

Dynamic Cutset Sampling Topologies for Intelligence, Surveillance, and Reconnaissance

Thrust Area 6.2: Intelligence, Surveillance, & Reconnaissance (ISR)

1. Introduction

Distributed data gathering and information fusion are at the heart of localization, identification, and efficient monitoring of objects and spatiotemporal phenomena of interest in a wide range of applications. They are thus enabling tools for *situational awareness*, which entails the detection, identification, containment, and remediation for various threats, ranging from biological/chemical and radiological weapons, through other mobile entities such as troops and (unmanned) reconnaissance and tactical objects. Of particular importance is the discovery of mission-relevant information, whose existence was not known or expected before the start of the mission. When missions involve reconnaissance/surveillance in irregular warfare, in addition to resource (e.g., energy) constraints, data gathering may need to be carried out under secrecy, with limited spatial and temporal access, as well as other constraints or adverse conditions.

The goal of the proposed research is to develop novel, unconventional, constraint-aware approaches for designing dynamic sensing structures and distributed analysis algorithms to be used in missions involving geospatial data gathering tasks. The proposed approaches will seamlessly integrate the management of: (1) spatial sensor deployment and/or data communication constraints, (2) signal characteristics (e.g., continuity, expected size and shape), and (3) unconventional tradeoffs in terms of balancing information gains with spatiotemporal and energy constraints. We aim at achieving *accurate and robust signal detection, reconstruction, and analysis* for the purpose of *information extraction*. The proposed technology will significantly enhance naval capabilities for remote detection and assessment of various *known* or *unknown* security threats, spanning from motion of actual physical entities through weapons of mass destruction.

We are particularly interested in situations where data cannot be gathered using conventional imaging approaches (e.g., taking pictures from a satellite or airplane). Instead, we rely on a number of sensors that can be deployed over some area in order to collect samples from some two-dimensional (2-D), or 3-D, scalar-valued field (temperature, humidity, etc.). Complementary to this, instead of deploying a number of sensors there might be one sensor on a vehicle that moves through the field and takes samples at various locations along its path. Based on these samples, the goal is to detect the presence of a (potentially threatening) object or event, to identify it, to localize it, to estimate its size and other characteristics, and if it is spatiotemporally varying, to track it. All this can be done with or without reconstructing the field at all locations.

The reliability of detection and accuracy of estimation depends on the characteristics of the field, the deployment strategy, the measurement model, the accuracy with which the sensor locations are known, and of course, the reconstruction algorithms. In addition, the deployed sensors could measure more than one field at each location, and the reconstruction methods could take advantage of inter-field correlations. In particular, we are interested in unconventional sampling strategies, where, due to energy or spatiotemporal sensor placement constraints, it is advantageous to deploy the sensors densely along a collection of lines or curves (in 2-D and 3-D space) or surfaces (3-D space).

Examples of fields to sense include temperature, humidity, atmospheric pressure, vibration/sound intensity or frequency, concentration of a chemical compound, water depth (e.g., a ship mapping sea floor with sonar) or current velocity (measured by sensors dragged by a ship), elevation (an airplane mapping topography with radar?), etc. The field may be generated by an active source (emitting sound, vibrations, radio waves, etc.), whose location we may want to

estimate, or it may represent a distributed phenomenon of interest (e.g., a depth field). In some cases (spreading of a gas or liquid chemical compound), environmental factors (variable winds or the composition of the medium through which the chemical propagates) may make it difficult to accurately localize the source; however, estimation of the field may be important in its own right and may also provide valuable information about the source.

1.1 Technology Innovation and Technical Risk Areas

The main novel contribution of the proposed approach, which we will refer to as *cutset sampling*, is that it gathers data (one or more spatially collocated scalar values at the location of the sensor) densely along a *family of lines or curves* in 2-D space. In 3-D space, cutset sampling amounts to sampling data values at points belonging to curves or planes. While one may argue that the conventional sampling approach of sensor placement at uniformly spaced points on a lattice is the most efficient in terms of information gain, such setups may not be optimal or even attainable in surveillance and reconnaissance missions for several reasons, including (1) spatiotemporal constraints on sensor placement; (2) requirements for frequent repositioning of the sensing resources due to (detected or predicted on the basis of current measurements) changes in the monitored phenomena; (3) energy efficient communication among sensors.

More specifically, in a variety of geospatial data gathering situations, a dynamic cutset topology offers marked advantages over conventional topologies. These include: (1) situations where sampling is spatially restricted, e.g., to city streets as opposed to anywhere within city blocks, or to forest-boundaries as opposed to open prairies; (2) sampling from a moving vehicle (air, sea, ground) for which a cutset topology substantially reduces the number of passes to be made by the vehicle over the area of interest; (3) wired sensor networks, for which cutset topology substantially reduces the number and length of wires; and (4) wireless sensor networks, for which cutset topology substantially reduces the energy required per sensor and in total.

The potential benefits spur the need for novel techniques for: (1) sensor deployment, (2) data gathering and transmission, (3) spatial segmentation of the data on the cutset, (4) extending the segmentation to the entire field, and (5), if necessary, spatial interpolation to reconstruct the data values in the entire field. Based on context-aware collaboration among such techniques, we will develop signal processing methods that perform key tasks such as target/event detection, identification, localization, parameter estimation (size, shape, strength, etc.) and tracking.

We will consider a number of different scenarios for situational awareness. These will be determined on the basis of (1) sensor deployment constraints (static or mobile, e.g., on a moving vehicle); (2) sensor communication constraints (wired or wireless); (3) data processing constraints (local or centralized); and (4) the situational awareness distribution requirements (local or centralized). Data gathering and processing (segmentation, field reconstruction, information extraction) can be done at one central location, often called a *sink*; or, it can be done locally, and only a limited amount of high-level information can be shared between neighboring locations and transmitted to the sink. Similarly, in some situational awareness scenarios, the information produced by the system may need to be distributed to a centralized sink (e.g., a command center) or to agents distributed throughout the operating region (war fighters, vehicles, command posts), who respond when a target or threat is detected in their vicinity.

In certain settings, a combination of in-network distributed detection/tracking may need to be combined with data in command/control centers. For instance, a locally detected spread of a toxic phenomenon, along with temperature sensing, may need to be combined with maps of wind direction and precipitation potential [45], in order to estimate the most likely direction and speed of the toxin spreading in the next, e.g., 30 minutes.

We will also develop techniques for adaptive reconfiguration of the cutset topologies and the deployment of heterogeneous sensors in order to increase accuracy and reduce uncertainty in target/threat estimation. Our methods will couple the timeliness and efficiency of processing and communication with precision requirements and domain-based deployment constraints. Particular attention will be paid to network reliability, especially its resistance to node failures, including physical attacks. We will consider different modalities, e.g., wired and wireless sensors; mobile and static sensors; slow-moving robots and fast UAVs; etc.

Finally, we will develop design-enabling methodology to predict the performance of such methods and to compare them with conventional techniques.

1.2 Summary of Objectives and Impact to ONR Goals

The main objectives of the proposed research are the following:

1. Design and deployment of cutset sensor topologies for data gathering, analysis, and interpretation, in order to provide situational awareness.
2. Understanding and incorporation of spatiotemporal constraints on sensor placement.
3. Modeling of communication constraints and costs (timeliness, energy consumption) and incorporation in sensor deployments strategies and algorithm design.
4. Analysis of network reliability and resilience to node failures and physical attacks.
5. Development of algorithms for segmenting the cutset, extending the segmentation to the entire field, and field interpolation.
6. Development of algorithms for object/event detection, identification, localization, parameter estimation, and detailed reconstruction.
7. Adaptive reconfiguration of cutset technologies, and deployment of heterogeneous sensors to meet accuracy/uncertainty needs.
8. Incorporation of auxiliary data from various sources (maps, wind direction, etc.), methodologies for coupling historic and real-time data, and high-level programming tools to specify strategies and reactive behavior.
9. Development of different situational awareness scenarios and detailed analysis of the interplay/impact among different contexts: (a) Centralized vs. distributed (sensing, decision making/distribution, action); (b) Wired vs. wireless, (d) Static vs. mobile sensors, including heterogeneous sensors; (d) Static vs. moving targets
10. Designing testbeds for evaluating the performance benefits of the proposed approaches and for comparing with conventional techniques.