a soil moisture Sensor Web to serve as an adaptable calibration test site to meet the measurement validation objectives of space-borne soil moisture sensors. Such *in situ* measurements acquired through the intelligent wireless Sensor Web can potentially be used in the validation of products from the Soil Moisture Active/Passive (SMAP) mission of NASA. The next paper, by Tschudi *et al.*, discusses a method for tracking the movement and monitoring the changing surface characteristics of Arctic sea ice by an integrated analysis of multi-sensor satellite remote sensing data. The final paper of this special issue, by Song *et al.*, is an application of Sensor Web to volcano monitoring and hazard mitigation. This paper describes an optimized autonomous Sensor Web which is composed of both *in situ* and space sensing assets. The *in situ* sensors are deployed into the craters and around the flanks of Mount St. Helens. The Sensor Web detects events, and requests for space-based observations are automatically linked to the command and control of the NASA Earth Observing One (EO-1) satellite.

The papers in this special issue not only show that Sensor Web is an active and vibrant research area but also that the research is beginning to make a real impact in society through real-world applications. We hope that this special issue provides a beneficial overview of recent progress on Earth Observation Sensor Web research. As the technology continues to mature, the Sensor Web vision will enable global Earth observing systems to autonomously interoperate, resulting in improved forecasts, event monitoring, and disaster response. The goal of this issue is to stimulate interest and further work in this promising technology research area.

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