Title

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Abstract. Distributed embedded sensor networks are now being successfully deployed in environmental monitoring of natural phenomena as well as for applications in commerce and physical security. While substantial progress in sensor network performance has appeared, new challenges have also emerged as these systems have been deployed in the natural environment. First, in order to achieve minimum sensing fidelity performance, the rapid spatiotemporal variation of environmental phenomena requires impractical deployment densities. The presence of obstacles in the environment introduces sensing uncertainty and degrades the performance of sensor fusion systems in particular for the many new applications of image sensing. The physical obstacles encountered by sensing may be circumvented by a new mobile sensing method or Networked Infomechanical Systems (NIMS). NIMS integrates distributed, embedded sensing and computing systems with infrastructure-supported mobility. NIMS now includes coordinated mobility methods that exploits adaptive articulation of sensor perspective and location as well as management of sensor population to provide the greatest certainty in sensor fusion results. The architecture, applications, and implementation of NIMS will be discussed here. In addition, results of environmentally-adaptive sampling, and direct measurement of sensing uncertainty will be described.

1 Introduction

The first generation of networked embedded sensing systems have been successfully applied to distributed monitoring of environments. These first applications have stimulated rapid growth of applications based on an unprecedented capability for characterizing important environmental phenomena.[1] The primary challenges for operation of networked embedded sensing systems first appeared in the development

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of scalable, low energy networking and cooperative detection. While progress has been made towards addressing these challenges, the deployment of first generation sensor networks has revealed a new class of problems associated with optimizing sensing fidelity and sustainability in complex environments. Specifically, the unpredictable evolution of events and the presence of physical obstacles to sensing introduces uncertainty in sensing and the results of sensor data fusion. Most importantly, the inevitable presence of unpredictable physical sensing obstacles is fundamental to environments of interest and creates a pervasive limitation that threatens to degrade the performance of distributed sensor systems.

2 Coordinated Static and Mobile Sensing

Perhaps the most important challenge for sensor networks is the development of capabilities for sensor network self-awareness where the sensor network itself is capable of determining its own sensing fidelity. Of course, with only a fixed sensor distribution and an accompanying unpredictable set of obstacles, this self-awareness may be unachievable since obstacles may not be identifiable within an environment by fixed sensors alone. Now, since it is the presence of physical obstacles that create uncertainty, then physical reconfiguration of sensors is required to circumvent obstacles. This introduces further challenge, of course, since such mobility must be autonomous and generally sustainable in the environment. However, a new generation of networked embedded systems incorporating controlled and precise mobility is now being explored. These Networked Infomechanical Systems (NIMS) directly address the fundamental objective of self-awareness by enabling motion of sensor node networks to circumvent obstacles, probe sensing fidelity, and optimize sensor and sample distribution.[2]

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 also introduces infrastructure-supported mobility to enable low energy transport and retain inherent low operating energy, rapid deployment characteristics, and environmental compatibility of distributed sensors.

3 Coordinated Static and Mobile Sensing Systems and Applications

The first investigations of natural environment phenomena with NIMS have revealed characteristics of fundamental field variables that were not visible with previous sensing methods based only on static sensing. An example is the spatiotemporal distribution of solar illumination, important in the understanding of fundamental ecosystem phenomena. The complexity and rapid evolution of light fields immediately demonstrated that fixed sensors or even simple actuated sensor scanning methods would be inadequate for high fidelity mapping. A series of new methods have been developed that merge static sensing (providing constant vigilance for temporal change in environmental phenomena) with mobile sensing, providing the ability to intensively sample phenomena. These include adaptive sampling and task allocation methods that provide a means to efficiently manage the distribution of sampling points in a variable field to achieve a specified fidelity threshold.[3] Others include methods that exploit controlled mobility to benefit network performance.

NIMS systems include multiple embedded platform types. Horizontally actuated nodes operate with motion along a horizontally suspended cable. This embedded device, hosting adaptive sampling and other applications also controls the motion of an independently operating and vertically actuated sensor node. This latter device carries microclimate monitoring devices. These nodes maintain network access to the static nodes also distributed in the environment with static nodes suspended by the cable itself or distributed at the surface. Imager systems carried by the horizontally actuated node include angular perspective actuation. New embedded software systems include embedded statistical computing tools for in-network processing in support of adaptive sampling. The runtime environment and software interfaces connecting application level software systems and sensor and actuator systems follows the Emstar architecture.[4]

NIMS system applications and this tool is being adopted by a community of researchers. First, at the James San Jacinto Mountain reserve,[5] 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.

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