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NSF Science & Technology Centers

Center for Embedded Networked Sensing

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Center for Embedded Networked Sensing

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CENS

Project Summary

During the last decade, networking technologies have revolutionized the ways individuals and organizations exchange information and coordinate their activities. In this decade we will witness another revolution; one that involves observation and control of the physical world. The availability of micro-sensors, micro-actuators and low-power wireless communications will enable the deployment of densely distributed sensor/actuator networks for a wide range of biological and environmental monitoring applications in marine, soil, and atmospheric contexts. Moreover, this same technology will be used to monitor, and in some cases control, engineered structures such as buildings and vehicles. The technology will transform the ways in which we understand and interact with the physical world. In the context of scientific applications, these capabilities will not only change the way scientists collect data, but change the nature of the data that can be collected, and consequently the models that can be developed and verified through data assimilation.

The research focus of the Center for Embedded Networked Sensing (CENS) will be the *fundamental science and engineering research needed to create scalable, robust, adaptive, sensor/actuator networks*. The vision of densely-distributed, networked sensing and actuation requires advances in many areas of information technology. Moreover, there is a critical interplay between the technology and the applications and physical context in which it is embedded. By conducting research in the context of specific and high-impact scientific applications CENS will enable new scientific discovery through high resolution, in situ monitoring and actuation. At the same time, CENS will explore the fundamental principles and technologies needed to apply embedded networked sensing to a wide range of applications.

The Center will focus initially on fundamental technology and on four experimental application drivers: habitat monitoring for bio-complexity studies, spatially-dense seismic sensing and structure response, monitoring and modeling contaminant flows, and detection and identification of marine microorganisms. To support this scope, CENS will combine the expertise of faculty from diverse engineering disciplines with the expertise of biological, environmental and earth scientists. During the lifetime of the Center, we will pursue additional opportunities for applying the technology to natural and engineered systems.

The CENS educational focus will be twofold: 1. new hands-on experimental capabilities for grades 7-12 science curriculum through access to real-world, real-time, sensor-network interrogation, along with materials for teacher-training, and 2. undergraduate research opportunities in cutting-edge technologies (e.g., wireless systems, MEMS, embedded software) and scientific applications (e.g., bio-complexity, seismic and environmental monitoring), with emphasis on under-represented minority students.

The focus of CENS, embedded networked sensing, is a unique technology that offers broad and profound opportunities for scientific discovery and technological advance. However, significant progress is not achievable within isolated disciplines. The wide range of component technologies and the breadth of applicability require the structure of a Center. The technology research must draw on a diverse set of researchers within engineering, from distributed system design, to distributed robotics, to wireless communications, signal processing and low-power multi-modal sensor-technology design. In addition, the physically-embedded nature of this technology calls for significant experimentation and exploration within the context of the target application domains in order to identify the true challenges and opportunities. Continual iteration between technology and application development is required. The center’s research will integrate our understanding of solutions across domains and develop general methods and techniques to realize the technology’s full potential.

The design of networked embedded sensing systems raises fascinating challenges for Information Technology and communication research, as well as for their application domains. Perhaps the most challenging is the shift from manipulation and presentation of symbolic and numeric data to the interaction with the dynamic physical world through sensors and actuators. Moreover, while all good distributed systems are designed with reliability in mind, these target applications present a level of ongoing dynamics that far exceeds the norm. These systems must be long-lived and vigilant, and operate unattended and often untethered, raising critical challenges for low-power system operation. Finally, considering the other characteristics of the problem space traditional (Internet) scaling techniques are not directly applicable, and alternative techniques must be developed.

To achieve scalability, robustness, and long-lived operation, sensor nodes themselves will execute significant signal processing, correlation, and network self-configuration inside the network. In this way these systems will emerge as the largest distributed systems ever deployed. Within this context we have identified four initial technology objectives: Adaptive self-configuring wireless networks, Coordinated actuation, Distributed collaborative signal processing, and exploiting new Micro-sensing components.

We will pursue our research in the context of particular scientific applications because of the inherently physically-coupled nature of the technology. To this end, the Center will focus initially on four experimental domains that stress different aspects of this technology design space. The habitat sensing array for bio-complexity mapping emphasizes the need for continual automatic self-configuration of the network to adapt to environmental dynamics, and the use of coordinated actuation in the form of programmed triggering of sensing and actuation to enable identification, recording and analysis of interesting events and trends. The spatially-dense seismic sensing and structure response application emphasizes real-time distributed signal-processing and coordinated actuation. The monitoring of contaminant transport exploits distributed detection using coordinated chemical micro-sensing. The detection and monitoring of marine microorganisms requires coordinated mobility and distributed micro-sensing in a liquid environment, in addition to innovative methods of organism identification.

These particular projects were chosen because of their potential scientific contributions and the diverse technical challenges they pose. These projects span diverse physical media—from subsurface ground and water to terrestrial and atmospheric monitoring and observation. Moreover, the projects span temporal and spatial scales. This diversity will allow us to develop general approaches to the science and technology of embedded networked sensing. During the lifetime of the Center, additional opportunities for embedded network sensing will emerge, and the Center will have developed initial expertise and understanding to apply these techniques and technologies.

The planned 7-12 educational program has strong tie ins to the technical and application activities of the center. Initial education activities will focus on developing two pilot curricula to support *inquiry-based* science education: Middle-school Life Science curriculum based on iterative experimental design and data collection using the James Reserve Habitat network, and High school Physical science curriculum based on data collection and analysis using the UCLA seismic facilities. During the first 5 years of the center, these pilot developments will be evaluated, generalized to other subjects, integrated into teacher-training, and ultimately packaged as technology and curricula kits provided to the larger education community. CENS will also have significant impact on human resource development by working with the UCLA CARE program to involve undergraduate students from UCLA and CSLA in research opportunities associated with the Center's technology and application projects. This effort will emphasize involvement of under-represented minority and U.S. students. The Center team includes Social Scientists, Middle/High School Science teachers and curriculum developers, and is further supported by two organizations experienced in creating effective undergraduate intern programs for under-represented minority students.

CENS will benefit from and contribute to a large web of related activities on the participating campuses, and in the larger research and education community, including: UCLA's California Nanosystems Institute, Institute for Pure and Applied Mathematics, Nanoelectronics Research Facility; USC's Information Sciences Institute, Wrigley Institute for Environmental Studies; UC Reserve systems; Cal State and GLOBE Teacher training programs; INEEL, JPL government laboratories; DARPA, and NSF related research activities. Moreover, many of the constituent technologies will have near and long term commercial relevance.

The Center for Embedded Networked Sensing will focus on the development of high-impact, elastic, Information Technologies. By working across several application domains, we will identify and develop general theories and techniques that will help the technology to proliferate in the style of Internet and personal computing. However, **this** revolution will extend beyond information and visual spaces to the monitoring and control of our physical world. The Center for Embedded Networked Sensing is under consideration by the National Science Foundation for initial funding under the Science and Technology Center Program.

Participants

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Technical Narrative

Distributed sensor/actuator networks will enable continual spatially-dense observation (and ultimately, manipulation) of biological, environmental, and artificial systems; from plankton colonies to endangered species, to physiological status information about medical patients, and even airplane wings constructed out of smart materials. The technology will transform the ways in which we understand and interact with the physical world. In the context of scientific applications, these capabilities will not only change the way scientists collect data, but change the nature of the data that can be collected, and consequently the models that can be developed and verified through data assimilation.

This proposal addresses the technological opportunities and challenges associated with embedded networked sensing, and presents specific experimental application domains. These applications play three critical roles in the Center's activities: 1. the physically-coupled nature of the technology requires that it be explored in the context of concrete domains and applications in an ongoing, iterative manner; 2. the application domains themselves will be transformed by the technology's spatially-dense and temporally-continuous monitoring capabilities; and 3. by exploiting the unique data and experimental capabilities offered by the deployed systems, we can explore the opportunities and challenges faced in incorporating this innovation into grades 7-12 science education.

After introducing the technology design space we describe four proposed foci of technological innovation and four experimental domains. We then describe the introduction of embedded-sensing data and experimentation into grades 7-12, and an undergraduate research internship program focused on under-represented minority students. We conclude with an outline of the proposed organizational structure and budget.

1 Embedded Networked Sensing Technology

To achieve scalability, robustness, and long-lived operation, sensor nodes themselves will execute significant signal processing, correlation, and network self-configuration inside the network. In this way these systems will emerge as the largest distributed systems ever deployed. These requirements raise fascinating challenges for Information Technology and communications research, as well as for their application domains: 1. Physical-coupling: a shift from manipulation and presentation of symbolic and numeric data to the interaction with the dynamic physical world through sensors and actuators; 2. Environmental dynamics: target applications present a level of ongoing dynamics that far exceeds the norm; 3. Energy constraints: these unattended wireless systems must be long-lived and vigilant and the energy constraints on un-tethered nodes present enormous design challenges; 4. Scale: existing distributed system scaling techniques are not directly applicable given the extreme conditions under which our target systems must operate.

Certainly, existing deployed systems such as networked weather sensing or battlefield surveillance encounter similar challenges. However, networked embedded sensing technology is so widely applicable, and faces systems-challenges along so many dimensions, that it calls for a concerted, broad-based effort in understanding the technology across spatio-temporal scales and sensing modalities. This is an understanding that cannot be obtained from point solutions that consider only one application domain. To develop this broad-based understanding of embedded networked sensing, we have identified four initial technology objectives: Adaptive self-configuring wireless networks, Coordinated actuation, Distributed collaborative signal processing, and exploiting new Micro-sensing components. The choice of these four technologies is motivated by the expected capabilities of embedded networked sensor systems: they are autonomously deployed, they monitor the environment, and automatically react to environmental stimuli. The first capability requires adaptive self-configuration of the network, from self-assembly at the lowest levels to geo-localization and energy-aware routing. The second capability requires the development of microsensors that will drive applications, and sophisticated signal processing techniques that enable accurate sensing and tracking of objects in the environment. Finally, methods for distributed actuation will provide the reactivity of these networked sensor systems. Our technology objectives are described briefly in Sections A-D below.

We will pursue our research in the context of particular scientific applications. The feedback provided by such experimentation is essential because of the inherently physically-coupled nature of the technology. To this end, the Center will focus initially on four experimental domains that collectively span this technology design space (see Figure 1). The spatially-dense seismic sensing and structure response application emphasizes real-time distributed signal-processing and coordinated actuation. The habitat sensing array for bio-complexity mapping emphasizes the need for continual automatic network self-configuration to adapt to environmental dynamics, and the use of coordinated actuation in the form of programmed triggering to enable identification, recording and analysis of interesting events. The monitoring of contaminant transport will exploit distributed detection using coordinated chemical micro-sensing. The monitoring of marine micro-organisms requires coordinated mobility and distributed micro-sensing in a liquid environment, in addition to innovative methods for organism identification.

Figure 1	Seismic	Habitat	Contaminant	Micro-organism
Distributed Signal processing	X		X	
Adaptive Self-conf wireless		X		
Coordinated Actuation	X	X		X
Micro-sensing			X	X

Thus, our technology objectives are carefully chosen to span our space of experimental domains. In addition, our experimental domains are carefully chosen to cover a variety of situations in which embedded networked sensing will be employed. This technology will fundamentally alter the spatial and temporal scales with which we can observe and interact with the physical world. However, not all systems will operate at the same physical and temporal scales. Different physical scales can imply vastly different resource availability, (e.g., computation, storage, communications, energy); while different temporal scales imply vastly different performance requirements. Our four experimental domains will span the combined spatial-temporal application space (Figure 2).

	Figure 2	
	Temporal Scale	
Spatial Scale	Meso	Macro
Meso	Marine Micro-organism Monitoring	Contaminant Transport
Macro	Seismic Sensing Structure Response	Habitat Monitoring, Bio-complexity map

This strategic vision for the direction of the Center will help develop and define the science and practice of networked embedded sensing. This is only possible under the auspices of a Center, for two main reasons. First, a Center will allow significant experimentation with this technology. While many hypotheses can be posed regarding the fundamental underlying principles of distributed and embedded systems, it is only through relatively large-scale experimentation that they can be tested. By pursuing a broad range of experiments, researchers at the Center will lay the groundwork for a comprehensive theory of autonomous cooperation. An experimental focus also ensures that theory remains grounded in the real world, with constant critical scrutiny of models that may themselves suggest the next set of experiments. Such large-scale experiments demand much care and preparation. The Center will become a national resource for how to test, measure, and evaluate embedded networked systems. Second, a Center will enable the examination of multiple experimental domains. By doing this, we are less likely to be sidetracked by features that are unique to one set of distributed problems, and more likely to discover the fundamentals. Moreover, this choice of application domains makes it likely that we will be able to cull out *system building blocks* for embedded networked systems. Even though these systems are likely to be vertically integrated, this building block approach will avoid having to re-implement common tasks (e.g., data dissemination, localization, time synchronization, networked signal processing). These building blocks also represent reusable instantiations of these techniques; they will therefore promote robust systems since, over time, each building block will have been used in different experimental domains. In addition, a Center can serve as a repository of experimentation techniques and empirical data for other researchers, as well as form a marketplace for micro-sensor technologies for which the demand is not yet large enough to motivate vendor production.

After describing our four initial technology objectives, we will return to a discussion of our experimental applications and overall theoretical goals.

A. Adaptive self-configuring wireless systems (Estrin, Govindan, Pottie, Soatto, Srivastava, Sukhatme)

Unattended monitoring in remote and inaccessible spaces requires locally-powered, wireless systems that can self-configure and adapt automatically. The sheer number of distributed elements in these systems precludes dependence on manual configuration. Furthermore, the environmental dynamics to which these elements must adapt prevents design-time system pre-configuration and optimization. Thus, realistic deployments of these unattended networks must self-reconfigure in response to node failure or incremental addition of nodes, and adapt to changing environmental events and conditions, while actively managing system resources to extend system lifetime. Moreover, if we are to exploit the power of densely distributed sensing, these techniques for adaptation and self-configuration must scale to the anticipated sizes of these deployments. In recent years, some work has begun to allow networks of wireless nodes to discover their neighbors, acquire synchronism, and form efficient routes [Pottie-Kaiser00]. However, this nascent research has not yet addressed many fundamental issues in adaptively self-configuring the more complex sensing and actuation systems described here, particularly those arising from deploying embedded systems in real-world, environmentally-challenging contexts.[Estrin-et al.99] Driven by our experimental domains, we will develop:

- Integrated and scalable self-assembly and self-healing techniques for these deeply distributed systems, that enable self-configuration not just at the lower-level communication layers, but also at higher levels such as distributed name spaces. These systems require power-aware, adaptive, distributed resource management techniques that enable energy-efficiency beyond what is feasible with low-power hardware design alone.

- Multi-modal protocols that exploit spatial and modal redundancies in the sensor networks will extend system longevity without sacrificing accuracy and rapidity of detection. For example, vigilant, remote, passive sensing via optical sensors consumes large amounts of energy. The network must adaptively self-configure to determine which sensors (cameras) should be on and recording, processing and transmitting. In order for a node to command an action, it can process other local sensory information to detect and characterize an event of interest (presence of an event, determination of motion vector).

- Simple localized algorithms will effect coordinated data collection and processing to achieve measurement aggregation or higher-level alert generation [Abelson-etal00]. Preliminary research indicates that a particular paradigm for network organization, directed diffusion [Intanago-et al.00], can efficiently achieve such coordination and resource allocation needs, but considerable experimentation and modeling work is still required.

- Sensor network coverage algorithms for planning and monitoring regular as well as ad hoc spatial deployment of sensor nodes to achieve desired probabilities of detection of various events. Our preliminary investigation has suggested that results from computational geometry and percolation theory are useful tools for studying sensor network coverage [Meg-etal01] Successful deployment of embedded networked sensing will require sensor network health monitoring systems that warn of system resource depletion or indicate overall network health.

- Techniques for time synchronization and localization in support of coordinated monitoring. Given the small physical size of many targeted-application nodes, we cannot rely on the global positioning system

(GPS) alone. Similarly, our applications require scope, availability, lifetime, efficiency, convergence time, and precision that are different from traditional networks and distributed systems, thus rendering timing synchronization approaches from computer networks inadequate. Our timing synchronization and localization approaches will be robust to errors, energy-aware, and will be tunable so that precision and energy can be traded off.

Key to the above techniques will be a systematic exploitation of redundancy of hardware elements to compensate for ad hoc deployment, and adaptive fidelity processing to make trade-offs between energy, accuracy and rapidity. By solving and implementing sensor network problems in a concrete application context, we will also address a fundamental dilemma in sensor networks; namely, that the seemingly optimal ways of solving a problem often result in algorithms whose energy costs exceed their benefits. Our long-term goal is to develop an analytic foundation along with a performance evaluation framework for sensor networks.

B. Coordinated Actuation (Sukhatme, Estrin, Govindan, Hamilton, Pottie, Soatto)

In some contexts the ability of a node to move itself (or selected appendages), or to otherwise influence its location will be critical. Distributed robotics [Mataric95] in a constrained context will greatly extend the capabilities of these systems. Benefits of including self-mobilizing elements [Sukhatme99] include: self-configuration to adapt to realities of an inaccessible terrain, developing a robotic ecology for delivering energy sources to other system elements, and obtaining coverage of a larger area.

Mobile robots provide an additional link between the sensor networks and the physical environment. On the one hand, they can be sensed, monitored and assisted by the sensor network, particularly in the built environment. On the other hand, and more central to this work, the robots are nodes in the network with added potential for mobility and actuation in general.

Actuation has three broad categories, listed here in increasing order of generality and degree of difficulty. The Center's activities will incorporate actuation at all three levels. 1. Actuation without mobility: local actuation will be informed by data from the sensor network. We will develop mechanisms that allow the spatial focus of attention within the actuator network to change as a function of the sensor data without gross motion of the sensors or actuators. In situ, data collection will occur with actuators attached to immobile sensors. The principal research challenges in this area are to increase low-level autonomy in the sensor/actuator network and develop coordination algorithms for directed sensing and actuation. 2. Actuation for limited range mobility: directed monitoring will use limited forms of motion within limited range, e.g., by using mechanical tethers. Examples include marine monitoring tanks, as well as acoustic, video and other sensors/actuators mounted on tracks to allow multi-elevation monitoring and experimentation. This requires significant new effort in the design and development of the tethered robots and their programming [Hert96] before they are ready for deployment. 3. Actuation for mobility: unconstrained mobility will be needed to apply sensing and actuation across a wider space than fixed infrastructure can feasibly cover; this requires autonomous mobile robots. An example is the use of robotic nodes to fill in gaps in remote monitoring locations. Here we will experiment with coordination and control algorithms for autonomous robots [Sukhatme00] with the intent of ultimately applying these techniques to more fully self-configuring systems.

The distributed, scalable control of a large number of actuators is a significant research area. The application drivers of the Center force us to think about general coordination and control strategies for distributed actuation across the full range of actuation.

C. Distributed Sensor Signal Processing, Analysis, and Data Management (Yao, Muntz, Pottie, Govindan, Soatto)

Ultimately, distributed sensor networks, having limited communication capabilities, will not be able to scale if all raw sensor data is sent back to a central repository for processing. For this reason architectures based on processing of data inside the network and correlating of events before reporting back are essential. We use the term collaborative signal processing to refer to this class of solutions. Such data reduction, simplification, and decision-making, will require data exploration, modeling, and prediction using data clustering techniques for finding similarities and differences in the sensor data. This must be achieved in real-time. Proper use of these methods will advance many of the application fields. The applicability of recent advances in data mining will also be explored.

We will conduct basic research on signal and array processing for a group of networked sensors that, in unison, perform tasks more capably than just the sum of the individual sensor. In particular, these results will be applied to the high spatial resolution seismic network and the habitat network described later in this proposal. Most conventional sensor array processing systems assume narrow-band waveforms and precisely known sensor geometry and responses. One problem is for arbitrarily placed sensors to use the time-of-arrival at different nodes to perform coherent processing, enhancing the signal-to-noise-ratio of the desired signal and rejecting other noise and interference. Another problem is to use these data to estimate the direction-of-arrival or location of the source. One interesting approach is the use of novel blind beam-forming array and least-squares estimation methods to address both problems for broadband acoustic/seismic waveforms and arbitrarily placed and perhaps only partially calibrated sensors. These results will yield insight into the proper deployment of sensor density and locations applicable to various proposed networked sensor systems. [Yao-etal98].

We will also investigate less-traditional data analysis techniques. For example, the use of correspondence analysis (CA) for data mining to determine the amount of similarity/difference among the sensor data will be explored. This non-parametric and non-statistical approach using only sensor observed data can provide insights on the deployment of sensor density and locations, as well as, effective representation of high-dimensional data to lower-dimensional characterization and display. CA exploits the proper usage of singular value decomposition for practical data analysis [Greenacre94, Yao93]. More recently, generalizations of CA and principal component analysis (PCA) techniques proposed for pattern recognition work such as constrained PCA (CCPA) [Takane97] and kernel PCA (KPCA) [Scholkopf99] may also be relevant for our applications.

Finally, existing database management technology exhibits severe limitations in the sensor-enriched environments described here. [Imielinski-Goel00] Traditional databases assume that data resides at a centralized server or set of servers accessed by applications. In our context data is highly dispersed over a geographical space and originates in small computing devices with limited storage, processing and communication capabilities. Moreover, the nature of data generated corresponds to highly dynamic spatio-temporal data sets. This introduces many new challenges in the representation, tracking, optimization and processing of motion-specific queries. In addition, sensors allow us to capture and create very large data repositories. Techniques to support multi-resolution representation of spatio-temporal data sets that allow efficient approximate and progressive query evaluation need to be devised. Similarly, techniques need to be devised to support effective and efficient interpretation, exploitation and visualization over very large and dynamic spatio-temporal data sets.

The techniques for localization, time synchronization, and power-aware resource management developed under Technology Objective A will be combined synergistically with these collaborative signal processing algorithms and sensor data management techniques. For example, the localization algorithm may make use of the data analysis of different sensor modes to combine them for improving the localization accuracy.

D. Micro/Nano Sensor Technology (Ho, Judy, Tai, Daneshgaran, Harmon, Requicha, Zhou)

Sensors and actuators are the pathways between an engineering system and the external world. In the past, traditional manufacturing technology had difficulties in fabricating mechanical parts smaller than 1 mm and was incompatible with the lithographic processing used for integrated circuit (IC) fabrication.

Micromachining, which emerged in the 1980s, removes this roadblock and makes it possible to monolithically integrate the mechanical and electronic elements. Micro-electro-mechanical-systems (MEMS), with their integrated micron-size mechanical and electronic parts, will be able to sense the physical world, process the information, and then manipulate the physical environment through actuators. Many environmental and biological applications ultimately require chemical, physical, and biological micro-sensors. MEMS technology provides the capability of developing these sensors at the micron scale, and this will substantially increase the spatial resolution of deployable sensing. Design, and particularly, the intelligent interfacing and use of these components, are crucial.

During the past decade, the UCLA/Caltech group has developed a complete series of MEMS fluidic sensors, which include temperature, shear stress, velocity, and pressure sensors [Ho-Tai98, Ho-Tai96]. These sensors are fabricated by compatible technology and, therefore, they can be monolithically integrated. This feature allows us to decompose the mutually dependent sensitivities and greatly facilitate the calibration process. The sensors have frequency responses ranging from hundreds of kHz to MHz and can be fabricated in large arrays.

One of the most promising aspects of distributed networked sensing is the ability to employ heterogeneous sensors to calibrate and cross-check. We will explore the development of multi-modal sensors in which co-located sensors of different types collaborate with distributed sensors of the same and different type to enable distributed detection at low concentrations and more precise detection at higher concentrations. We will explore the application of networked sensors in marine, soil/sediment and groundwater monitoring scenarios.

Novel sensor technology is also needed for the study of structural response to seismic activity. The Cal State LA Center is investigating the use of fiber optic based sensors. An optical interferometer is well suited for accurate displacement measurements. To reach strain sensitivities of 10^{-6} or better, the beam path has to be stabilized. In the case of laser interferometers, the stabilization of the beam has been achieved by using vacuum pipes. However, these laser interferometers are cumbersome and cannot be used at all at some locations. We will investigate the use of fiber optic interferometers as a more flexible and lower cost strain meter and integrate them into the distributed structural response monitoring system described later.

2. Scientific applications and prototypes

The four experimental domains described below span meso- and macro- spatial and temporal scales. (The experimental facilities are described in more detail in the Shared Facilities Section.)

A. Habitat Sensing Array for Biocomplexity Mapping (Hamilton, Allen, Estrin, Govindan, Pottie, Rotenberry, Rundell, Soatto, Srivastava, Sukhatme, Taylor)

The two overarching and interconnected research themes of global change and biocomplexity challenge ecologists to develop new and innovative methods to study combinations of interactions of organisms within terrestrial and aquatic ecosystems, in ways that integrate information across temporal and spatial scales, while considering multiple levels of organization [NSF00, Walker-Steffen97, Gell-Mann95]. Long-term data collection for systematic and ecological field studies, and continuous environmental monitoring, are the domain of Biological Field Stations, and offer opportunities to establish cross-cutting and integrated investigations [Michener-et al.98, Lohr-et al.95]. Over the past two decades we have seen extraordinary developments in the field of remote sensing and automated data collection, resulting in dramatic increases in spatial, spectral and temporal resolution at a geometrically declining cost per unit area [Colwell98]. Other key technologies include tools to study large and complex data sets, provide global data access, implement distributed data processing, and conduct research using virtual proximity and tele-robotic operation of remote sensors.

Our experimental theme is to explore the use of embedded network sensing to monitor the interactions of terrestrial organisms in their habitats, at multiple coordinated temporal and spatial scales. Current tools for sensing of organisms in situ range from satellite and airborne sensors that document "top down" biodiversity (e.g. spatial complexity of dominant plant species, patterns of environmental disturbance such as fire), to radio-telemetry and tags attached directly to animals to monitor their location and physiology. While many scientists and land managers study biodiversity using remote sensing tools, the fact is that the vast majority of the biodiversity, and resulting combinations of interactions within an ecosystem exists at very small scales, and is not readily observable with even the best airborne and satellite based sensors [Keitt-Milne97]. To get down to where the complexity is, so to speak, sensing and monitoring needs to become ground based [Hamilton92, Hamilton00]. Within these scales of observation are very limited tools to automatically sense organisms and habitats. Mainstream approaches to field studies involve labor intensive manual observational methods (e.g. distance or plot sampling, mark and recapture of organisms, and vegetation mensuration techniques). Although there is currently an enormous investment in these manual methods, the long-term cost and repeatability/reliability of these methods often preclude their application over large spatial scales or for the long term.

Breakthroughs in VLSI digital signal processing, ultra-miniature sensors, low-power micro-controllers, global positioning systems, and wireless digital networks will make it practical to develop cheap and nearly ubiquitous ground-based monitoring systems for outdoor field use. Data collected in this way can be more automatically integrated with spatial data such as hyperspectral imagery and geographic information systems. Observation techniques involving cameras and microphones are in increasingly widespread use, however they involve small numbers of devices and require continuous human observation, greatly constraining their capabilities in natural environments. Unattended, heterogeneous sensors/actuators will enable a vast range of new habitat studies via continuous monitoring techniques. The data from such a network will need to be filtered and partially analyzed within the network e.g. seismic sensors could trigger data-intensive assets such as cameras. The proposed technology offers the chance for programmed observation, triggered response with specified patterns, and automatically recorded and reported responses. Such capabilities require the development of robust, adaptive techniques for coordinating across distributed and heterogeneous sensor/actuator nodes, many of which may be wireless and energy-limited.

The availability of inexpensive environmental sensors for light, moisture and solar will also enable the application of embedded network sensing to ecophysiological research (Pearcy 1990, Baldocchi and Collineau 1994). Although the response of photosynthesis to radiation is well studied at the leaf level, scaling leaf processes to the whole canopy remain poorly developed yet critical in applications of ecophysiological research to the ecosystem-level (Ehleringer and Field 1993). Remote sensing of whole canopy processes has provided one approach, but the technology now exists to network large arrays of sensors for leaf-level microenvironmetal parameters to directly assess integrated plant canopy performance. We propose to integrate empirical data collected from such sensors to enable the development and parameterization of a new generation of canopy ecophysiological models (Kull, and Kruijt 1998, Anderson et al. 2000). The chaparral shrub canopies of Southern California present a size and canopy structure appropriate for integrating data from environmental arrays of sensors with architectural models of light interception and temperature distribution (Valladares and Pearcy 1999).

Fundamental technological advances are needed to enable adaptive, programmable multi-modal networks to identify ecological indicators of interest and use those to trigger analysis, correlation, and recording of events. Moreover, current techniques will not scale to very large numbers of wireless nodes and do not make effective use of multiple sensor modalities. To realize this goal we will develop and deploy unique and innovative capabilities at the James San Jacinto Mountains Reserve in Southern California (one of the University of California Natural Reserve System sites, and a member of the organization of Biological Field Stations)

We will develop and implement coordinated sensing and actuation to support experiments including: (a) triggered emission and recording of acoustic signals from target species, (b) monitoring and correlation of plant and soil chemical and physical properties, and (c) coarse and dense atmospheric monitoring. Multiple perspective imaging monitoring will be integrated through the addition of tower-based video cameras for stereo mapping of canopy topology and volume, monitoring of seasonal phenology of overstory tree species, and mid-ground level vegetation within the monitoring grids. Mobile nodes will also be integrated, such as an all-terrain robot for remote viewing, high resolution imaging, and the capability of filling spatial gaps in data collection within each monitoring grid. In the long term we will incorporate tagged-animals into the system through the use of micro-RFID tags. All of these capabilities will require application of self-configuring and energy-conserving algorithms and protocols to achieve ad hoc, wireless system deployment and operation in uncontrollable environmental conditions. Simultaneously with deployment we will develop user interfaces by which scientists and students can readily experiment with new data filtering and triggering rules to explore hypotheses and refine data collection.

This facility will allow us to develop scalable techniques for non-destructive, multi-scale spatio-temporal sampling and data visualizations, thus enabling the rapid and low-cost mapping of new dynamic scales of species diversity, ecosystem structure, and environmental change. The facilities will provide on-site and Internet-based opportunities for graduate students and faculty to utilize these new tools, including training and research application consulting. In concert with the educational plans described later in this proposal we will provide outreach applications of these tools and databases for integration into science and environmental education (K-12 and university) and local community-based biodiversity stewardship.

B. Spatially dense seismic sensing and structure response (Participants: Davis, Conte, Kohler, Daneshgaran, Estrin, Pottie, Yao)

Many of the scientific applications for embedded networked sensing are motivated by the need for finer granularity (higher spatial or temporal resolution) data in order to develop and validate models of physical phenomena. The theme of this experimental project is to bring high spatial resolution to seismic sensing and to correlate monitored activity with structural response. Currently installed seismic arrays are too sparse to adequately sample the seismic wave field. The TriNet Seismic Network in Southern California is one attempt to remedy the situation. [Mori-etal98] However for urban seismology an even greater density of stations is required, ideally at 100 m spacing to sample an unaliased wave field. Networking of thousands to tens of thousands of sensors will require development of new low power sensors and telemetry, inter station communication, in-network processing, data compression and development of graphical representation of massive data sets.

Several buildings on the UCLA Campus have been extensively instrumented for strong ground motion during an earthquake. The UCLA Factor building, with a state-of-the-art 72-channel accelerometer array, is the most instrumented building in North America. However, a thorough understanding of building response and damage incurred during an earthquake requires installation of a free-field seismic array. The nearby free-field and ground-level time history should be known in order to quantify the dynamic interaction between soil and structure. Presently engineers rely on free field readings from one or two seismic stations. These stations may be 10 km away and, therefore, are unrepresentative of the true ground motion, or may be so close to buildings, it is difficult to distinguish earthquake from building generated motion. Furthermore, during an earthquake the soil in which the foundations are rooted undergoes large strains, causing it to exhibit non-linear behavior compared to the linear motion of the underlying bedrock. Our proposal will install a seismic array of sufficient spatial density to completely characterize the seismic wavefield, including sensors at depth to characterize its non-linearity. A soil and structure seismic array should provide information to reconstruct the response of the structure in enough detail to compare it with the response predicted by mathematical and laboratory models, with the goal being to improve computational modeling and simulation methods for predicting response. Interfacing ground motion seismology and earthquake engineering is crucial to make further significant progress in reducing the earthquake hazard on the built environment.

The seismic wavefield exhibits spatial coherence over a distance equal to one wavelength of the frequency under consideration. Damage to buildings during an earthquake is often the result of shaking at resonant periods, given approximately by 0.1 seconds per story. Thus a full understanding of the seismic wavefield responsible for earthquake damage requires measurements at all frequencies up to 10 Hz. For typical seismic waves traveling at 1000 m/s this requires a network on a 100 m grid spacing.

Present seismic networks have not taken advantage of recent developments in Internet technology, array processing, and collaborative signal processing. Our effort will take advantage of the STC expertise in embedded networks, wireless radio, data mining, multicast routing, and will combine scientists involved in earthquake seismology with those involved in analyzing and designing earthquake resistant buildings, non-linear soil response, and network technology. The seismology investigators are also active members of the Southern California Earthquake Center.(SCEC). The results of this project will complement the mission of SCEC and will be shared at workshops and scientific meetings with SCEC scientists working in related disciplines.

We propose to construct and install a prototype 100-station, wireless, networked, seismic array covering the UCLA campus, in order to measure an unaliased seismic wavefield for a wide range of seismic objectives. The proposed array will provide several unique capabilities. Time-varying, wireless, subsurface imaging--this network will provide the most spatially dense temporally continuous seismic data available, potentially serving as a prototype for other 4D seismic networks. Strong motion engineering--the array will provide the first spatially unaliased free-field data for comparison with recorded building motion. It will permit deconvolution of building effects from the ground motion and provide essential data on linear and non-linear soil and structural response. Building activation--we will develop protocols to use a wireless networked array to optimize the use of building actuators at the time of an earthquake. Presently designed actuators rely on in-situ motion monitors. Advance information on seismic waves before impact from this array could be used to optimally detune a building to avoid resonance with incoming seismic radiation, such as those that toppled high rises in Mexico City in 1985. [Housner-etal97] As part of this project we will incorporate novel fiber optic strain sensors that promise to offer much greater flexibility and lower cost while retaining the accuracy of laser interferometers.

C. Contaminant transport monitoring (Harmon, Judy, Ho, Tai, Turco, Estrin, Khachikian)

The effectiveness of contaminant transport and fate investigations in any environment is limited by sampling density. This limitation is particularly well exemplified in the subsurface environment, where the transport medium cannot be visualized. In this domain, current researchers must be satisfied by discrete, labor-intensive samples collected intermittently over coarse synoptic and temporal grids. They are then forced to close information gaps using theoretical transport models. While many important research findings emanate from such studies, one cannot help but wonder how much further we might advance the field of environmental monitoring were it not for the limits imposed by sampling. This proposed CENS project is motivated by the need to revolutionize the observational mode for monitoring contaminant transport and fate in soil, air and water environments.

The project will team CENS environmental, electrical and mechanical engineers, computer and atmospheric scientists with the goal of accelerating the incorporation of networked chemical sensors into environmental transport modeling investigations. The team will initially attack the subsurface (soil/groundwater) problem, and do so at the intermediate scale. Intermediate-scale models are laboratory-fabricated so that the medium's geometry, however complex, is well known. Thus, these systems provide contaminant hydrogeologists, environmental and agricultural engineers and others with a realistic yet definable venue in which to test transport and fate hypotheses. At the same time, intermediate-scale systems offer an excellent venue in which to test sensor networking for two reasons: (1) The sampling network density required for these systems increases massively with increasing realism of the porous medium under investigation, and (2) As the sampling synoptic and temporal density increases, the data supplied by these systems become plagued by sampling-induced artifacts.

The approach is stated in the form of the following objectives: 1. Develop and test a dense network of immediately available sensors (for electrical conductivity)) to characterize the hydrodynamic dispersion aspect of solute transport in a previously studied porous medium; 2. Exercise and evaluate the sensor network in a variety of complex (i.e., heterogeneous) porous media, and 3. Extend the mass transport study to include more complex mass source/sink conditions (e.g., chemical dissolution and biotransformation) through the development of novel biochemical sensors.

The project will be laboratory-based and will make use of a previously calibrated physical aquifer model for simulating the dissolution and transport of contaminants (chlorinated solvents) in a groundwater system [Chrysikopoulos-etal00; Sciortino-etal00]. Dispersion characterization for this physical model is now manually executed on a relatively coarse grid in a procedure requiring 1-2 days per event and one- to two-week recovery times between events. Tritiated water is employed to provide the most accurate results. Despite painstakingly careful procedures, the results are significantly biased by the sample removal process. Thus, the current procedure consumes about 9 to 12 months and yields results subject to significant uncertainty. The project team proposes to equip the physical model with a dense sensor network that is capable of continuous, automated sampling. This network will provide a data set that is continuous and more complete than any manually derived one, and will do so in less than one month for a typical experiment.

After successful demonstration of dense network sampling in this model system, we will extend the work to larger, more realistic model systems. The U.S. Department of Energy is currently planning to install an intermediate-scale subsurface transport and fate testing facility at the Idaho National Engineering and Environmental Laboratory (INEEL). INEEL personnel have visited UCLA and will collaborate with the proposed STC investigators by (1) Incorporating STC sensors and sensor-network designs in INEEL intermediate-scale experiments and (2) Sharing INEEL sensor developments with STC personnel.

The research techniques and technology developed will have broad applicability to other environmental monitoring research. Once ready, the sensors and networking protocols useful in the design of large-scale sensor networks will be deployed in the field for a wide variety of environmental health monitoring and management applications. For example, sensors and networking strategies developed in the soil-water systems will be adapted for deployment in surface water and atmospheric monitoring regimes. Sampling will target conventional meteorological conditions (e.g., temperature, wind speed) as well as pollutants in gaseous and particulate-bound phases. One near-term future project will attempt to instrument and orchestrate the dense atmospheric monitoring of pollutants on the UCLA campus, and at urban regional scales in the Los Angeles Basin (LAB). Such an effort is a natural extension of the atmospheric monitoring planned for the Habitat Phase I project. In particular, at the campus scale, the ability to monitor the concentrations of specific chemicals emitted by laboratory and facility operations offers valuable information to administrators and faculty on the efficacy of emission controls. Moreover, this experiment would provide a prototype for similar environmental monitoring systems at industrial and commercial sites. The longer-term application will be at the urban scale. Systematic regional monitoring of pollutants at resolutions currently unattainable would offer an invaluable means of assessing health impacts at the level of neighborhoods, would provide needed data for assimilation into models used for predictions and analysis of pollution sources, and would arm policy makers with dense data sets needed to make informed decisions.

D. Monitoring of Marine Microorganisms (M^3) (Caron, Requicha, Estrin, Sukhatme, Ho, Tai, Zhou)

Our primary long-term scientific goal is to understand and ultimately predict the conditions under which specific populations of marine microorganisms develop in nature. A fundamental requirement for attaining this objective is the correlation of environmental conditions with microorganismal abundances at the small spatial and temporal scales that are relevant to the organisms. This is not possible with extant technology and methodological approaches. Sampling the environment with high resolution and identifying microorganisms *in situ* in near-real time will constitute revolutionary advances in the study of the ecology of marine microbial species. In addition, the rapid identification of aquatic microorganisms will be extremely valuable for the early detection of harmful organisms and the mitigation of their effects on the environment and the human population.

Marine microorganisms such as viruses, bacteria, microalgae, and protozoa have a major impact on the ecology of the coastal ocean. For example, blooms of harmful and/or toxic algae (e.g. red, brown and green tides) in aquatic ecosystems have increased dramatically on a global scale in recent years [Anderson97]. These events result in the loss of human life each year, and economic losses in the billions of dollars due to effects on fisheries and tourism. Likewise, the increasing encroachment of humans along coasts has resulted in the recognition of potential public health issues as a consequence of the introduction of pathogenic microorganisms into these waters from land runoff, storm drains and sewage outflow. Similar concerns exist regarding the potential for contamination of drinking water supplies with harmful, pathogenic or nuisance microbial species. Today, the environmental factors that stimulate the growth of such microorganisms are still poorly understood, and tests for their abundances are not sufficiently rapid to detect the onset of major outbreaks. This aspect of the CENS will specifically address these issues.

Our initial work will be done in the laboratory, in two environments. The first is a meter-scale tank in which we will deploy a large number of centimeter-scale sensors. The goal here is to coordinate the sensors and collate information arising from them. These sensors will be tethered and mobile, albeit in a restricted fashion. They will be programmed using the distributed techniques discussed in this proposal, and include some of the physical and chemical sensors developed by CENS. Important parameters such as temperature, salinity and O_2 content will be measured with centimeter resolution. Microoganismal abundances will be determined in water samples collected and analyzed in the lab using currently available DNA-based or immunological approaches (which destroy the cells and tend to be slow and elaborate) [Caron-etal99a; Caron-etal99b].

The second environment is a centimeter-scale “liquid cell” of a Scanning Probe Microscope (SPM). Here data can be collected with a spatial resolution on the order of a micrometer (or even less), although there is only one sensor (the SPM tip) which is programmed in a centralized manner. The SPM environment will be used principally to develop new techniques for rapid, non-destructive microorganism identification based on antibody-antigen interaction. We will use a specific single-celled microalga (*Aureococcus anophagefferens*, a harmful bloom-forming species) which we know how to culture and for which we have developed a highly specific monoclonal antibody. The microorganism will be detected by using tactile sensing — in essence, by determining the force between an antigen on the organism’s cell surface and an antibody attached to the SPM tip. We will experiment with flexible tip-antibody linkers [Hinterdorfer-etal96] and also with functionalized carbon nanotube tips. We have several years of experience in SPM programming for imaging and manipulation in air and in liquids [Resch-etal98], we also have the necessary know-how for carbon nanotube tip preparation and operation [Dai-etal99], and therefore are extremely well qualified for this work.

The laboratory work, when fully developed, will constitute a revolutionary step in the tools presently available for investigating the ecology of aquatic microorganisms, as explained above. It will serve also as a test-bed for initial investigations of the issues that arise in monitoring the coastal ocean, which is a major application of the research we propose. Imagine, for example, that a set of instrumented buoys is deployed in the Pacific Ocean, near the mouth of the Los Angeles river, to monitor the impact of the river effluent on the coastal ocean ecosystem. Effective strategies for tracking the microorganisms carried by the fresh water can be developed, simulated and assessed at a reduced scale, in the tank environment, by injecting into the tank a suitable flow and using the network of tethered sensors.

This project will also make major contributions to the science and engineering of sensor/actuator networks, because of the requirements it imposes on the network: (i) mobility – to track microorganisms and assess their abundance with a reasonable number of sensors, these must be mobile; (ii) size – to gather information at a spatial scale comparable to the size of the microorganisms and to avoid disturbing them (especially in the laboratory environment), the sensors must be very small; (iii) liquid environment – combined with the small sensor size, this raises many difficult issues in mobility, communications and power, which in turn strongly impact network algorithms and strategies; and (iv) sensing – *in situ*, real-time identification of microorganisms is an unsolved problem, which requires the development of new sensors. In addition, the M^3 project involves all the algorithmic problems identified in the technology sections, such as coordination, triggering, and so on.

Over the expected ten year duration of the CENS there will be major advances in nano and micro sensors and actuators, and in strategies and algorithms for programming distributed, physically-coupled systems. Many of these advances will come directly from CENS research. Most of what we will learn from our research in marine monitoring and single-cell identification is expected to be applicable to an even more important liquid environment – the circulatory system of higher organisms, including humans.

3. Summary

These initial applications were chosen because of the potential for high-impact scientific contribution and the diverse technical challenges posed. The experimental systems span diverse physical media—from subsurface ground and water to terrestrial and atmospheric monitoring and observation. Moreover, these applications represent the scale and complexity of the natural and manmade environment. This diversity will allow CENS researchers to develop general approaches to the science and technology of embedded networked sensing. Techniques and technologies will be further refined and developed as we engage additional scientific applications in the CENS.

CENS will begin with the four application described. However, during the course of the Center's lifetime we will expand to pursue opportunities based on new demands, as well as new supporting technologies. Potential areas include: In Situ Planetary Exploration in collaboration with JPL CISM, and 2. BioMEMs as early warning systems for a myriad of public health concerns (e.g., monitoring cattle, crops).

Education and Outreach

CENS focuses a significant portion of its resources on grades 7-12 science education. In addition, CENS contributes to the education of graduate and undergraduate students by involving them in state of the art engineering and scientific research and system development.

1. Grades 7-12 Science Education

CENS's embedded networked sensing technology enhances 7-12 science education in ways that promote students' authentic inquiry into science as advocated by current standards. These standards call for inquiry to be a central strategy of science teaching [NRC96]. Students should understand that the sciences "are defined as much by what they do and how they do it as they are by the results they achieve. To understand them as ways of thinking and doing, as well as bodies of knowledge, requires that students have some experience with the kinds of thought and action that are typical of those fields" [AAAS92]. We recognize that such inquiry poses many challenges for teachers and students. Sustainable efforts to use real scientific data in middle and high school classrooms require well-structured curricula that help students explain their world, and a cadre of teachers who can make such curricula meaningful to students' lives [Hood-etal99]. Therefore, our grade 7-12 educational and outreach program consists of: (1) Developing 7-12 *Inquiry Modules* that transfer real-time, real-world data into standards-based classroom learning; (2) Evaluating and refining the *Inquiry Modules* and CENS instructional materials; (3) Preparing 7-12 science teachers to integrate these modules into their classrooms; and (4) Dissemination of materials and outreach.

1.1 Inquiry Modules

The first years of CENS' educational program focuses on two of our four CENS application domains (habitat monitoring and seismic sensing). By working with the two domains that are the most conceptually accessible of the CENS projects, we can focus on the educational opportunities and challenges of in situ sensing in detail. Once these issues are resolved, development of Inquiry Modules for other domains will follow.

With CENS's embedded networked sensing technology, students remotely observe complex systems in nature. This alone is exciting to grade 7-12 aged children, but CENS goes further in that it allows students to address *their* original questions by *their* creation of new experiments that direct the networked sensors to collect data in a way *they* design. We realize that providing real data to middle and high school students is, in itself, no guarantee that good learning will occur. Indeed, students have several difficulties when initially trying to conduct their own inquiry into rich scientific problems, including asking un-testable questions, designing undiscriminating experiments, incorrectly interpreting data, and so on [Krajcik-et al.98]. Also, the data representations professional scientists use are usually too cryptic for students to comprehend [Gordin-et al.94].

The CENS brings together the combined expertise of educational researchers, information scientists, natural scientists, and teachers into a collaborative model to address these issues. The result of this collaboration is the *Inquiry Module* that transfers CENS capabilities into the classroom effectively and efficiently. Each *Inquiry Module* is developed by focused, collaborative teams including domain experts, grade-level teachers, educational researchers with experience developing and studying inquiry-based learning environments, and information scientists experienced in integrating complex data and interactive tools into curricula.

Working with our initial partner schools, the Buckley School (unique for its Chaparral habitat) and New Roads School (unique in its cultural diversity and experience with seismometers), we will initially develop two *Inquiry Modules*. Drawing from anticipated sensor data, these modules will include staging activities that introduce students to needed concepts and skills to conduct their own inquiry, guided inquiry activities that scaffold students through active exploration and experimentation using CENS capabilities, and follow-up activities that help students tie their own investigative activities to important subject-matter conceptions and to broader ideas about the nature of scientific knowledge and practice.

Our team has substantial expertise in such collaborative design, including the development of technology-supported inquiry curricula for biology following the above model [Reiser-et al.]. Dr. Orville Chapman at ULCA et. al. have developed and field-tested a new educational tool known as Calibrated Peer Review, CPR, (http://cpr.molsci.ucla.edu).This tool has been shown effective in developing students' abilities to think and write critically about scientific ideas and experimentation [Russell-et al.]. We will develop CPR's potential to link student remote sensing activities to standards-based classroom learning. We will use Perceptual Learning Modules (PLM's) developed by Dr. Phil Kellman of UCLA to help students quickly and efficiently learn to identify salient patterns in experimental data [Wise-et al.]. UCLA's Alexandria Digital Earth Prototype Project (ADEPT) (funded by the NSF Digital Libraries Initiative) is an innovator in integrating data obtained from remote sensing into the undergraduate curriculum. During the initial years of the CENS projects, ADEPT participants will use their experience to advise on the complementary in situ data collection and interrogation capabilities in the context of grades 7-12. In the longer term, when longitudinal studies and correlation with remote-sensing data capabilities are added, their expertise in digital libraries also will be essential in managing and deploying the repositories of sensing data in educational applications

The formation of CENS leverages the efforts of these existing groups with the Center's educational team to produce exciting new curricular possibilities. The following two *Inquiry Modules* will be developed in parallel but will leverage large amounts of shared design, development, software, testing, and methodology. Weekly meetings will be held with the education staff, as a whole and regular interaction will be maintained with the UCLA CPR program as well. *Inquiry Modules*, as described above, will be developed around the following activities.

Inquiry Module #1 - Middle School Life Science Application: Habitat Monitoring

During the Center's first year, CENS will initiate a hummingbird behavior and Western Bluebird habitat-monitoring project with The Buckley School and the James Reserve. Students will access, via the James Reserve's web site, video data from eight existing web cams focused on nest boxes and a feeding station of the Western Bluebird and on a hummingbird feeder frequented by Anna's Hummingbird. By the end of year one, two webcams, activated by "off-the-shelf" sensors, will be constructed and deployed at the James Reserve and The Buckley School campus. At this point, students will pose simple questions such as, "Does habitat influence the behavior or change the physical appearance of a species?" To find a possible answer to this question, students will compare the populations of Anna's Hummingbirds in a chaparral community (The Buckley School) with those in a coniferous forest (James Reserve). Simple observations such as this have not been feasible previously because it required sifting through hundreds of hours of video to isolate only the events of interest. The triggering mechanisms introduced by CENS will bring streamlined experimentation capabilities to the classrooms. In addition to being able to iterate on the posing of questions and collecting of data, students will iterate on their experimental method and address questions of correlations and experimental controls

In year two, Western Bluebirds will be tagged with a barcode-like, information-encoded band. Acoustic, barcode-reading sensor arrays will monitor the movement of the Western Bluebird within the James Reserve. Students will collect behavioral data and identify individual birds. Students can, at this stage of sensor development, propose more sophisticated hypotheses such as, "Mobbing behavior in birds is an adaptive behavior of juvenile males who seek the attention of females; the more aggressive mobbers would have greater reproductive success." To test this hypothesis, a "fake predator" could be introduced and students would observe the behavior of tagged birds and use the video data to determine in which age group the mobbers belong.

By year three, sensor arrays deployed throughout large areas of the James Reserve will monitor wildlife corridors. Students could ask questions such as, "Do mule deer exhibit territorial behavior?" Students will also manipulate environmental variables, such as mechanically releasing different sizes of bird feed to study food preferences. Data collected by the wildlife corridor arrays will also interest research scientists and organizations such as the Nature Conservancy and the Audubon Society.

In years four and five, a "smart grid" will permit simultaneous data collection allowing students to study the reserve as a complex system. Students will use the bio-complexity data collected by the habitat sensing arrays to model collective behavior with other educational software, such as StarLogo (Resnick, 1992; 1993; Colella, Klopfer and Resnick, in preparation). This software can help students understand the concept of decentralized phenomena. Participation in this and other similar activities will be evaluated as a training tool for inquiry-based learning.

Inquiry Module #2 - Upper School Physical Science Application: Seismic Sensing

The physical sciences are initially addressed by a partnership with the Los Angeles Physics Teachers Alliance Group's seismometer project. This project, made up of 20 schools, has distributed 10 seismometers to schools in the Los Angeles Basin. In year one, the CENS staff will devise solutions to the problem of synchronizing the timing of these 10 seismometers and bringing the seismic sensing online concurrently with the initial UCLA campus seismic facilities. The educational software development staff will work with students during this development year to digitize a map of the region and write software that places a mark on the map for a given latitude and longitude. Once these tasks are completed, students will log onto the USGS web site each day to get the location, magnitude, and time for any earthquakes that have occurred in Southern California. Students will compare this information with the seismometers at each school with millisecond timing accuracy. They will also have access to similar data collected by the UCLA campus grid. Using the digitized map and the software, students will determine if their school's seismometer detected the earthquake. A mark indicating a "yes" or "no" will, over time, help the students visualize the location of "seismic wave-guides" that exist in the region. This phenomenon was observed in the recent Northridge earthquake. Assuming several seismometers detect an earthquake, the students will use triangulation to verify the location of the epicenter. Magnitude can be determined with software developed for the seismometers using standard algorithms. Note that low-level seismic activity is frequent enough that every class is certain to have the experience of analyzing events during the course of a semester.

In years one and two, CENS faculty will develop Perceptual Learning Modules™ that train students to distinguish between earthquakes and noise as well as determine the location of the primary and secondary waves in a seismic trace. Faculty will also transfer the remote sensing activity into the classroom by developing science standards using Calibrated Peer Reviews™. During years three through five, the curriculum will be refined and extended to study input from sound waves collected by acoustic sensors.

1.2.Evaluative Process

UCLA's Graduate School of Education and Information Studies (GSEIS) will design and conduct a formative *external* evaluation throughout the project, beginning with baseline data in year one. The evaluation data will be employed continuously and iteratively to drive the design of our *Inquiry modules*. By the fourth year, we will be gathering summative data on pedagogy and learning. We will employ a combination of qualitative (e.g., interviews, small groups, classroom observation) and quantitative (e.g., student testing, online monitoring data of student activities) methods, within the usual human subjects/Institutional Review Board guidelines. Two core interests guide the evaluation research: a) student learning and b) teacher integration.

Student learning: Inquiry-oriented approaches such as ours are valued because they can improve a) student learning of important domain concepts (e.g., about ecosystems or seismic events), b) student ability to conduct scientific inquiry, c) student interest in science; and d) student understanding of the nature of science. We will evaluate each CENS *Inquiry Module* in each of these four areas. Conceptual learning is assessed primarily through domain-specific tests. Where feasible, we draw on previous assessments, such as National Assessment of Educational Progress (NAEP) items, as well as on the cognitive literature on students' conceptions in applicable domains. Where CENS modules go into novel domains, we will develop appropriate conceptual assessments. We will make extensive use of existing data from the CPR group, and will work with them closely to learn from their experiences. We can assess students' skills at conducting inquiry through a variety of assessment instruments, such as NAEP or the Science Process Skills Inventory [Germann-et al.96]. We will also conduct ethnographic classroom studies to examine in detail how students work with sensor data, design investigations to use sensors, and so on. Such fieldwork will be essential to evaluating our software and curricular designs. Students' interest in science and beliefs about the nature of science will be measured through a variety of existing questionnaires and interviews.

Teacher integration: Since the kinds of data that the CENS sensor arrays allow students and teachers to explore are quite novel, just as it is for the scientists on this project, a major focus of our educational research effort will be to understand how teachers integrate the use of such data into their curricula. We will conduct field studies with our initial partner teachers as soon as usable *Inquiry Modules* can be developed, probably starting in year two. These observational studies allow us to document how teachers guide students' effort to work with sensors and interpret the data they get from them. We also will examine how teachers' scientific knowledge of CENS domains deepens through their professional development experiences, as well as how teacher experiences with authentic science changes their ideas about the nature of science. As the number of teachers using CENS modules expands in years three through five, we will use surveys and questionnaires to evaluate teachers' experiences with these modules.

1.3. Faculty Training

Another major strength of CENS is how it leverages existing professional development programs such as those at California State University at Fullerton, Los Angeles, and Northridge. These Universities play a pivotal role in teacher pre-service and in-service training and are anxious to explore methods for training faculty to integrate *Inquiry Modules* into their classrooms.

At UCLA, the Graduate School of Education & Information Studies' Center X is a national leader in urban teacher education and professional development and has strong partnerships with urban Los Angeles middle and high schools that, arguably, are most in need of the rich science experiences CENS can offer. UCLA also houses the California Science Subject Matter Project, a statewide teacher professional development program. Another CENS partner is the Science Standards with Integrative Marine Science (SSWIMS) outreach education program at UCLA. Approximately 80 schools in California have a science teacher trained by SSWIMS, an NSF-funded training program for teachers of grades 5-12 that designs curricula in accordance with the California State Science Content Standards. Additional teacher training will be explored through existing programs such as that managed by the Los Angeles County Museum of Natural History. The Los Angeles County Museum of Natural History has partnerships with five neighboring inner city schools. Beyond our commitment to and connections in Los Angeles, teachers across the country can learn about teaching with these new sensor technologies through publications and workshops held by the National Science Teacher Association.

1.4. Dissemination and Outreach

In the first two years, CENS will develop and deploy sensor arrays. The Inquiry Modules developed by CENS will be alpha tested during years two and three. During years four and five they will be beta tested in the greater Los Angeles area through existing CENS partners. Formative evaluation by GSEIS will help refine the materials to meet our educational objectives. At the end of the fifth year, materials will be made available to educators across the country. The results of our evaluation of teacher integration of the use of CENS data will be reported in journals and professional conferences. Our partners will utilize CENS materials and teacher practices in their faculty training and workshops programs.

As CENS evolves, so will its educational applications. Embedded networked sensing will enable educators to reveal the many connections between life and physical sciences and further students' understanding of complex systems. Future applications of this technology will bring new, exciting science investigations into the classroom. The timeframe of an STC will give CENS the chance to adapt to opportunities as they arise. However, even at this early date we can identify areas to which CENS hopes to contribute and further disseminate its findings and technology:

1. Environmental Monitoring — As the technology for environmental monitoring develops, it will provide unique opportunities for students to engage in scientific investigations that are of clear concern to their lives, namely the monitoring of contaminants and pollutants in the environment;
2. Planetary Exploration –The ability to field a multitude of scientific monitoring stations on planets such as Mars will revolutionize our ability to search for evidence of signatures of life, as well as provide for a revolutionary capability to perform distributed scientific observations. A planned JPL CISM national test-bed would serve as an excellent educational vehicle that would expose students of all ages to exciting space-science applications;
3. Longitudinal Studies — as the Digital Library technologies develop, CENS educational materials can be extended to support collection and analysis of longitudinal data so that students will be able to base hypotheses on previously collected data and to compare their results and make them available to other groups of students across the country;
4. CENS Technology Kits — as the sensor network technology develops we hope to design and work with other organizations to make available technology kits for instrumenting other environments and thereby facilitating wider usability of the approach and promotion of related curriculum development and teaching innovations;
5. Collaboration with Existing Educational Programs–Existing programs (e.g. Telescopes in Education (TIE) and The California High School Cosmic Ray Observatory (CHICO)) are interested in utilizing the educational tools and expertise of CENS to better serve their student and faculty participants.

2. Research Internships for Undergraduates (Estrin, Daneshgaran, UCLA CARE Program office)

The second component of our education emphasis will be research experience for undergraduates in the form of internships. These internships will give undergraduate science and engineering students' exposure to emerging micro-sensor technology, wireless communications, and embedded software technologies, as well as with the scientific and environmental applications. The students will be involved with assisting in system deployment, data collection, as well as with development of software for educational delivery and user interfaces.

The program will be run by the UCLA Center for Academic and Research Excellence (CARE) program office, which has over 10 years of experience and an excellent track record for recruitment, retention, and advancement of under-represented minority students. CARE was established in 1991 to meet the needs of underrepresented minority science students in an institution like UCLA, i.e. a large, public research university. CARE's mission is to increase the retention of underrepresented (African American, Hispanic American [Chicano and Latino], Puerto Rican, Native American, Alaskan Native, and Pacific Islander) students in science and engineering majors and to increase the number of such students who go on to careers involving research. CARE membership is open to all UCLA science and engineering students who have faced educational, economic or social barriers making them less likely to benefit fully from the educational opportunities offered at UCLA.

During the academic year CARE sponsors numerous career development workshops and seminars and supports the research activities of approximately 100 undergraduate research students through the CARE Undergraduate Research, CARE Scholars, UC LEADS, MARC, and Howard Hughes Programs. The CARE Undergraduate Research and CARE Scholars programs provide employment or stipends totaling \$500-\$1,000 to students engaged in research to replace outside jobs as a source of income. The UC LEADS Program provides eighteen juniors and seniors with \$13,000 per year to support their research activities. The MARC Program provides 10 undergraduate fellowships covering all student fees. The HH program supports 10 outstanding research students during the academic year ($1,000 per term) and summer ($2,500). CARE also administers Journal Clubs for UC LEADS, Howard Hughes and MARC students and supports seminars by UCLA and visiting faculty.

Students will be placed with CENS research projects and will participate in CENS activities (meetings, workshops, conferences). Each undergraduate will be assigned a graduate student mentor in their associated project, providing both sets of students with a unique and highly valuable mentoring experience. CENS undergraduates will similarly have the opportunity to act as mentors to students participating in the 7-12 educational programs. All students will be invited to informal weekly "teas" and to monthly CENS symposia, as well as special workshops and annual meetings.

Research in the area of distributed sensor networks information processing has been traditionally confined to large research institutions due to both the costs associated with conducting research in this area and the lack of expertise in many Minority Institutions (MIs) to initiate research in this very active and vital field. The UCLA CARE Program, and other similar programs around the country have found one of the most effective vehicles for change is to introduce students to hands on experiences in a real laboratory setting early on in their education. One of our objectives is to bridge the gap between undergraduate and graduate education for our minority students in this technologically vital field and encourage the pursuit of advanced degrees.

A significant fraction of the students to be chosen for the CENS research internships for undergraduates program will be outstanding minority students from Cal State University, Los Angeles (CSLA). CSLA is one of the 22 campuses that constitute the California State University system. Both the student population of 19,000 and the faculty are highly diverse, reflecting the demography of the area that CSLA serves. It is a minority institution; specifically, it is a Hispanic Serving Institution, and is one of the few minority institutions with an accredited Engineering school. A study of the California Post-secondary Commission revealed that CSLA ranks first in California in terms of the proportion of its Engineering degrees awarded to minority students. In a nationwide survey published September 16, 1996 in US News & World Report, CSLA was ranked in the top-20 among the best Engineering schools without Ph.D. programs

The research and teaching assistantships available to our diverse student body will have a significant benefit by enhancing our students' abilities to solve real life problems, providing them with in-depth technical knowledge in a very specialized field in high demand, increasing their effectiveness in communicating their ideas in both oral and written forms, enhancing their ability to work cooperatively and collaboratively with others, improving their ability to use computers for communication and for solution of technical problems, and motivating them to continue their learning experience by attending graduate school.

In summary, CENS will pursue educational contributions through the three phases of: (1) prototype curriculum development that exploits innovative CENS technologies and facilities, (2) classroom trials and teacher training to refine and evaluate curriculum approach and software, and (3) preparation of materials for distribution through appropriate channels, including curriculum, teacher training, and sensing-technology kits to a broader community. *We anticipate numerous opportunities for such curricular developments during the course of the CENS lifetime.*

To summarize, the early years of the CENS educational program will be carried out in three phases: 1) Technology and user interface development in concert with prototyping the curriculum; 2) Pilot teaching with prototype technology and educational software, including iterative redesign; and 3) Development of in-service and pre-service teacher training modules and packaging for use by other teachers.

Knowledge Transfer

The Center for Embedded Networked Sensing (CENS) will be perfectly situated both physically and programmatically to draw on a wide variety of outlets for knowledge transfer. We describe the key linkages between CENS and government laboratories and educational, research, and industrial entities. We also describe strategic interactions with other existing entities across the participating campuses. The transfer of knowledge is applicable to all foci in this proposal: Technology development, Application development/facilitation, and 7-12 education and outreach. Technological innovations developed in CENS will be of vital interest to those corporations engaged in the development of both core technologies and application support. Moreover, the constituent technologies and the applied systems to be developed at CENS are of great interest to a wide range of government agencies from early adopters such as DARPA and DOE, to EPA and FDA as well as to the broader scientific community. Finally, the educational innovations and materials will be made available and actively transferred through teacher training and kit-development.

1 Industrial partners/collaborators

There are numerous opportunities for commercial applications of embedded networked sensing and its constituent technologies. For example, it is estimated that 98 percent of the 8 billion computer processing units produced in the year 2000 ended up embedded in the world around us. Clearly, low-power wireless communications will have an early impact in “smart spaces”. However, such systems will also require the robust self-configuring techniques developed by CENS. In the future, a broad range of commercial applications (e.g., sophisticated industrial process control facilities, and precision agriculture) will also require the advances in distributed integrated sensing and data analysis to be developed in CENS.

Industrial partners will benefit directly from CENS activities across an array of applications. This breadth will complement the narrower experiences typically afforded by a competitive market place. Partners will benefit from access to early developments through quarterly online updates, annual meetings/workshops and faculty / industry researcher interaction. Moreover, CENS students will bring CENS research directly to the corporate community through summer internships. Eventually, through permanent hiring by industry CENS graduates will provide the highly skilled scientific and technology workforce of the future. In addition, CENS will develop opportunities for visiting industry engineers to will allow them to learn about and experience CENS technology and applications first hand.

By partnering with industry on specific component technologies CENS can develop systems that may be otherwise unfeasible or unaffordable to build on campus. Moreover, industry funding will be used to augment support for the CENS graduate and undergraduate internships program and to co-sponsor workshops and symposia. Industry partners to date include: Intel, Sun, Xerox, Cisco, Crossbow, WindRiver, ST Microelectronics, and TRW. The letters are indicative of the significant opportunities for industrial support as commercializable technology emerges from this work.

2. Government laboratories and agencies

CENS technology is of great interest to the full range of government laboratories and agencies; in particular DOE, DOD and NASA. DARPA, as one of the early developers and adopters of wireless sensor network technology, has significant interest in a wide range of technological developments, as well as application experiences. DOE and its associated laboratories conduct some of the most sophisticated research in areas such as contaminant transport. Our activities will benefit these government laboratories and their broader research communities. Moreover, National Laboratory facilities will make excellent complementary test-beds and present opportunities for evaluating the generalization of our approaches. NASA requires technology for remote planetary exploration that share much in common with CENS application systems. JPL is a full partner in the center and will be a conduit for expertise available in the Space Sciences community, as well as an outlet for CENS technology developments

Interaction with Government laboratories and agencies will be through participation of government and National Laboratories speakers in CENS symposia and in joint research projects. Summer internships for CENS students in agency and National laboratories will provide a rich vehicle for collaboration and knowledge transfer.

3 Larger academic/research community

CENS will also support knowledge transfer to and from the academic community at large. CENS will coordinate and serve as a repository for the design of common components (e.g., special sensors, actuators with packaging and interfaces and software so that it can be integrated easily into experimental apparatus). Currently, the commercial market for many sophisticated sensors is insufficient to justify industry investment. By coordinating this demand, CENS will enable more sensor based experimental research to be conducted nationally. To this end we will collaborate with the newly funded NSF Engineering Research Center at the University of Michigan - the Center for Wireless Integrated Microsystems (WIMS).

CENS will also collaborate with the California State University, Los Angeles (CLSA) research unit CEA CREST. This NSF-funded center focuses on providing interdisciplinary research training in the environmental sciences at the MS level. Such a collaboration is mutually beneficial: CEA CREST investigators gain access to CENS-generated knowledge and CENS investigators are exposed to a wider array of environmental test beds for their technologies.

CENS will also serve as a community builder and catalyst by organizing local workshops and panels at national technical conferences. Continuously updated information on experimental infrastructure, data and methodology will be readily available at the CENS website.

4 Science education community

Finally, as described in the Education and Outreach section of this proposal, CENS will be heavily involved in significant knowledge transfer to the Science education community. CENS will integrate its technology opportunities into sample middle and high school curricula. As described in Section 6 of this proposal, based on trials in the classroom, CENS will partner with existing teacher training programs to prepare training modules for the integration of interactive-sensor network access into the science curriculum. Finally, we will engage in the production of prototype curricula and kits to distribute the techniques more widely. CENS will pursue these objectives by working with existing innovators in science curricula. Similarly the teacher-training program will be integrated with existing teacher-training programs such as GLOBE, CEACREST/CSLA, and the UCLA STEP (Science Teacher Education Program).

The strength of the education and outreach component lies in the breadth and depth of its constituents, namely: the experienced classroom professionals associated with the 7-12 project (one with 27 years experience, the last nine in distributed, sensor-based instruction); educators of classroom teachers such as the California State Universities which are expert in pre-service and in-service training and responsible for the training of a large portion of all teachers in California; current educational projects involving remote monitoring such as the Ocean Globe Project, the Los Angeles Physics Teachers Alliance Seismometer Project, and the Alexandria Digital Earth Prototype Project.

5 Interaction with External organizations

One of the distinct advantages of UCLA is that the Medical School, the School of Engineering and the College of Letters and Science are all on the same contiguous campus. This not only affords a distinct advantage to interdisciplinary research projects like CENS but allows the kind of outreach which brings into the program scientists and organizations that might not ordinarily collaborate or participate in such a multidisciplinary way. This same benefit exists in the physical proximity of the partnering institutions: UCLA, USC, UC Riverside, Caltech and California State.

At the UCLA Campus, CENS will formally interact with the following centers, institutes and programs that represent the mathematical, engineering, physical, life and educational sciences.

5.1 Related UCLA Research Institutes, and Projects

The NSF Institute For Pure and Applied Mathematics (IPAM) is a newly established NSF Mathematics Research Institute whose mission is to launch new collaborations with a broad spectrum of mathematicians and scientists, to communicate on interdisciplinary problems and to broaden the range of applications in which mathematics is used. CENS interactions with IPAM will allow longer-term opportunities for developing mathematical foundations of large, distributed, physically coupled systems— in particular, collaborative signal processing, self-organizing systems. Dr. Estrin is a member of the organizing committee for the IPAM 2002 Program - Large Scale Communications that focuses on the ill-understood dynamics of large-scale complex internetworks. In addition to training post-doctoral scholars, IPAM offers an undergraduate program through the Harvey Mudd College Math Clinic. CENS will offer summer project opportunities for IPAM/Harvey Mudd undergraduates.

California Nanosystems Institute (CNSI) is one of three new Science Institutes established in 2001 by Governor Davis in California. CNSI, a partnership between UCLA and UCSB, will provide a multidisciplinary laboratory for the development of key 21st century biomedical and information based technologies at the nanoscale. CNSI will present opportunities for CENS to consider the applicability of techniques developed for meso- and micro-scale systems, to nano-scale elements. Moreover, CENS systems will provide early application opportunities for CNSI-developed technologies. This interaction will be fostered through joint symposia, collaboration between faculty in each center, shared planning of graduate academic and research programs, and coordinated recruiting.

The Institute for the Environment (IoE) is a unique academic unit at UCLA devoted to interdisciplinary research and teaching related to environmental issues. Its faculty represent a broad range of disciplines-- the sciences, public policy, engineering, law, business and public health. IoE has an extensive program of outreach to the K-12 and public community. CENS applications research faculty Turco and Harmon are both members of the Institute (Turco is the Director and Harmon a founding member). We anticipate an extended and productive association between IoE and CENS and see IoE as a long-term identifier of high impact areas for environmental monitoring and a portal for CENS outreach programs. As described, the development of dense atmospheric sensing projects is already planned.

The UCLA Medical Center/The UCLA Biomedical Engineering Program was established in 1997 and follows in the long UCLA tradition of interdisciplinary education and research. Its focus is the integration of life and engineering sciences and its application to the problems of healthcare and biology. Current and future opportunities in research and education exist between the Biomedical Engineering program and CENS specifically in the development of technologies for physiological and public health monitoring. As the program expands faculty will exploit this connection to pursue the application of CENS technologies to biomedical applications.

The UCLA Graduate School of Education & Information Studies (GSE&IS) was established in 1994 via the merger of the Graduate Schools of Education and Library and Information Sciences The latter now incorporates a wide range of research, teaching, and outreach activities in information technology, behavior, policy, and institutions. The Education Department is internationally recognized for its research in urban schooling, research methods, comparative education, and higher education, and includes an acclaimed teacher education program. Faculty from both departments are involved in CENS and represent the synergy of research in the school. GSE&IS' Center X, a research and professional development center with extensive ties to schools and teachers in Los Angeles, will support the dissemination of CENS-developed education modules

5.2 Related University of Southern California Research Institutes

Information Sciences Institute is one of the nation's leading university-based information processing research centers. ISI programs blend basic and applied research through exploratory system development. The Institute has a long history of successful technology development, and in particular high-impact contributions to shared infrastructure and the development of reference implementations for the networking community. ISI also provides a tight connection to the DARPA research community, which has developed some key aspects of CENS technologies.

Wrigley Institute for Environmental Studies maintains facilities at the USC campus and a marine laboratory and educational facility on Catalina Island, off the coast of Southern California. The Wrigley Institute is a truly interdisciplinary environmental institute involving the life, physical and engineering sciences as well as law, business and public policy. It has rich programs in research, education and outreach to the K-12 and public communities. The Wrigley Institute will provide CENS with significant opportunities for fielded experiments as well as a portal for education and outreach.

5.3 Related Education Research, Training, and Outreach

Local Science Museums will be engaged as outlets for adapted CENS curricula, as well as a vehicle for teacher training. We will work with the Natural History Museum to help them take advantage of the habitat monitoring capabilities, both at the James Reserve, as well as other remote regions such as the UC Stunt Ranch reserve.

UCLA Center for Academic and Research Excellence (CARE) Program is designed to provide enrichment opportunities for historically underrepresented students interested in careers in scientific research and teaching for UCLA and its partner institutions, the California State University System and the California Community College System. The CARE program funds both summer and yearlong research internships for UCLA and partner institutions' students. CENS will partner with CARE to provide such opportunities in both CENS technology and applications laboratories.

Alexandria Digital Earth Prototype Project (ADEPT) Digital library project will advise CENS on the integration of CENS-based research and education with remote sensing data currently addressed by ADEPT. In the longer term, as longitudinal studies and correlation with remote-sensing data capabilities are added, expertise in digital libraries is essential for managing and deploying the repositories of sensing data in educational applications.

The UC Natural Reserve System of outdoor classrooms and laboratories is available specifically for long-term study and supports a variety of disciplines that require fieldwork in wildland ecosystems.

Management Plan

The Center for Embedded Networked Sensing will be a source of revolutionary innovations in critical information technologies, scientific and environmental monitoring applications, and inquiry-based science curriculum in grades 7-12. To achieve these ambitious and highly intertwined goals, we will adopt the following organizational structure to select and prioritize activities, integrate across projects, allocate resources, and manage involvement of other groups.

UCLA will be the lead institution. Estrin will serve as Director and will integrate across the technology, applications and outreach components of the Center. Professor Estrin has initiated and managed many large, complex, multi-million dollar projects involving significant numbers of personnel and integrated funding sources. She currently serves as Director of the UCLA Laboratory for Embedded Collaborative Systems (LECS). The director will be supported by a Deputy Director position that will rotate every two years among eligible UCLA faculty. Pottie will serve as Deputy Director for the first term, followed by Srivastava for the second two-year term. The Deputy director will coordinate laboratory activities and technical symposia.

Each focus area – technology, applications, and education - will have an Area Lead. Initial area leaders will be as follows. These positions can also be rotated on a two-year basis:

1. Information technology areas: Srivastava/Govindan rotating for systems;
2. Scientific application areas: Requicha for marine microorganism monitoring, Hamilton for biocomplexity mapping, Harmon for contaminant monitoring applications, and Davis for earth-science applications;
3. Education: Griffis/Wise rotating for 7-12 Curriculum development

An 8-person **Research Executive Committee** will be composed of the Director, Deputy Director and the Area leaders. The membership of the Research Executive Committee may potentially increase in future years, correlating with increases in the number of application areas. The Director, together with the Research Executive Committee will oversee coordination across research projects, resource allocation, research and education integration, and outreach to the larger scientific community. The Research Executive committee will meet on a monthly basis and during the initial start up phase of the center will hold weekly teleconferences. Each quarter the Executive Committee will meet to discuss long term, directions and redirections. Prior to the annual External Advisory Board, this quarterly meeting will focus on strategic planning.

Center management will balance the need for the faculties' ability to conduct pioneering research with that of creating and maintaining a coherent program. In particular, this balance must be reflected in the process for resource allocation (research funds, laboratory facilities and personnel-time, and space), and for assimilating external funding (e.g., from industry and other sources). The initial allocation of technical personnel to applications and technology areas is as described below. Although a considered overall budget in these areas has been proposed and personnel allocations initially determined, the Research Executive Committee, as described above, will re-evaluate the allocation of graduate students, equipment and materials and travel funds on the basis of brief research justification papers that will be reviewed semi-annually according to a predetermined schedule and in conformance with the overall mission and research plan of the CENS. In addition, a small number of off-calendar projects will be considered when particular opportunities arise (e.g., appropriate industrial funding opportunities, unforeseen project or travel requirements, etc.). The allocation of technical personnel will be evaluated on both an annual and as-needed basis in response to feedback from PIs and other senior personnel. The Center will encourage CENS personnel to seek additional sources of non-federal funding, e.g., from industrial or private sources to support the CENS program.

An **External Advisory Board** will provide advice to the Center Director with respect to strategic directions and management policies and to ensure consistency with the Center's vision, goals and objectives. The External Advisory Board will be comprised of scientists, technologists, educational experts, and members of appropriate commercial and government sectors. This committee will meet once a year in California. Additional teleconferences will be scheduled as needed. The following distinguished members have already agreed to serve on our external advisory board**:** Dr. Wally Baer (RAND), Ms. Marjory Blumenthal (National Research Council/CSTB), Senator Debra Bowen (California State Senate, Redondo Beach), Dr. Vint Cerf (MCI/Worldcom), Dr. John Dracup (UCB, Civil/Environmental Engineering), Dr. Ted Huller (Environmental Ecology, Cornell), Dr. Bruce Kutter (UCB, Civil Engineering), Dr. Richard Muller (UCB/SCRC Director), Dr. John Ober (UCOP, Digital Libraries), Dr. Ramesh Rao (UCSD/California wireless center), Dr. Mitchel Resnick (MIT/Education technology), Dr. Nambi Seshardi (Broadcom/Communications).

The CENS Director will be accountable to the UCLA Chancellor through the Vice Chancellor for Research. Each year the External Advisory board will report to the Vice Chancellor's office on the progress of research, education, and industrial collaboration in the Center and on the Center leadership.

The management of the Center will be supported as follows. The **Administrative Manager** will oversee the general administration of the Center: financial accountability, personnel recruitment and management, space and facilities planning, program and proposal development, and technology transfer. S/he will interface with users and partners in the commercial sector and identify opportunities for advancing technology partnerships. S/he will also interface with appropriate University offices of technology transfer and communicate intellectual property guidelines both within the Center and to its partners. S/he will report to the Center Director. An **Administrative Assistant** will assist the Administrative Manager in day to day operations. A **Financial/Budget Coordinator** will be responsible for financial management and reporting systems, generating operational and program development budgets and purchasing. An **Education/Outreach Coordinator** will organize the deployment, training and evaluation components of 7-12 education and will act as liaison to the UCLA CARE undergraduate internship program. S/he will coordinate outreach activities for the general public, and will supervise special activities such as open houses and research conferences. S/he will oversee the Center's Web site. A 50% **Network Coordinator** will provide computer networking support.

The **technical staff** will be distributed across the participating institutions as appropriate for the focus area/projects and will be supervised by center faculty. We anticipate the following technical staff: 3 Embedded systems hardware development engineers and 2 Embedded systems programmers (in years 1-3 we will begin with 2 engineers and 1 programmer, and ramp up to 3 and 2, respectively); 1 sensor technology engineer; 2 Educational delivery software programmers; a total of 5 experimental test-bed implementation and deployment personnel (with domain-specific backgrounds) to include engineers, technicians and post-docs; and eventually 28 graduate research assistants (after ramping up from 24 in years 1 and 2) and 10 undergraduate interns. GSRs will contribute significantly to the development of software for both technology related projects, and experimental test-beds. In the first few years of the project technical staff will be ramped up to the target numbers to meet the needs of the then deployed application test-beds. The technical staff will report directly to the PIs managing the particular projects, as well as to the Deputy director of the center. The educational staff will report to the educational coordinator. Although coordinated closely with the educational lead, educational delivery software engineers will report to the technical lead.

In the first year we will initiate an informal monthly seminar series for the Center as a whole to familiarize Center faculty and student with each other's research and disciplines. We will establish a program for joint recruitment of CENS graduate and post-doctoral students. We will also move quickly to establish the technology labs and begin application-centered planning.

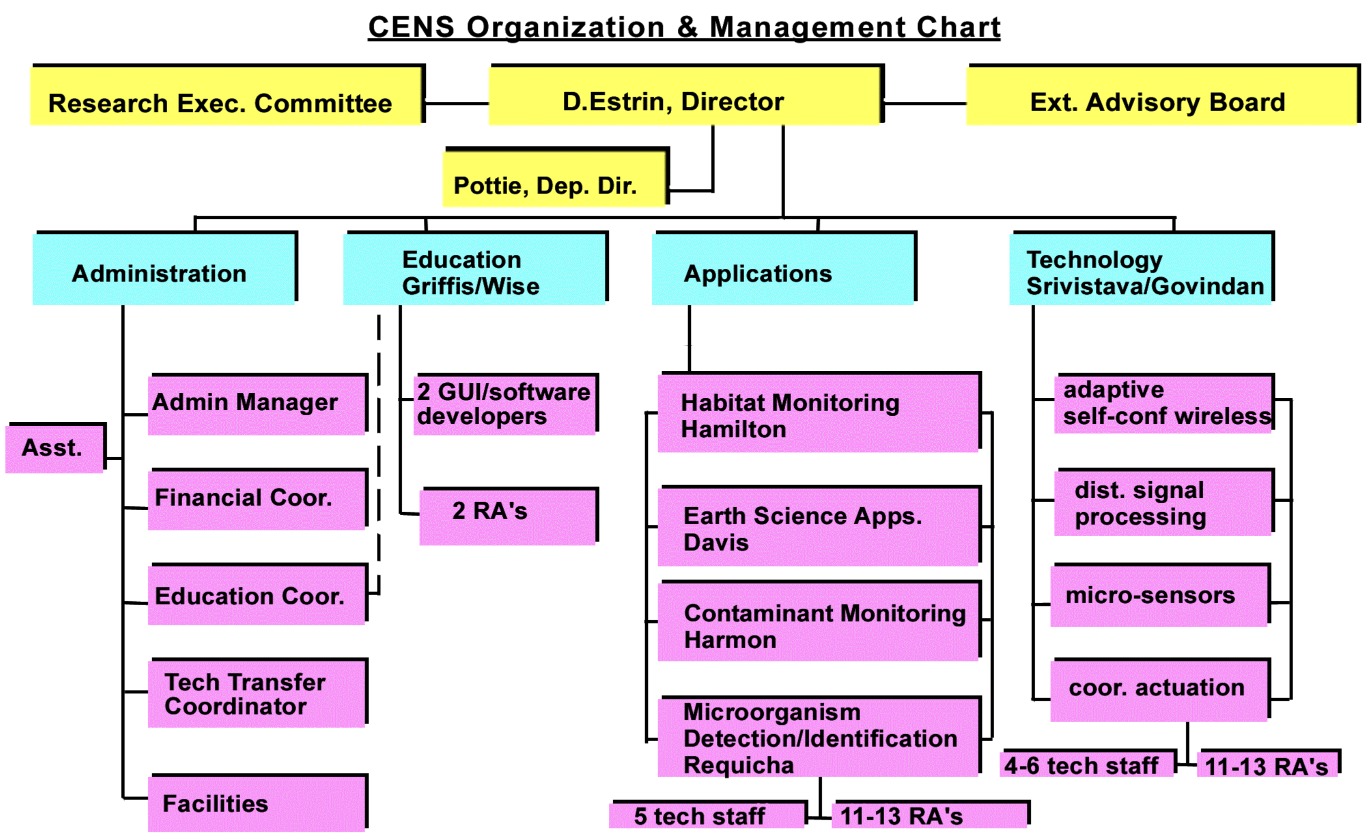
A new Engineering Building of 140,000 square feet, planned completion date of 2004, will be built at UCLA. Within this new building the CENS is scheduled to occupy space sufficient to accommodate its programs. The other major tenant slated for this building is the California Nanosystems Institute, which will encompass various research facilities including a state of the art computational and visualization laboratory. Within the **transitional space** made available to CENS in UCLA's Boelter Hall, will be an Administrative suite sufficient to house all proposed administrative staff, the Director's office with an adjacent meeting room, and dedicated laboratory space. Initially, there will be two primary Technology Laboratory facilities at UCLA, one for the development and testing of self-organization, networking, and sensor-integration (Boelter Hall), and the other for testing and data collection aspects of micro-sensor systems and wireless communications (Engineering IV). In addition UCLA will house the contaminant-flow monitoring experimental facility and the dense-seismic grid. The UCLA Nanoelectronics Research Facility will make its MEMs design and fabrication facilities available to the CENS. USC will house a Marine Microorganism and a Robotics/Actuation laboratory, and the James Reserve will house the experimental test-bed for habitat monitoring. Caltech will participate in support of MEMS related activities. The technical personnel will occupy office cubicles within these lab spaces, as will key technical graduate student researchers. The remaining graduate and undergraduate students will initially be provided with space by their supervising faculty. When the permanent CENS space is available in the new UCLA Engineering Building, there will be additional formal and informal meeting space for small group meetings and to foster graduate and undergraduate student interaction and interactions with visitors.

Facilities are currently available on the UCLA campus for planned symposia and informal seminars that will be held in conjunction with other entities across the campus and the region. The Computer Science and Electrical Engineering departments have meeting facilities in very close proximity to the Center offices that can accommodate up to 50 people. Moreover, Boelter Hall contains a large auditorium that seats over 100, and the UCLA campus has meeting facilities that can house upward of 300. See our extensive list of collaborators in the previous section on Knowledge Transfer.

Cross-disciplinary and cross-campus interaction will be essential to our success. Such interaction will be promoted and supported through several vehicles. First and foremost, the majority of the project areas are inherently interdisciplinary and involve multiple campuses. However, to supplement this inherent interaction, the CENS will sponsor weekly informal "Teas" for all participants. Our monthly seminar series will provide a more formal and technical context in which participants will gather to discuss progress, approaches, and opportunities. Bi-annual meetings involving external speakers and visitors will provide further opportunities to hear formal presentations on recent progress and plans across projects and campuses. The CENS will make use of the most up to date web-based collaboration tools to create a culture in which information and discussion, drawings and results are shared early and often and posted for purposeful as well as informal observation by others.

Milestones and Timeline

Before CENS begins operations, the administrative manager, budget personnel and networking staff will be hired so that budget and personnel policies, procedures, structures and space are in place and ready beforehand. We plan to quickly hire the remaining staff so that operations can proceed without delay. During the first year of operation CENS will develop its technology laboratories and design initial deployments in all four application areas. Simultaneously, the educational curriculum developers will lay the groundwork for later developments by taking advantage of existing facilities in new sample pilot curricula in life and physical science. Undergraduate research interns will be involved in initial laboratory setup and application experiments. We will hold a kickoff meeting of the center 2 months after initiation and plan the tentative schedule for the first two years of symposia and workshops. Year two will see initial technical results emerging from the technology laboratories. More significantly, these results will be integrated into application systems for initial evaluation and testing. The iteration between technology development in the laboratory and evaluation in the field will be ongoing during the center's lifetime. This year will also see the first application research results emanating from the CENS facilities. Years three through five will see continued advances in the sophisticated triggered sensing and actuation, as well as collaborative signal processing. Technologies will move out of the laboratory to the field. Similarly, educational developments will move out of our pilot development classrooms to a larger array of classrooms through joint teacher training programs. Application developments using CENS technologies will continue and will feedback o the technological requirements. During the course of the center's lifetime, funding will shift increasingly to industrial support.



Shared Facilities

The Center for Embedded Networked Sensing will create the following infrastructure shared among the Center participants.

1 Technology Laboratories

There will be four technology labs operating as part of CENS. The Laboratory for Embedded Collaborative Systems will explore, develop, and validate: self-configuration, coordinated actuation, multimode and distributed sensing, actuation, and data analysis techniques. This laboratory will be available to Center participants and housed on the third floor of Boelter hall at UCLA. The Distributed Sensing Measurement Facility will be set up for detailed measurement and data collection experiments. The lack of useful data sets is one of the greatest inhibitors to the maturation of embedded networked sensing technologies, and in particular collaborative sensing techniques. This laboratory would provide not only the Center participants, but also the larger community with a resource with which to collect and then use and reuse carefully collected and calibrated data. It will be held in the Engineering IV building at UCLA. The Nanoelectronics Research Facility will support fabrication of otherwise-unavailable sensors to support the application test-beds; it is housed at UCLA and will obtain assistance from Caltech as well. The USC Robotics Laboratory will support development and experimentation of distributed robotics technologies and systems. The full range of actuation types will be explored in conjunction with sensor network technologies; it will be housed in Powell Hall at USC. The USC Laboratory for Molecular Robotics will develop techniques for marine microorganism detection and identification.

A key center-wide shared resource developed and maintained will be a web-accessible sensor network simulation platform. The simulator would provide extensive libraries of sensor networking protocols, collaborative signal processing algorithms, and models for sensors, RF propagation, terrain, and power consumption. While students and researchers would contribute models to these libraries, the ultimate maintenance would be done by the full-time staff in the Center to ensure continuity of the knowledgebase. Moreover, we envision a hybrid simulation capability whereby the simulator would be aligned with instrumented versions of a variety of real sensor nodes to allow detailed modeling of a few nodes in a large network that is being simulated. A web interface would allow application users to do performance evaluation of their planned systems by rapidly composing alternative sensor network architectures, and studying their performance in terms of traffic characteristics, energy consumption, latency etc. Specialized visualization tools would allow non-technology participants of the Center to understand the results of the simulation. Easy web accessibility would also make this simulator a valuable resource to students using Center resources for classroom projects. We anticipate this simulation facility to evolve in part out of the current preliminary work being done on the simulation tools by the researchers.

A related shared facility that would complement the web-based sensor network simulator would be a prototyping test-bed. The test-bed would provide a variety of radio (e.g. Bluetooth, RFM, 802.11 etc.), sensing modules, and protocols in the form of well-characterized open source hardware and software designs, and plug-and-play components for rapid assembly of custom sensor node configurations for application evaluation. The designs and the test-bed would be maintained by the Center staff in the Technology Labs as a shared facility. Specialized labs of the various Center participants would provide the initial designs and prototype implementations of sensor nodes and radios as the seed for this facility. For example, the Networked Embedded Systems Laboratory in UCLA EE and the Laboratory of Embedded Collaborative Systems in UCLA CS have several sensor node designs of varying complexity that would be contributed to this facility.

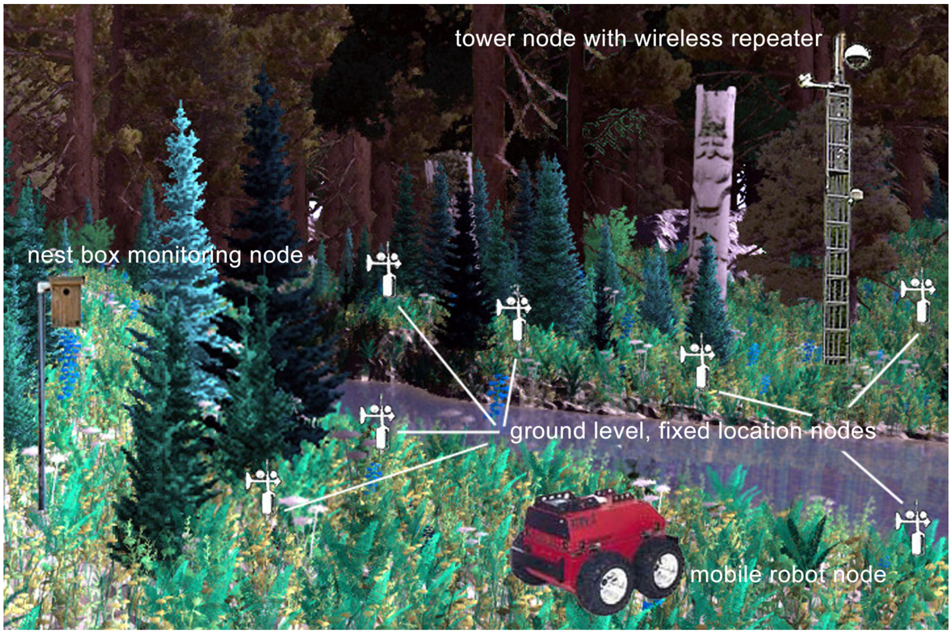
2 Application test-beds

The application test-beds will provide unique resources for testing, evaluation and measurement of experimental technology, as well as for the collection of scientific data in their respective domains.

2.1 Biocomplexity mapping (UCR)

The Habitat Sensing Array test-bed for biocomplexity mapping will be designed and installed at the University of California, James San Jacinto Mountains Reserve (www.jamesreserve.edu), a unit of the University of California Natural Reserve System (nrs.ucop.edu),and a member station of the Organization of Biological Field Stations (www.obfs.org).

The 529 acre James San Jacinto Mountains Reserve and surrounding Hall Canyon Research Natural Area (US Forest Service) are located at an elevation of 5,400' ASL on the western slope of the San Jacinto Mountains, the highest and northernmost of the California Peninsular Ranges. The reserve provides access to diverse protected ecotypes ranging from subalpine coniferous forests to the western edge of the Colorado Desert, and serves as a base for research and teaching throughout the mountain range and surrounding areas. The reserve protects for research a wide variety of plant communities and wildlife habitats including old growth Sierra mixed conifer forest, oak woodlands, montane chaparral, alder-willow-cedar riparian forest and perennial stream, and meadows.



Existing University-owned facilities include the Trailfinder Lodge, with a self-service kitchen, meeting room, six bedrooms with 32 beds, Biodiversity Visualization Laboratory (for remote sensing/GIS/ecological database management), library, vascular plant and bryophyte herbarium, vertebrate and invertebrate collections, digital weather station (with real-time web-access), and a 384kbps frame relay connection to the Internet. Comprehensive biodiversity and remote sensing databases are available on-site and via the Internet. A series of 14 streaming video web cams are situated near the Lodge and allow wildlife and habitat viewing at feeder stations, inside of avian nest boxes, bat roosting boxes, tower mounted, and on a prototype wireless mobile robot. In addition to the Resident Director (Dr. Hamilton), there are 2 full-time staff members (a biologist, and a data manager/programmer), and a part-time facilities maintenance worker.

The test-bed created as part of CENS will consist of three 25-node monitoring grids, each situated within distinct different ecotypes (forest, chaparral and meadow/riparian). Habitat sensing modalities within a grid will involve three types of wireless, multi-sensor monitoring systems (for visual, acoustical and environmental/plant physiological sensing), each environmentally resistant to moisture and temperature extremes for montane and desert climates, and independently powered by solar-photovoltaic power supply. Each grid will specifically include a fixed location tower-based multi-sensor systems, an all-terrain 4-wheel drive autonomous (and via remote-control) multi-sensor robotic platform, and up to 25 ground-based (but transportable) multi-sensor wireless nodes.

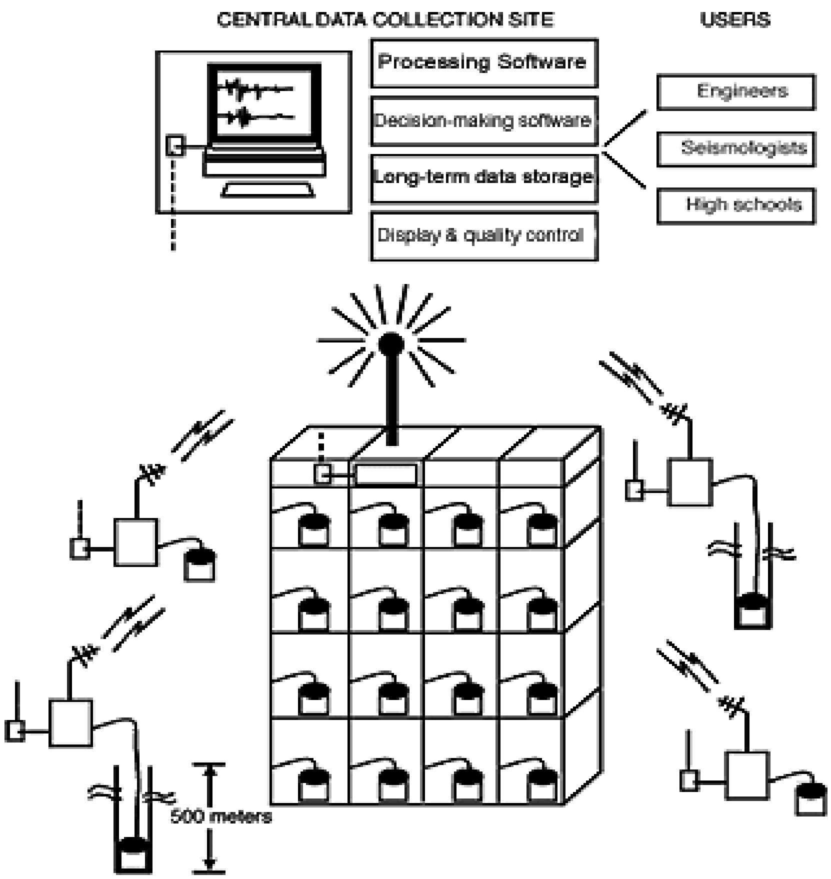
Data streams from nodes will be relayed the nearby tower-mounted repeater, and then via digital spread spectrum wireless Ethernet, to servers in the a Biodiversity Visualization Laboratory at the Trailfinder

Lodge, Individual nodes for particular in-situ applications and conditions will be modified at the James Reserve or at the appropriate CENS technology laboratory. Additional equipment to be provided at the James Reserve include a wireless Ethernet LAN, custom software, and computer workstations/servers for use in sensor communication, database and data archival, data synthesis and visualization, and web-interface design. Real-time data streams as well as archival data sets will be available via the Internet. Interface design for Internet access will include three application areas; 1) field testing of engineering aspects of multi-sensor hardware design and support software systems, 2) ecological, organism, and biocomplexity research investigations, and 3) educational applications with K-12 and public outreach.

2.2 Dense Seismic monitoring (UCLA)

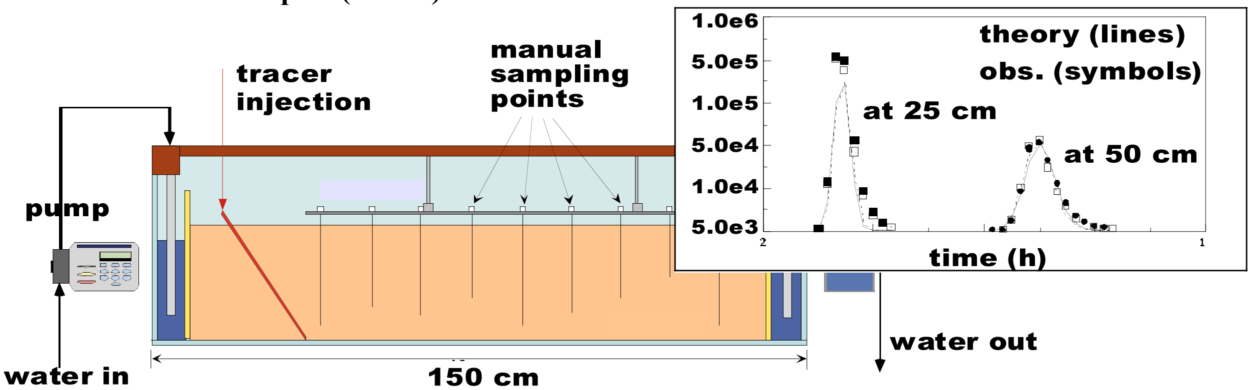
The dense seismic network will involve monitoring building and ground motion via sensors placed on each floor of UCLA's Factor Building and free-field sensors on the UCLA campus. Strong-ground motion sensors have already been installed in the 17-story, steel-frame construction Factor Building; thus the first phase of the seismic application test-bed consists of recording, transmitting, and processing building motion recorded by those sensors.

The second phase consists of installing strong- and weak-ground motion sensors in the ground at 100-m spacing in a 1 square km area comprising the UCLA campus, and weak-ground motion sensors in the Factor Building. The continuous time-series data will be individually time synchronized using GPS receivers installed on top of the Factor Building and around the campus. In addition, the real-time continuous data will be transmitted to a central processing and long-term data archival center via Internet connections located in a CENS laboratory.



Access to the data and processing center will be available to all Center participants, including educational partners. Test-bed activities will be coordinated with the Technology Laboratories, in particular with groups developing new wireless communication hardware enabling the wireless transmission of the seismic data, and communication with and among the sensors. The Technology Laboratory wireless communication hardware and software will be used in the development of building actuator response as a function of real-time data recording of the sensors. It is envisioned that the seismic network could serve as a prototype for monitoring any structure or region (e.g., bridges, multi-level highways, active fault) that would require continuous seismic monitoring for hazard reduction, emergency response, or retrofitting requiring real-time decision-making based on event detection and response to ground shaking.

2.3 Contaminant transport (UCLA)



The test-bed for sensor networks in support of contaminant transport studies will begin on the bench scale, where prototype sensors and sensor networks will be deployed and tested in a three-dimensional physical soil model (see schematic below). This model is currently housed in a temperature-controlled chambered (5 to 35 ± 0.1 °C) in the Civil and Environmental Engineering Water Quality Laboratory at UCLA. It is equipped with a purified water flow-through system and can be operated in fully or partially saturated flow conditions. The hardware can withstand a variety of environmental perturbations (e.g., temperature, pH, and salinity fluctuations). The first sensor array slated for deployment and testing will be micro-conductivity probes. The prototypical dense sensor array will be fabricated using 0.5 mm o.d. conductivity microsensors on a 5 cm x 5 cm x 0.5 cm grid in the physical model for a total of 320 continuous monitoring points (as opposed to the 14-20 intermittently monitored points previously available manually). This array will be transitioned into one of biochemical sensors when appropriate versions are completed. A number of chemical sensors of the type needed here are becoming available [Rogers-Gerlach99]. However, noninvasive deployment in the physical aquifer model will require micro-electro-mechanical-system (MEMS) fabrication of the desired chlorinated solvent sensors. Thus, we propose beginning the study with conductivity microsensors so that the networking aspects of the project can be developed immediately.

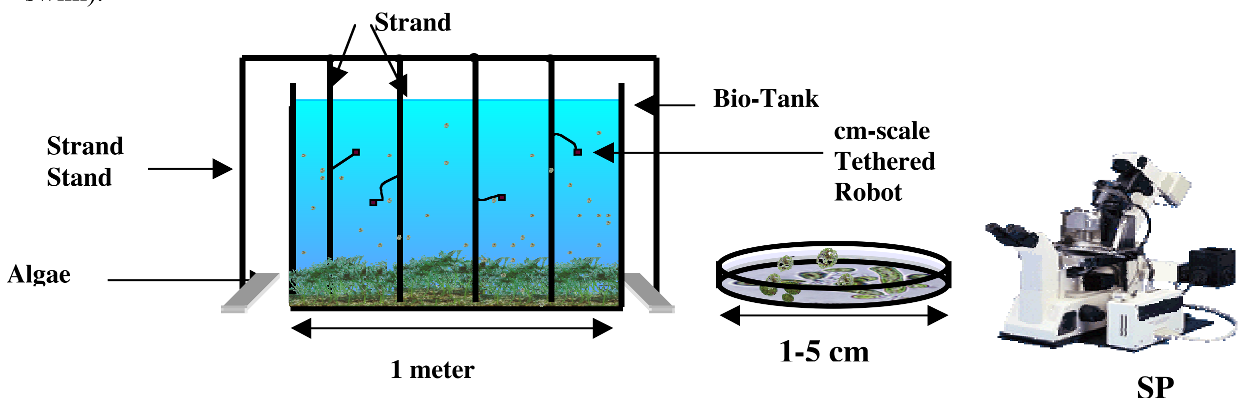
Subsequently, the soil model will be available for collaborative efforts with the other CENS labs. Most notably there will be regular usage by the Technology Lab members seeking (1) simulated subsurface conditions in which to test prototypical sensors and (2) a pre-calibrated system in which to test network designs. The other first-phase applications will also benefit from this resource. For example, the habitat and seismic sensing applications may require a controlled test-bed in which to test sensor resistance to soil moisture, corrosion and other environmental influences. As the combined capabilities (sensors, networks and applications) mature sufficiently, this test-bed will expand to encompass the UCLA campus. Sensor networks extending from below ground level to the rooftops will be devised to track local meteorological and contaminant levels (e.g., emanating from laboratory fumehoods). This larger test-bed will also invite joint efforts with the Technology Lab and other applications. For example, comparisons can be drawn between sensor network performance (and environmental conditions) in natural and urban airsheds.

2.4 Marine Micro-organism Monitoring (USC)

The proposed experimental test-bed is composed of two parts. The first is a system of tethered robots attached to vertical strands (see figure below). The second is a scanning probe microscope (SPM) which will be used “offline” to analyze samples collected by the robots.

Each strand will have multiple robots attached to it via tethers. We envisage two arrangements for the tethers. The first is a rigid tethering system in which each tether will be a 2 degree of freedom arm with two actuators and rigid links. Our preliminary estimate is that there will be 10 strands and 10 tethers per strand leading to a total of 100 submerged robots. The second arrangement (actually shown in the figure above) uses the same strand stand but with flexible tethers. The number of robots remains the same.

The robots themselves will be very simple. In the first phase of test-bed development we will focus on packaging the robot controller (PC/104+ or smaller form factors) so it is waterproof. We will also equip the robots with communication and sensing. It is likely that communication will be a wired serial line though we plan to equip some robots with wireless transmitters and receivers to test the viability of RF wireless communication for short ranges underwater. Candidate sensors on the robot are a thermometer, an infrared opacity sensor, etc. In addition to sensing, each robot will be equipped with a simple mechanism to take a fluid sample. This will be a spring loaded, binary actuator-driven "trapdoor" which can be retracted to expose a small cavity to the surrounding fluid. Sampling will consist of opening and closing this trapdoor in succession. Once a sample has been taken the robots will be brought to the surface manually and the sample will be transferred to the lab bench for analysis. When the tethers become flexible we will also equip each robot with actuators that allow it to position and orient itself (i.e., to swim).



The samples collected by the robots will be analyzed offline. We will operate in an SPM "liquid cell", which has overall dimensions on the order of 1 cm and therefore can contain very large numbers of microorganisms. The SPM will be used for DNA-based and antibody-based technology for developing biological sensors that will identify and (ultimately) quantify microorganisms. Parallel work in the lab will use oligonucleotide probes and the monoclonal antibodies for detecting microbial entities with very high specificity in mixed assemblages. In the future, we intend to miniaturize and ruggedize the sensing process so that it can be used in the field, and eventually by the robots themselves.

3 External Access

The Center will make some shared resources available to other university researchers, on a resource-availability basis. In particular, the micro-sensor system testing laboratory at UCLA, the JPL test-bed, the INEEL meso-scale test-beds, and the Nanostructures Research Facility all have unique resources. In particular, we expect CENS to coordinate joint requisition of certain low-power, MEMS based sensor fabrication, when the needed components are not available off the shelf; for example a particular chemical sensor needed for both contaminant and biocomplexity monitoring applications

The Center will maintain a large, visible, detailed, and up to date web page where technical descriptions, application issues, and curriculum developments can be publicized and discussed.

4 Operations and management

The technology laboratories will be overseen by faculty members/senior personnel and will be operated by the technical staff affiliated with the lab, with the assistance of graduate students. The application test-beds will similarly be overseen by supervising faculty, but will be operated by the technical personnel associated with the specific project. The facilities support staff for the center will assist with the management and operation of more generic computing equipment and networking.