Adaptation and Re-configuration in the Global Sensor Web

Andrew Gray, Payman Arabshahi, Warren Fox, Sumit Roy, Yi Chao, Bruce Howe

Summary

The following provides the motivation for the design and operation of an adaptive global sensor web:

> *"Our planet is changing on all spatial and temporal scales. The purpose of NASA's Earth science program is to develop a scientific understanding of Earth's system and its response to natural or human-induced changes, and to improve prediction of climate, weather, and natural hazards."*

Under this vision, and the deployment of the Earth Observing System, NASA has moved from designing single science missions to architecting and implementing operational sensor webs. This sensor web is in reality a science *campaign*, an *open system* composed of complex inter-related investments. In addition, the sensor web concept incorporates large heterogeneity in sensor type and period of design and operation. The design of such an evolvable campaign architecture, which can be modeled as a sequence of investments (missions or experiments) over time, is significantly different from that of a single investment. In the case of sequenced sensor web design and operation, one must pay attention to the facts that new information about the environment are obtained almost continuously, and various components of the sensor web design and implementation may be separated by days, years, or even decades. Under such a scenario there is significant motivation for the incorporation of flexibility and adaptability into the design, across varying time scales, and at various *levels* of the sensor web architecture. These levels range from individual *sensors* (e.g. adaptive antennas or lenses), to *sensor platforms* (e.g. orbits of spacecraft), *sensor networks*, and *sensor web architecture* configurations (e.g. number and type of sensor networks in the aggregate web).

Adaptability in the sensor web campaign is motivated by the fundamental nature of science. Its characteristics vary considerably with issues such as rate of change, magnitude of change, scale of change, global versus regional coverage, etc. Adaptability comes at a cost as well. Thus a sensor web design framework should be able to model the value and cost of competing adaptation investments in order to determine the approach – *portfolio of investments* – that maximizes science return-on-investment. Such a framework is feasible if it's based on a variety of principles from analytical decision science, in particular sequential decision-making under uncertainty, operations research, industrial engineering, economics, and computer science. In summary, the primary goal of the framework is to act as a tool for (adaptive) sensor web campaign design – a tool that is scalable to design adaptive operations at the sensor, platform, and network levels to achieve various spatial and temporal resolutions of a variety of sensor types.

1 Introduction

The traditional approach to sensor web design and operation has several shortcomings from the perspective of sensor web *campaign* design and operation. First, even when designing a series of missions (or experiments), the typical approach optimizes one mission (experiment) at a time. This ignores the fact that the optimal choice for the first mission depends on the options available for subsequent missions, as well as their (probabilistic) outcomes. Second, the approach typically uses one of two comparison techniques: either setting requirements and comparing the cost of various design options; or setting a cost cap, and comparing the performance of various mission options. But even when designed to meet the same requirements, several design options often have different performance characteristics. More importantly, they often open up different options for the next mission in the campaign (for example, through technology feed-forward). Finally, the traditional approach does not explicitly and comprehensively take uncertainties into account. When considering design options for a second (N^{th}) mission in a sensor web campaign, it assumes a deterministic set of results from the first mission (missions 1 through (N – 1)). When viewed from the initial design phase however, the results of each mission are probabilistic. The mission could fail; it could be moderately successful; it could discover the unexpected, etc. Consider Fig. 1 from the perspective of period one, which in reality could be any point in a multi-minute/day/year sensor web campaign design; during each subsequent period an investment is made in a sensor web mission (or experiment), each with probabilistic outcomes. When designing a mission in period one, future missions (outcomes) should be considered to the extent that they can be modeled. By incorporating appropriate flexibility into the first mission, follow-on investments can be made more effectively.

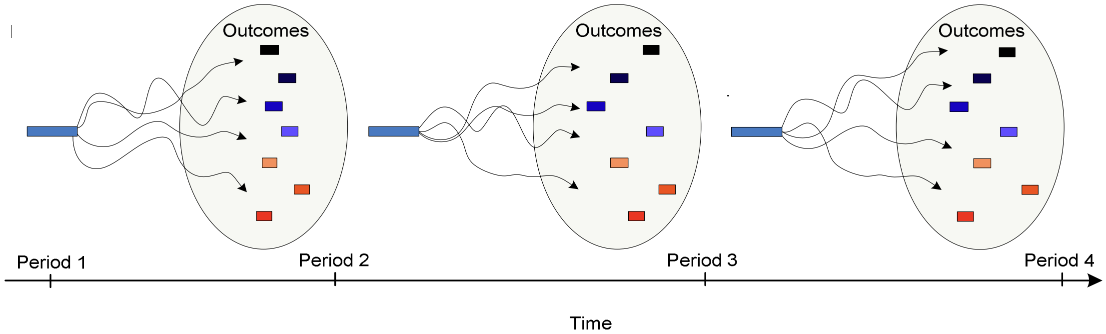

Figure 1: Sensor web campaign model: a sequence of investments and probabilistic outcomes

What the sensor web designer needs to select, is not one option for a mission design, but instead a *strategy*, i.e. a sequence of options corresponding to possible outcomes of the first and subsequent missions. The probability of each of these possible outcomes should influence the investment/design decisions. Adaptability, be it in the sensor, platform, system, or some combination of these, can provide the flexibility required for realizing these options. Adaptability can occur via manual intervention by human operators, or autonomously (e.g. with autonomous software), or via a hybrid of the two. Similarly control can be de-centralized (in-situ, on individual platforms, or even individual sensors) or centralized, or use a combination of both. The latter option is in itself a significant engineering design challenge.

The remainder of this white paper outlines the *nature of uncertainty* and *models of adaptability*, and provides a sensor network example and campaign example for more detailed context. The outline of a generalized and scalable *sensor web design framework* is then provided.

2 Nature of Uncertainty: The Drivers of Adaptability

From a high level the levels of uncertainty from nature fall into the following categories [1]:

A. Intra-Seasonal Climate
B. Extreme Weather – Tropical Storms
C. Changes in Sea Level
D. Earthquakes
E. The Availability of Water
F. Biosphere-Climate Interactions and Human Influences

Other uncertainties from economic and technical factors include:

A. Science model development (integration of information from the categories above)
B. Technical mission performance
C. Schedule
D. Cost

Each of these categories can be characterized in terms of statistics (e.g. likelihood of change) for a given period, and the period of change – which might also be characterized statistically (e.g. could include piecewise correlated science changes, or humans' ability to grapple with the science and propose experiments).

3 Models of Adaptability

The adaptability can occur at various levels in the sensor web:

- The sensor level, for example hyper-spectral imager, photon collector, etc.
- The sensor platform level, seaglider, spacecraft, etc.
- The sensor network level, configuration of multiple like sensors or platforms, network of seagliders, formation of spacecraft, etc.
- The sensor web architecture level, configuration of significant sensor web systems and operations, numbers and types of networks, information handling systems, overall operations.

Figure 2 provides an overview of the levels. An evolution in a lower level may, and often does, result in an evolution at the higher levels. For example, changes at the sensor level may result in a change in the sensor web architecture. An evolution in a higher level does not *necessarily* require a change in the lower levels.

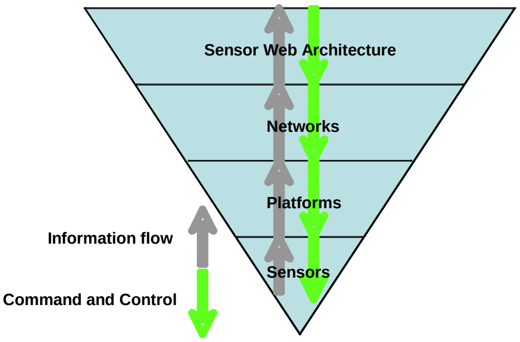

Figure 2: Levels of a sensor web

Figure 3 illustrates a very simple model of adaptability in a sensor web. The changes can occur due to operators of the web (using any source of information for the change), or can occur based on sensor input from somewhere within the sensor web, and may be autonomous. The changes can occur at any level theoretically, or at multiple levels, and the time scale for adapting the sensor web can range from sub-seconds (e.g. sensor level adaptability such as bandwidth in front of a spectrometer), to decades (e.g. architectural changes such as number of spacecraft).

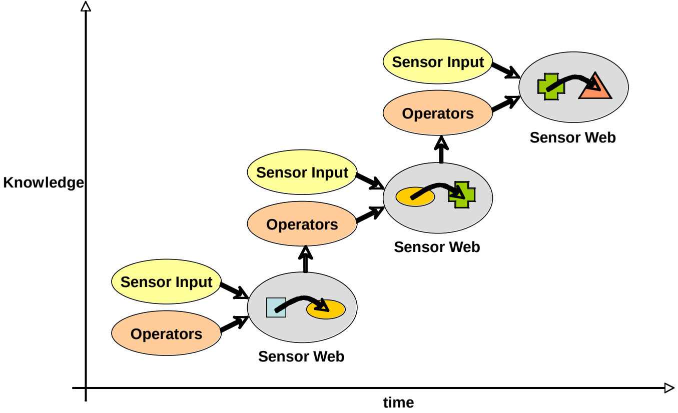

Figure 3: Model of adaptability

An adaptive sensor web as illustrated in Fig. 3 can be characterized by its:

- Ability to determine the drivers of change/evolution (environmental sensing input, or operator input, or both)
    - Determined locally, remotely, or both
- Infrastructure to implement the evolution (*command*, *control*, and *communication*)
    - A trade between local intelligence and communications, local intelligence and autonomy, or remote intelligence with very good communications.

    - The nature of the sensor web is such that the whole is greater than the sum of its (localized) platforms. This would imply certain centralized intelligence, communicating the control for reconfiguration to elements in the web.
- Flexibility at all levels: sensor adaptability, platform adaptability, network adaptability (including adaptable communications networks), and architecture adaptability (new platforms or networks, reconfiguration of platform locations, etc.).

4 Examples

4.1 Design of a Single Sensor Network

One goal behind implementation of sensor networks is to gather some type of information and to transmit that information around and outside the network. The main assumption is that there are cost/benefit trade-offs in the number of sensors deployed (related to the total monetary cost of the system) and the arrangement of sensors in the environment (which might be dynamic) vs. the quality and quantity of information that can be obtained and the speed with which it can be obtained. Determining the optimal system configuration can be framed in terms of a multi-objective optimization problem, e.g., attempting to maximize the data collection capabilities of a system while minimizing its monetary cost. These multiple objectives are often competing (as in the given example), in which case there is no unique solution, but rather a set of solutions illustrating the various trade-offs involved. The situation may be complicated by constraints, such as the requirement that all nodes must be within communication range of at least one other node. Typically a compromise is reached in the design phase regarding system composition, and when the system is emplaced, optimization is performed on system performance metrics only.

An adaptive sensor network is one that can sense aspects of its environment that affect its performance, and can self-adjust to optimize performance and satisfy constraints, ideally as the environment changes. An example is a network of undersea vehicles whose goal is to map the sound speed properties of a volume of ocean while maintaining one-hop communications capability such that the sensed information can be transmitted outside the network. On one hand, the system can adjust its sampling pattern based on observed data, e.g., it can sample more finely in areas of higher observed spatial variability. However, since vertical sound speed structure is a key determining factor in sound propagation, and hence underwater acoustic communications performance, the observed sound speed data can be used in a model-based framework to ensure that updated sensor positioning satisfies the communications constraint. There are obviously many issues related to centralized vs. de-centralized control of the vehicles and communications latencies, but this type of *feedback loop* involving information extracted about the operating environment and optimization of sensing network performance while satisfying operating constraints is a key consideration for future sensing network design.

An example of a data driven and validated adaptive sensor network with two-way interactions between the sensor web and predictive models is outlined in Fig. 4. The semi-closed loop dynamic sensor web system shown here represents an integrated in-situ/space based Earth observation system, where data gathered locally by an underwater sensor network is fed back and combined in near real-time with global satellite data, appearing nearly instantaneously on scientist workstations. This data is then used to augment, calibrate, and fine tune measurements made from space, increasing their accuracy and timeliness. While satellite observations provide a global perspective, the underwater sensors provide a continuous 3D presence in the local water column. The sensor web data will be first assimilated into predictive models with a goal to fill in the gaps where and when there are no measurements, and to reduce uncertainties of the model simulation and predictions. The assimilated model will then be used to guide the future observing strategy (or adaptive sampling), thus closing the loop of an end-to-end autonomous sensor web from measurement to predictive modeling.

4.2 Design of a Sensor Web Campaign

Example design of a space exploration campaign can be found in [2]. In particular the design method incorporates sequential decision making under uncertainty via probabilistic modeling. The future is modeled as uncertain outcomes (Fig. 5(b)) as opposed to deterministic ones (Fig. 5(a)).

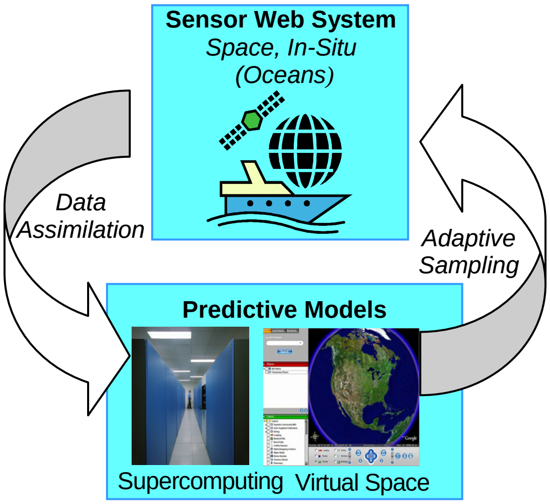

Figure 4: A semi-closed loop dynamic smart ocean sensor web architecture

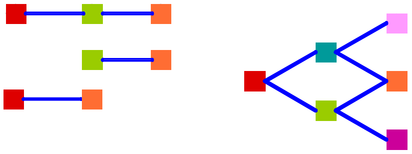
(a) (b)

Figure 5: Conceptual difference between traditional (a) and decision-analytic (b) approaches

One of the tools of this design approach is the Influence Diagram. This is a high level visual representation of a decision problem which is very useful in structuring extremely complex problems. From an influence diagram, a decision tree representation can be implemented and analyzed to determine: 1) the best campaign, for given assumptions – this is followed by a sensitivity analysis in order to determine the robustness of results, 2) the value of gathering further information, and 3) the value of flexibility/adaptability in the architecture. Finally, influence diagrams help define which information requires further uncertainty reduction, thus prioritizing the utilization of resources. Application of the framework is typically highly iterative and involves the steps discussed in [2]. It should be noted that this process may "live on" for the life of the campaign, providing new design iteration guidance and insight as the future unfolds with new information. One can readily apply the methodology discussed in [2] to design of sensor web campaigns.

5 Conclusions

The modern sensor web concept:

- Is characterized by heterogeneous sensor types and very large scale and scope of operation.
- Has very large dynamic range in period of design and operation.
- Can be modeled as a sequence of investments (missions or experiments) over time, with new information about the environment being obtained almost continuously and influencing how current sensors, platforms, sensor networks, and ultimately the aggregate sensor web operates, and how future ones should be designed and implemented.

Given these characteristics there is significant motivation for the incorporation of flexibility obtained via adaptability or reconfiguration into the design and operation of the sensor web across all levels of the architecture, and on varying time scales. The scale of adaptability being sought is unprecedented, and the development of feasible tools, approaches, and algorithms for designing and implementing these features in an integrated and consistent fashion represents significant challenges. The two examples in this paper represent varying ends of the spectrum. In the case of adaptive communications networks the adaptation is needed for real-time operation within the sensing environment to improve information infrastructure performance. This could presumably be implemented via a portfolio of algorithms in hardware and software. In the case of campaign design frameworks, the adaptation may be needed in the design of significant sensor investments (e.g. space missions) in order to maximize the science return on future investments, possibly separated by years or even decades. In this case the design and analysis is not in real time and may be performed periodically for the entire life of the campaign via program managers using a variety of software tools and the most recent sensor web data. Clearly much work is needed to perform analysis and design of flexibility in the sensor web in a systematic and comprehensive fashion.

References

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[2] E. Baker, E.L. Morse, A. Gray, and R. Easter, "Architecting space exploration campaigns: a decision analytic approach," *Proc. IEEE Aerospace Conference*, 4-11 March 2006.