Networked Infomechanical Systems (NIMS): Next Generation Sensor Networks for Environmental Monitoring

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***Abstract* — Embedded networked sensing systems have been successfully applied to environmental monitoring in a wide range of applications. These first results have demonstrated a potential for advancing fundamental environmental science methods and environmental management capability as well as for providing future methods for safeguarding public health. While substantial progress in sensor network performance has appeared, new challenges have also emerged. Specifically, the inevitable and unpredictable time evolution of environmental phenomena introduces sensing uncertainty and degrades the performance of event detection, environment characterization, and sensor fusion. Many of the physical obstacles encountered by static sensors may be circumvented by a new method, Networked Infomechanical Systems (NIMS). NIMS integrates distributed, embedded sensing and computing systems with infrastructure-supported mobility to enable direct uncertainty characterization, autonomous adjustment of spatiotemporal sampling rate, and active sensor fusion. NIMS actuation is also being applied to advancing sensor network performance through methods based on control of distributed, directional antenna systems. In addition to advances in fundamental research objectives, this presentation will describe the architecture, implementation, and application of NIMS now deployed and continuously operating in the field...**

***Index Terms* — Wireless networked sensors, mobile wireless networking.**

I. Introduction

Wireless embedded networked sensing (ENS) systems have been successfully applied to environmental monitoring in a wide range of applications.[1] These first results have demonstrated a potential for advancing fundamental environmental science and environmental management capability as well as providing future methods for safeguarding public health. The primary challenges for operation of networked embedded sensing systems first appeared in the development of scalable, low energy and self-organized networked sensing. Progress in solving these critical problems has enabled deployments of networked sensor systems. However, the applications for embedded networked sensing have revealed yet new challenges associated with either detecting events or characterizing field variables in the complex environments of greatest interest. This presentation will describe these problems in sensing and additional challenges that are encountered as well in sensor deployment, energy management, and finally in essential wireless networking capabilities.

A new solution to these problems, Networked Infomechanical Systems (NIMS) based on infrastructure-supported mobility will be described. NIMS introduces a new networked embedded system capability that provides the ability to explore large volumes, adds new networking flexibility and functionality, and new logistics for support of distributed sensors, as well as the capability for self-awareness. This requires, in turn, the development of new methods for scalable and optimized coordination of mobility among nodes for many possible objectives. NIMS infrastructure-supported mobility also enable low energy transport and retain inherent low operating energy, rapid deployment characteristics, and environmental compatibility of distributed sensors. Together, these features offer a dramatic expansion in available design options for networked sensors. This presentation will particularly focus on specific ENS design requirements and limitations. This includes discussion of the verification of the hypothesis that NIMS constrained actuation methods resolve these limitations. The recent development and deployment of NIMS and additional new challenges that lie ahead will also be described.

II. Environmental Monitoring by Distributed Networked Sensing: Static and Actuated Sensing

A wide range of important environmental monitoring applications may take advantage of the capabilities of networked sensing for matching the spatially distributed nature of phenomena with similarly distributed sensors. At the same time, environmental monitoring requirements present unique design challenges for networked sensing that have not been solved with conventional sensor network deployments. Thus, actuated sensing devices carrying the capability for physical reconfiguration must be introduced. The specific design requirements and associated applications of actuation and actuated sensor systems are discussed below.

1) *Sensing Uncertainty*: As ENS systems are deployed in increasingly important applications; there are increasingly severe requirements for reducing the uncertainty associated with sensing phenomena and detecting events. This uncertainty depends not only on the sensing element characteristics, but, also the propagation environment for sensors to view signal sources. The physical configuration

including the distribution of sensing elements for a static ENS network is determined by design at deployment time. While the ENS network may be optimized for sensing fidelity based upon the initial state of the environment, the inevitable and unpredictable time evolution of environmental phenomena may introduce obstacles to sensing, introduce sources of distortion or interference, or cause the spatial distribution of events to depart from the design-time distribution. All of these effects may dramatically reduce the ENS network ability to characterize phenomenon with a desired level of fidelity. An important hypothesis, therefore, is that an ENS network may reduce sensing uncertainty through the introduction of a limited, robust capability for physical reconfiguration.[3]

2) *Spatiotemporal Sampling*: A critical requirement for distributed sensor system design is associated with the selection of sampling points in space and time.[4] Static ENS networks may not be capable of detecting variation in the spatiotemporal distribution of a field variable in regions where sensors are not distributed. In particular, the spatiotemporal sampling rate required to reconstruct an environmental model with a required level of fidelity may evolve with time according to time development of phenomena. Therefore, a specified design-time distribution of ENS devices may not always provide required sampling rate. Thus, again physical reconfiguration is required to enable the adaptation required for continuously optimizing sample rate. In addition, through reconfiguration of sensor nodes, sensing uncertainty may be detected and provided along with a measure of environmental field variables.

3) *Characterization of Complex Environments:* Many important environments for ENS monitoring show characteristically large, complex, three-dimensional spaces where measurements must be acquired. Sampling point volume density required to characterize phenomena in large volumes may lead to requirements for excessively large numbers of sensors. Again, it is important to consider the role of actuation that may enable sensor systems to be relocated to service large volumes with a reduced number of sensor units. However, the new forms of actuation that enable ENS network reconfiguration must operate in these environments with stable physical position suspended in a space with required energy supply for sustainable sampling and network communication operation. New forms of sensor actuation are required to properly deploy and adjust sensor nodes to accommodate this requirement.

4) *Long Term Monitoring*: Many important phenomena require extended periods of observation over multiple seasonal cycles, for example. Not only are conventional battery sources inadequate for supporting many sensor element types, but also, energy harvesting methods for static nodes may not provide sustainability over the required time frame. Specifically, the energy sources (e.g. solar radiation) available for harvesting may not be spatially distributed in a way that matches the ENS node distribution requirements. Here, the introduction of appropriate infrastructure enabling energy harvesting and transport may address this limitation.

5) *Wireless Network Performance:* Conventional ENS systems that are distributed on surfaces suffer from severe path loss.[5] This is the direct result of the destructive interference of direct and surface-reflected radiation components. This severe path loss (showing a range dependent fourth power low characteristic) has a primary impact on the energy and performance of wireless sensor nodes. Indeed, this has lead to architectural design considerations where the energy cost of communication is dominant.[6] This may again be addressed, for some applications, with the introduction of actuated systems.

6) *Autonomous Physical Sampling:* Compact, low power, in-situ sensors are not available or practical for many phenomena investigations.[2] This is a particularly acute limitation in applications to water resource monitoring. Thus, the introduction of actuation can enable actual physical sample collection from the environment permitting distributed monitoring by sample collection, but, relying on remote analysis of physical samples.

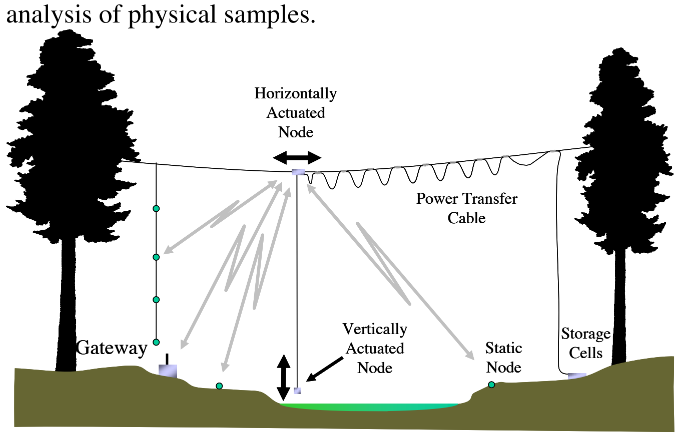

Figure 1. The Networked Infomechanical (NIMS) System provides infrastructure supported mobility for wireless sensor node systems. Both actuated and static sensor nodes are shown. The elevated location of the NIMS nodes provides advantages for sensing as well as for wireless network performance. In addition, actuation may not only enable improvements in sensing performance, but, also through adjustment of link range, improve wireless network characteristics for distributed low power sensors.

7) *Localization:* As ENS deployments have appeared, the challenge of node geolocation has been encountered. Specifically, the accurate location of an ENS node within a three dimensional environment is critical for many applications. Conventional methods, for example based on the global positioning system (GPS) are frequently not applicable in many environments where GPS signal reception is not possible. Sensor node geolocation measurements introduce the most complicated ENS problems associated with the generation and reception of ranging signals, synchronization, and communication, along with sensing uncertainty associated with ranging measurements. Again, as we will observe, actuated systems will offer a solution.

III. Constrained Actuation for Embedded Networked Sensors

It is clear that actuated sensor systems must be introduced to resolve the ENS limitations discussed above. However, the selection of actuation methods confronts a series of additional requirements that hinder the application of conventional methods.

First, conventional surface robotic devices offer a means to actuate sensors, however, these conventional methods do not permit access to the full three dimensional environment.

Conventional methods for distributing sensors in three-dimensional environments may rely on aerial vehicles. However, these lack the ability to sustain long term elevated station due to large energy requirements. Further, typical aerial vehicles also face complex navigation challenges. Finally, typical vehicles may also disturb the environment.

The need for sustainable operation in three-dimensional environments has lead to the introduction of the NIMS method where robotic devices are suspended on infrastructure cable way systems (see Figure 1). This provides elevation and simplifies navigation by permitting sensor nodes to propagate on linear cable ways.

The use of constrained actuation is based on the hypothesis that while deployment of infrastructure in the environment represents a one-time investment, the subsequent benefits of infrastructure to actuation will exceed the investment in infrastructure. It is important to consider then whether NIMS infrastructure-supported actuation and results from NIMS research addresses these ENS system limitations discussed above.

1) *Sensing Uncertainty*: First, perhaps the most critical ENS requirement is be assurance of high sensing fidelity. This is determined by the ability of the ENS system to circumvent the unpredictable obstacles to sensing in typical environments. Recent progress using constrained actuated sensing, relying on short distance linear motion has demonstrated a dramatic improvement in sensing uncertainty for imaging methods.[7] Thus, it is concluded that NIMS mobility, confined to a transect plane, will also reduce sensing uncertainty for a wide range of environments.

2) *Spatiotemporal Sampling*: Investigation of phenomena including the spatiotemporal distribution of solar radiation in the forest canopy has shown that adaptive distribution of sampling points is required for ensuring sensing fidelity. However, this has also been shown to be possible through the use of actuated sensing.[8]

3) *Characterization of Complex Environments:* The use of suspended infrastructure enables the NIMS system to sample phenomena over an entire transect plane, as shown in Figure 2. NIMS devices have been deployed in complex forest environments, as will be discussed and also within stream systems for water quality monitoring.

4) *Long Term Monitoring*: Long lived operation of NIMS systems has been demonstrated with the continuous operation of the NIMS system shown in Figure 2. These networked devices receive energy via the suspended infrastructure that is ultimately harvested from solar energy and supplied to the NIMS system as shown.[9]

5) *Wireless Network Performance:* However, as has been shown, the raising of antenna height above the surface reduces path loss and for sufficient height, eliminates this effect.[10] Clearly, this suggests yet another potential advantage of properly coordinated actuation. Specifically, sensor network nodes and their antenna systems may be elevated and adjusted in height and orientation to optimize network links. The NIMS system shown in Figure 2 establishes network connectivity via IEEE 802.11b wireless interfaces and protocols to both actuated mobile and fixed nodes.

6) *Autonomous Physical Sampling and Localization:* The capabilities for physical sampling are currently under development with water sampling devices that are conveyed by the NIMS system. Finally, localization methods also take advantage of NIMS infrastructure and are under development as well. These exploit NIMS imaging capabilities and precise actuation to enable NIMS nodes to locate objects by multilateration methods over a large field of view

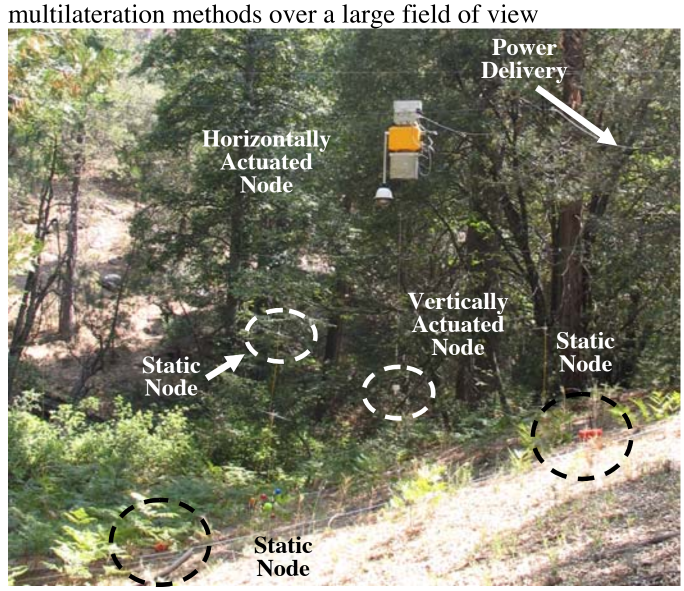

Figure 2. The Networked Infomechanical (NIMS) System deployed in a forest environment at the San Jacinto James Reserve.[12] The horizontal and vertically actuated sensor nodes are shown. Static sensor nodes distributed at the surface and also suspended from the cableway are shown as well (other compact suspended nodes are present by not visible in the figure). This image shows a segment of the 70m cableway that spans a canyon and stream. Through a wireless network all nodes operate in a local cluster for data acquisition and are also accessible remotely.

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IV. NIMS System Implementation

NIMS systems have been implemented with cableway infrastructure suspended within the environment. Anchoring of cableways exploits installed or naturally occurring structures or terrain a shown in Figure 1 and 2. This may include trees for operation in forest environments, or built tower infrastructure for river channels or interior or exterior urban environments. Energy harvesting may also exploit infrastructure where solar photovoltaic cells have been suspended from the infrastructure. Power distribution also uses the cableway for transport of power to nodes via folding cable systems as shown in Figures 1 and 2.

Figure 2 shows a NIMS networked system with three embedded platform types. A horizontally actuated node operates with motion along the horizontally suspended cable. This embedded device, supporting the Linux operating system and hosting adaptive sampling and other applications [8] controls the motion of the vertically actuated sensor node. These devices also maintain network access to the static nodes also distributed in the environment and shown in Figures 1 and 2. Imager systems carried by the horizontally actuated node include separate angular perspective actuation. Software interfaces between application level software systems and sensor and actuator systems follow the Emstar architecture.[11]

V. NIMS Applications

NIMS system applications and this tool is being adopted by a community of researchers. First, at the James San Jacinto Mountain reserve,[12] NIMS systems are in use for microclimate and solar radiation mapping. Also, at this same location, a second NIMS system has been adopted for investigation of interaction between surface and subsurface (forest soil) environmental phenomena including measurements of gas transport. NIMS systems have also been deployed for measurement of water quality and contamination in the Los Angeles area watershed. NIMS systems are also under development for deployment in the Merced River of California for characterization of the influence of agricultural processes on river water quality. Finally, a sensing architecture has been designed for deployment in tropical rain forests for characterization of fundamental biological science phenomena as well as for investigation of the impact of fragmentation on forest ecosystems. NIMS applications to indoor environments are also under development with a focus on object localization.

VI. Conclusion

The continued progress in ENS applications requires new methods that autonomously optimize sensing fidelity, ensure sustainable operation, and maintain wireless network performance. NIMS technology introduces a new actuation method that exploits infrastructure and provides these required new methods. NIMS provides capability for actively adjusting sensing nodes, introducing diverse new sensors, and reducing wireless link path loss. While the introduction of infrastructure also constrains the extent of actuation, this constraint is compatible with a broad class of monitoring applications. The first NIMS systems have been deployed and now operate in natural environments. Future research objectives now include the management of multiple NIMS systems and the development of methods that enable actuated sensors to detect and characterize dynamic phenomena.

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