The JPL Sensor Webs Project: Fielded Technology

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Abstract

As defined in the NASA Tech Brief [1]*, the Sensor Web is a dynamic infrastructure for sensors that provides a pervasive, continuous, embedded monitoring presence. By synthesizing information collected over large spatial areas, the Sensor Web obtains an environmental self-awareness. This innovation will revolutionize the way we explore, monitor, and control environments and will impact such diverse areas as planetary preservation, spacecraft infrastructure, and extraterrestrial exploration.*

The Sensor Web is unique since data gathered by one pod are both shared and used by other pods. Sharply contrasting typical sensor networks, a Sensor Web does not purposefully route or focus information towards the end-user. Consequently, each sensor pod matters to all its neighbors resulting in a global perception and purpose for the instrument as a whole (unlike in a simple distributed network). Since there is no distinction between instructions originating from either the end-users or other pods within the system, the Sensor Web is both a field-programmable and self-adapting instrument.

This paper will focus on various systems that have been deployed in a variety of environments including Antarctica, the Florida coast, Southern California, and a simulated Rain Forrest. Real-time, streaming data from several of these deployments may be viewed at http://sensorwebs.jpl.nasa.gov*. Opportunities for infusing this technology into future mission planning will be discussed.*

1. Introduction

In its most general description [2], the Sensor Web is a macro-instrument that allows for the spatio-temporal understanding of an environment through coordinated efforts between multiple numbers and types of sensor platforms. These platforms, or pods, can be orbital or terrestrial, as well as fixed or mobile. Each pod contains one or more sensors and communicates (usually wirelessly) within its local neighborhood, thereby distributing information throughout the instrument as a whole. Specific portal pods provide end-user access points for command and information flow. Much as intelligence in the brain results from the myriad of connections between dendrites, the Sensor Web derives greater functionality from a parallel-type architecture as sensor data are passed and locally interpreted on the fly, from pod to pod. The ultimate goal of a Sensor Web is to extract knowledge from the data collected and intelligently react and adapt accordingly.

To explore this vision, the JPL Sensor Webs Project has focused almost exclusively on *in situ* Sensor Webs, primarily terrestrial. Although initial generations of the Sensor Web pods were tested in either laboratory or controlled environments (such as greenhouses), more recent prototypes have been given directly to end-user collaborators and have been tested under a variety of demanding environments.

2. Basic Sensor Web Concepts

Typical sensor use involves placing a single transducer in an environment to monitor and record a particular aspect of it, as shown schematically in Figure 1. While the resolution of the phenomena may be spectacular, there is little information regarding the general nature of the dynamics associated with the phenomena, save that it took place at a specific place and at a specific time. Moreover, there is no way for the sensor to anticipate its environment. Consider instead the arrangement of sensors shown in Figure 2. Here, cheaper sensors are

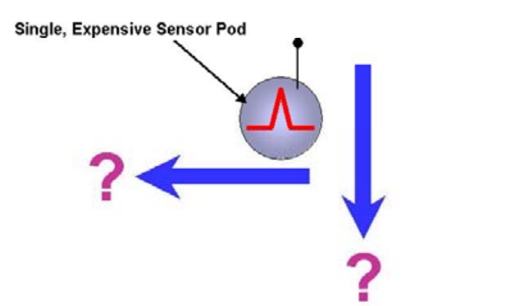

Figure 1. A single sensor does not give any information about spatio-temporal dynamics.

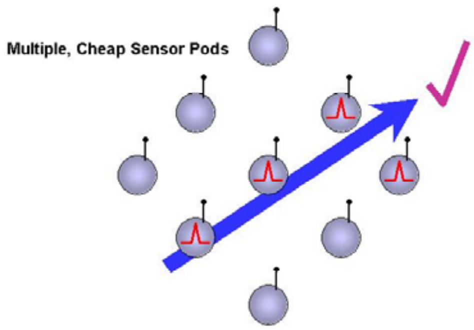

Figure 2. Multiple sensors provide lower resolution but more data and thus can yield sophisticated results.

used with a presumed reduction in measurement fidelity. Nevertheless, by correlating these measurements over space and time, it now becomes possible to extract spatio-temporal dynamics associated with a phenomenon. As a result, these cheaper sensors, correctly configured, can provide a different type of information altogether. This is the essence of a Sensor Web.

Sensor Webs provide a practical large-scale environmental presence with the precision of an *in situ* measurement. They are not a replacement for remote observation techniques (i.e. aircraft or satellite) nor rover technologies. Rather, Sensor Webs are a unique new way to monitor the environment and can provide data in ways that these other techniques cannot [2]. For example, neither remote nor rover operations can provide a continual, virtual presence simultaneously maintained over a large area (geosynchronous orbits provide an interesting, but limited, exception). Moreover, Sensor Webs can augment and work with other technologies. Obvious examples include ground-to-sky monitoring capabilities and omni-present intelligent direction for rover movements.

Sensor Webs are made economically practical by the present revolutions in computation and telecommunication hardware. The requirements for today's computers and cellular telephones are so complex that the only possible way to develop these technologies at all is to sell them to a mass market and rely on the economy of scale to provide the necessary financial capital for the next round of development. As a result, mass-produced, commercially available components often represent the state-of-the-art. This is in marked contrast to previous times where the state-of-the-art was represented almost exclusively in government, military, or university laboratories. Today, for example, hardware is so inexpensive that telephone companies will deeply discount, or even give away, cellular phones in anticipation of recouping the costs via telephone service.

3. Deployments

Early generations of Sensor Webs are documented elsewhere [3,4]. While both Sensor Webs 1.0 and 2.0 were technological advancements in their own right, Sensor Webs of the third generation were designed to not only provide increased capabilities but also to be handled by end-users directly. As a result, these pods were constructed for rough handling and rough environments. In addition, these Sensor Webs would report out to the Internet via a browser GUI for a simple, yet effective, data display (see Figure 3).

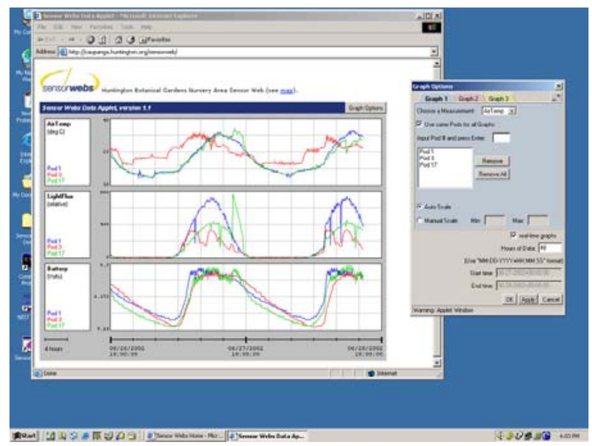

Figure 3. Browser-based GUI for Sensor Web as it appears on the desktop.

A listing of our Sensor Web deployments is found at sensorwebs.jpl.nasa.gov/resources/applications.shtml. In addition to the latest information on these deployment, the real-time streaming conditions of several of the sites is available. Some recent highlights are listed below.

3.1. Huntington Gardens, San Marino, CA

Sensor Webs have been at the Huntington Botanical Gardens since June 2000 and continue to remain a significant test site for Sensor Web technology [2]. Sensor Web 3.0 was deployed in October 2001 in the nursery area and remained there until August 2002 when it was replaced by Sensor Web 3.1. Canonical environmental variables measured by the pods include light levels, air temperature, and air humidity in 5 minute intervals.

The deployment of Sensor Web 3.1 occurred in two stages. Pods 0 (the mother or portal pod) through 11 were deployed in August 2002. The purpose of this initial deployment was merely to string the pods out over a large area and determine the robustness of the connectivity. It typically took 4 or 5 hops for the data from pod 4 to pod 2, the extreme points on the network at

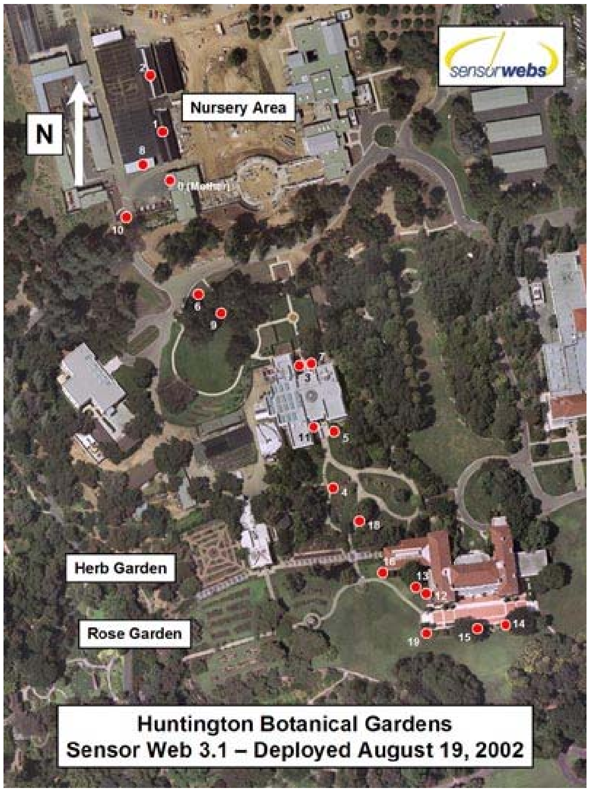

Figure 4. Huntington Garden Sensor Web deployment.

Figure 5. Pod 15 at the Huntington Gardens. Note the right antenna is chewed. The two subterranean probes measure soil temperature and soil moisture.

that time. (Local, short-duration hardware tests at JPL have demonstrated as many as 11 hops.) The second stage was deployed in late January 2003. Unlike the first stage, this deployment was performed with the close cooperation of the Huntington staff to help monitor key areas of interest. As a result, the pod placement is more

Figure 6. Sensor Web pod in front of Shuttle.

confined. As anticipated by the Sensor Web protocol design, the second set of pods seamlessly integrated with the first set and the new 19-pod system unified within a few measurement cycles. This was the second demonstration of augmenting an existing and functioning Sensor Web deployment, the first occurred at Lancaster Farms in the spring of 2002.

As shown in Figure 4, this Sensor Web extends over a large swatch of the gardens and is not protected in any special way. Figure 5 shows pod 15 with an antenna chewed, possibly from either a bird or coyote. Such abuse has not yet interrupted pod functionality.

Several of these pods (6, 12, 13, 14, and 15) measure soil temperature and moisture with modular subterranean probes. Rains in February 2003 have shown the surprising differences in these properties even on scales of a meter. This again points to using Sensor Webs for providing spatial resolution that is unattainable from most remote measurements.

Other agriculture or garden-like sites, such as Lancaster Farms in Suffolk, VA and a lettuce patch in Pomona, CA are documented elsewhere [2]. In particular, the Sensor Web 3.0 at Lancaster Farms has been operational since October 2001 and continues to demonstrate the inherent robustness of the system.

3.2. Kennedy Space Center, FL

A Sensor Web was deployed within 1/4 mile of an active launch pad for the Space Shuttle (39A) in July 2002 (Figure 6). The Sensor Web had to undergo a

Figure 7. Simulated rainforest greenhouse with misters off.

Figure 8. Pod hidden deep under the rainforest canopy.

serious of rigorous spectrum tests because of its proximity to the launch site. FCC compliance was demonstrated on all accounts. In fact, the Sensor Web operates in an open channel at approximately 916 MHz and is not intrusive on other radio communication. The Florida coast environment, with its humidity and salt air , has not been able to penetrate the Sensor Web packaging to date.

3.3 Rainforest Greenhouse, Pomona, CA

In collaboration with Cal Poly Pomona, we have outfitted a greenhouse that simulates a rainforest with a Sensor Web 3.1 system. This environment is extremely moist with misters running on a controlled basis (Figure 7). Moreover, as the thick canopy grows, the light levels available for energy harvesting for pods at ground level drops precipitously.

The deployment took place in September 2002 and continues to run. Real-time, streaming data from this site

Figure 9. Pod deployment in Antarctica. Note another pod in snowmobile in lower right portion of picture.

may be viewed on the Internet at the Sensor Webs Project homepage. To date, there has been no problem with moisture leaking into the sealed pods. A few pods have had to have their batteries recharged as a result of the dim light (Figure 8). Nonetheless, we estimate that pods in this configuration can run for several months without any energy harvesting at all.

3.4 Antarctica

In cooperation with researchers hunting for meteorites in Antarctica [5], a Sensor Web was deployed on the East Antarctic Icesheet [6]. International treaty prevents leaving equipment in the remote fields unattended and consequently this deployment was limited to 3 weeks starting in December 2002. Nevertheless, the Sensor Web would have to prove itself in an extreme test environment with low-temperatures, constant wind, and dry air.

The deployment was a test of the system in preparation for extended studies of biological activities in cryogenic environments. The Sensor Web is an ideal instrument for such studies because the more hostile the conditions, the more widely distributed biological blooms will be in both time and space. The continual monitoring presence of the Sensor Web, coupled with its capabilities to react to the changing conditions, overcome inherent monitoring concerns.

The 14 pod Sensor Web was distributed about the home base site over a distance of 2 km (Figure 9). Typical temperatures over the deployment were lower than –10 C with extremes below –20 C. The system not only performed well under the harsh, dry conditions, but also was easy to set up by the researchers (as is often the case, no members of the Sensor Web team assisted in the actual deployment). Under severe weather conditions,

Figure 10. Pods have also been extensively tested in snowy environments.

such issues are critical for mission success. In addition, the pods were also extensively tested in snowy conditions (Figure 10).

4. The Future

The Sensor Web has proven itself robust, both electrically and mechanically, in a number of terrestrial environments, including extreme heat, cold, and coastal conditions. We are currently working on command and control issues using the Sensor Web as the information management infrastructure.

The system should be considered as a serious component of any environmental monitoring mission, both robotic or manned. The core technology developed for terrestrial applications is translatable for extraterrestrial ones. Typical deployment issues have been discussed elsewhere [3]. In addition, Sensor Webs can also play a role on the Space Station providing global monitoring and control of the habitat.

In designing a Sensor Web application, the end-user must consider a variety of experimental issues as a Sensor Web is no more a universal technology than a satellite. A series of checklist questions to help scope an end-user's thinking has been published [3] and an interactive website based on this checklist is available [7].

5. Acknowledgements

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