A Web of Sensors: Enabling the Earth Science Vision

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Abstract—**Highly coordinated observations and autonomous decision-making are needed to improve our ability to detect, monitor, and predict weather; climate; and the onset of certain natural hazards. The 'sensorweb' concept has been proposed as a potential solution to this requirement. This paper presents two candidate uses for the concept, describes its capabilities and unique architectural properties, and outlines challenges to overcome for successful development of a sensorweb architecture. The conclusion proposes that the primary challenge to implementation of sensorwebs—beyond the obvious technical obstacles—will be our ability to develop and execute a long-term strategy that provides for the deployment of a series of compatible missions that deliver the full promise of envisioned sensorweb capabilities.**

INTRODUCTION

Socio-economic benefits are a primary driver for the National Aeronautics and Space Administration (NASA) Earth Science (ES) Enterprise vision for the year 2025. Scientific knowledge and technologies that enable routine prediction of weather, climate, and prediction of the onset of certain natural hazards produce direct economic benefits to the public, industry, and to federal; state; and local governments [1]. Weather and climate forecasts provide advance indication of winds; temperature; precipitation; clouds; humidity; and air quality, and we depend on these data to plan our travel, tourism, and leisure and work activities on a daily basis. In addition, a large segment of our economy includes industries–such as farming, airlines, and gas; electric; and water utilities–that are affected by climate and thus rely on reliable forecasts to manage their short- and long-term operations. Likewise, information about the onset and severity of hurricanes, tornadoes, floods, droughts, thunder and winter storms, forest fires, earthquakes, and volcano eruptions would allow communities and government agencies to prepare for impending hazards and to manage relief efforts such that loss of life and property is mitigated and scarce resources are effectively utilized.

VALUE OF SENSORWEBS FOR ES

The sensorweb concept proposed by NASA [2] defines a virtual organization of multiple numbers and types of sensors combined into an intelligent 'macro instrument' in which information collected by any one sensor can be used by any other sensor in the web, as necessary to accomplish a coordinated observing mission [3]. This web configuration allows inter-system collaboration not possible with stand-alone sensors and thus provides the foundation needed to develop systems capable of adaptive behaviors. As the technology matures, sensorweb-observing systems could be combined with software 'agents' [4] that perform real-time analysis and decision-making to implement advanced sensorweb-enabled systems that autonomously execute complex adaptive observing strategies.

Preliminary work in this emerging field suggests that autonomous sensorwebs have potential to improve the performance of weather and climate predictive systems such that the useful range of forecasts would be extended. Also, sensorwebs could perform focused observations needed to predict, detect, and monitor the development and effects of certain natural hazards. The value of sensorweb capabilities in these predictive scenarios is illustrated by the two examples described below.

Advanced Weather Forecasting

Fundamental weather forecasting improvements could be achieved by an architecture that exploits the adaptive capabilities of the sensorweb concept [5]. By introducing a feedback path between a forecast model and a sensorweb-based observing system, *future observations* could be tailored to the specific data acquisition needs identified by the forecast model. For example, a simple implementation of this 'control loop' could direct changes to the types and schedules of data collections, or engage additional assets / sensors to observing at locations where perceived needs are greatest, and where greatest forecast impacts from those data are likely to be realized. The specific observing strategy implementation might be driven by where and when a model predicts rapid significant future development, by where the model forecast shows greatest uncertainty, or by where observations reported real-time from the sensorweb reveal deficiencies in model performance. These approaches apply the flexibility of the sensorweb to enable observing strategies that produce special data sets *when and where it makes sense* to have the highest impact on the forecast model run.

Hazard Prediction, Detection, and Monitoring

Sensorweb-enabled observations linked with predictive models could drive decision-support systems to provide reliable warnings of the onset of certain natural hazards. Additionally, such systems could perform monitoring of events to provide real-time updates needed to guide rescue and relief efforts in affected areas. A similar approach is being implemented by OK-FIRST, an existing decision-support system that gathers real-time data from federal and statewide sources via the Internet and presents it to Oklahoma-state officials who evaluate impending hazards and issue warnings [6]. Since its inception, OK-FIRST has allowed safety officials to take preemptive actions that saved lives.

Sensorweb-based warning systems could predict the likelihood of events, estimate and convey the expected effects of events before they develop, and monitor developments to provide real-time updates. Such information would help communities make preparations and guide planners to take actions such as evacuations. A more advanced application would provide forecasts and real-time assessment of the accessibility of areas (e.g. condition of highways, bridges, and waterways) to help planners direct relief efforts that involve delivery of personnel, equipment, and supplies to affected areas.

SENSORWEB CAPABILITIES

The ES Vision proposes notional observing scenarios where sensorweb capabilities enable a unique set of observing behaviors. Knowledge of distinctive system capabilities is the first step towards defining the range of science and technology advancements needed to implement sensorweb architectures. According to proposed ES Vision scenarios, an advanced sensorweb system would display the following behaviors:

1) Autonomously implements interactive observing strategies. It responds to both the 'observed environment' and its 'internal state' (e.g. as depicted within a model simulation). Executes opportunistic and routine observations in response to seasonal or event triggers, or when directed by decision-making components linked to the observing system.

2) Collaborates at the subsystem level to manage system-level resources and its overall configuration. This includes taking actions such as reconfiguration, temporary binding and retirement of assets, allocation of bandwidth, management of consumables, and maintenance of power and thermal balance.

3) Is aware of what sensors and resources (e.g. processors and databases) are connected, or available for connection to the sensorweb. Further, it has knowledge of the 'state' of connected assets and can direct them.

4) Will dynamically acquire unique resources as needed to perform tasks. This could be processor time, archived data sets or knowledge, and sensors. In addition, it can initiate the generation of data products needed to perform decision-making tasks.

5) Performs secondary system tasks unattended by humans. This includes navigation, formation flying and maneuvering, enforcement of system constraints, self-maintenance (e.g. graceful degradation and repairs), and safing.

UNIQUE ARCHITECTURAL PROPERTIES

The basic infrastructure needed for the sensorweb architecture (e.g. autonomy, collaboration, and distributed assets) has already been identified for formation-flying systems [4]. However, sensorwebs expand the formation-flying concept to include unique properties that are described below.

Autonomy

The goal of autonomy is to enable systems that operate without human intervention for extended periods in dynamic environments [7]. Such an environment is characterized by uncertainty, which can be systemic (e.g. component failures) or environmental (e.g. changes in the phenomenon). For both cases, the fundamental requirement is complex decision making without human intervention. In formation-flying architectures, automation is applied to implement planning and scheduling based on high-level goals, and to perform ancillary system functions [4]. The *sensorweb architecture duplicates these functions but adds an additional requirement: to enable decisions that involve selecting one of several possible high-level goals.* This property applies to sensorweb systems with assets that can be used to generate more than one data set (i.e. research or applications measurements). The 'intelligence' capability of advanced sensorwebs must deal with uncertainty, react adaptively to changing circumstances, but most importantly, must recognize and exploit opportunities to apply its resources to alternative top-level goals while avoiding conflicts.

Heterogeneity

Formation flying systems have well defined configurations; sensorwebs must dynamically accommodate a diverse combination of hardware and software components. At the macroscopic level, these components can be other sensorwebs or platforms that host instruments on the ground; sea; air; and space. At the microscopic level they are a wide variety of subsystems such as detectors, platform sensors and actuators, auxiliary electro-mechanical subsystems, embedded analog and digital processors, and control and data processing software [4]. System collaboration requires that assets and components communicate to share information that may include science and engineering data, data products, commands, and telemetry. In some cases, data fusion will be required to perform decision-making tasks. *The sensorweb architecture must provide standard languages, policies, and protocols that enable transparent communication across layers of a system, as well as across systems.*

Scalability

Unlike typical formation-flying designs, sensorwebs are by definition dynamic structures (e.g. additional wind-measurement sensors may be added only during hurricane season). *The sensorweb architecture must support incremental addition and retirement of assets while providing commensurate levels of functional performance.* Scalability enables the system to expand or contract with consistency and provides the flexibility needed for dynamic reconfiguration of the web (e.g. attach and release assets on a permanent or temporary basis). In addition to new sensors, assets may include processing or communications components that can be shared to enhance the performance of the system.

Human-Interface Consistency

Significant human-interface issues must be resolved, most likely by extensive use of visualizations. *The challenge is to develop a human interface that provides a consistent picture across all the layers and components of the architecture; some that are physical (e.g. inter-platform data paths), others logical (e.g. collective behavior of assets in response to decision making).* The architecture's interface must decompose the complexity of the system while providing human operators with a consistent view that integrates the reasoning layers, inter-system interactions, and system components down to the subsystem level. In addition, the interface's rendition must be dynamic so that it maintains and presents to the operators a view that reflects the web's configuration. These interface properties are crucial for circumstances that require humans to diagnose and resolve system problems or failures.

SENSORWEB DEPLOYMENT CHALLENGES

To reap the full benefits of this technology our understanding of how to apply the concept's capabilities in ways that provide value to ES Enterprise constituents has to develop. Specifically, forecast data—hazard warnings in particular—must be presented to communities and decision-makers in ways that help them use the information correctly to generate positive value.

As with any emerging technology, a research and development curve must be traversed to make sensorwebs viable. For instance, we need to learn how specific research and application areas will benefit from sensorweb-enabled observations, and how to apply the concept's 'intelligence' to optimize various observing tasks that can be shared by one sensorweb while avoiding conflicts. Finally, the most complex technologies (e.g. intelligent agents) must be developed and proven before they are adopted and become fully operational.

Advanced capabilities such as autonomy and inter-system collaboration require compatibility of components at all levels. Successful development of technologies needed to implement sensorweb architectures would benefit from an integrated systems approach that coordinates the development of architecture-related standards and components across technical disciplines.

Construction of sensorweb systems will require incremental deployment of assets that serve a stand-alone purpose when deployed and can be subsequently connected to the web by an intelligence layer. On a grand scale, sensorweb connections could involve the use of inter-agency and international platforms that are shared to collaborate for certain tasks. International participation will require deliberation of topics related to inter-operability standards, intellectual property rights, and technology transfer. Such topics will emerge as we begin to jointly develop the highly integrated systems needed for autonomous collaboration.

CONCLUSION

The deployment challenges presented above suggest that to successfully develop sensorweb systems, NASA must craft and execute a strategy that defines a *long-term systems migration pathway* that allows incremental deployment and connection of assets across the full range of sensorweb-capable ES missions. At the technical level this will include developments such as new standards that ensure homogeneity of the architecture. For the programmatic level this could involve a review of how well our current mission planning, selection, and procurement practices could support this new approach. Finally, at the inter-agency and international level, this will require new levels of commitment from all parties.

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REFERENCES

[1] R. A. Williamson, H. R. Herzfeld, J. Cordes, and J. M Logsdon. "The Socioeconomic Benefits of Earth Science and Applications Research: Reducing the Risk and Costs of Natural Disasters," *Space Policy,* Vol. 8, Number 1, February 2002, pp 57-65.

[2] NASA Headquarters Press Release 00-65, "NASA developing space–based 'Sensor Web'–an Internet for Earth Observing satellites*,"* April 25, 2000.

[3] L. Lemmerman, et al. "Earth Science Vision: Platform Technology Challenges." IEEE Geoscience and Remote Sensing Symposium (IGARSS), Sydney, Australia, June 2001.

[4] C. C. Chao, E. T. Campbell, D. J. Dichmann, R. A. Gick and G. E. Peterson. "Distributed Spacecraft Vision for NASA/GSFC Earth and Space Science Missions." Aerospace Report No. TOR-2001(2131)-3. The Aerospace Co., September 2001, pp 8-13, 55-56.

[5] M. W. Kalb et al., "Advanced Weather Prediction Technologies: NASA's Contribution to the Operational Agencies," unpublished. A study report prepared for NASA's Earth Science Technology Office, March 2002.

[6] OK-FIRST, State of Oklahoma. "Early Warning of Severe Weather Saves Lives." Government Executive Magazine, January 2002, p. 26.

[7] B. Hine and D. Clancy. "The Role of Information Technology in Human Space Exploration," unpublished white paper. NASA Ames Research Center, 2001.