Research Statement

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Most sensor network research in the last decade has followed a bottom-up approach, motivated by issues such as miniaturization, platform constraints (*e.g.,* energy, bandwidth, processing and form factor), inherent uncertainty (*e.g.,* randomness of failures, deployments and measurements) and basic services (*e.g.,* time-synchronization, routing and localization). While this approach has resulted in a rich set of ideas, platforms, systems and principles drawn from several disparate disciplines, I believe that in the next decade sensor network design must embrace a top-down approach that is guided by the requirements and constraints of practically deployable applications such as structural health monitoring and meteorology. Successful adoption of sensor networks will be crucially dictated by abstractions (*e.g.,* socket API in the Internet) and basic services that foster a conducive environment for application development in various fields. *My research interests lie in architecting programmable sensor network based systems that application developers from diverse fields can use without having to delve into the intricacies of the underlying sensor network.*

The synergy between two of my primary strengths forms the underlying basis of my research - first, a multi-disciplinary research background, and second, a rich set of experiences that I have acquired while designing, implementing and deploying real sensor network systems. A decade of explorations in diverse areas such as signal processing, pattern recognition, networking and recently, structural health monitoring, has honed my ability to identify and apply common sets of principles across various disciplines. In addition, my implementation and deployment endeavors have not only exposed me to the challenges of architecting, programming and debugging real sensor network systems, but have also provided me with insights into their inherent constraints and uncertainties. I therefore believe that I am well-suited to both innovating in the inherently multi-disciplinary world of sensor network research, and translating ideas into practical, useful contributions through the development of real world sensor network systems.

Given that sensor network applications cut across a wide variety of disciplines and requirements, are there abstractions, architectures, services and algorithm design principles that apply uniformly across specific classes of applications? How do various application requirements such as physical scale of deployment, data rates, real time constraints, computation patterns, uncertainties and correlations in data etc. impact sensor network system design? How do we architect systems that cater to the needs of various application developers while conforming to the constraints posed by platforms? These are some of the questions that will need to be answered before we can build systems that are willingly adopted by application developers and the world is truly ushered into a sensor-actuator network era. I believe that by virtue of my exposure to diverse disciplines, coupled with my experience in architecting practical sensor network systems, I am ideally suited to embark upon answering these questions. My doctoral thesis serves as an encouraging example and evidence of this by bridging the disconnect between requirements of Structural Health Monitoring (SHM) applications - a class of applications that strive to assess the integrity of structures such as buildings, bridges, off-shore oil rigs and aerospace vehicles - and issues governing the design of practical sensor network systems.

NetSHM- A Programmable Sensor Network Based SHM System

The main focus of my doctoral work is NetSHM- a programmable system for implementing structural vibration based SHM techniques. NetSHM provides an API that allows structural health engineers to program in a higher level language such as C/Matlab[1] and implement new SHM algorithms without having to delve into the details of programming motes, or the intricacies of the underlying sensor network. An initial prototype for NetSHM has been implemented and deployed successfully in scaled models and real structures to detect and localize damages.

Structural health monitoring draws heavily from several disciplines such as civil engineering, signal processing, stochastics and control systems. While I learnt the basic tenets of structural dynamics from civil engineers, my background in the latter three disciplines allowed me to not only grasp different SHM techniques rapidly, but to

[1] Most SHM engineers prefer using Matlab/Nastran for implementing and testing new algorithms.

also develop novel SHM algorithms that adhere to sensor network design principles, such as in-network processing and duty-cycling. Working with SHM engineers to deploy real-world SHM applications, and using NetSHM on scaled models and real structures, I learnt to appreciate and understand the "SHM application developers' points of view", *i.e.,* their requirements and constraints. My practical experience with sensor network platforms helped me to translate them into the set of basic services, architectural principles and abstractions that a sensor network system should provide so that SHM application developers need focus only on programming SHM algorithms.

NetSHM leverages a two-tier hierarchy comprising a tier of impoverished mote-class nodes (*e.g.,* micaZs) which interact with the physical world, and the more endowed gateway class nodes (*e.g.,* Stargates, PCs). These gateway class nodes are necessary to accommodate the high aggregate data rates generated by several mote-class nodes. NetSHM isolates the application developer from the mote-class devices by requiring that application-specific code may reside on only the gateway class devices. The mote-class devices provide a generic library of tasks (*e.g.,* sampling, FFT, computation of ARMA coefficients *etc.*) that can be invoked by the gateway class nodes by transmitting command packets comprising command type and parameters. NetSHM follows a model where mote-class devices are triggered by significant events(such as an earthquake), or by task schedules specifed by gateway devices allowing for low duty-cycle modes of operation.

Practically deploying NetSHM in real environments exposed me to the vagaries of sensor network systems, such as variability of link characteristics and routes, noise and calibration errors in data, noise introduced due to fixed point calculations on motes, memory and processing constraints and, most importantly, the unseen problems that emerge from the interaction of a combination of protocols. I believe that all these experiences will greatly assist me in designing and implementing systems and algorithms for sensor networks in the future.

Adhoc Localization

My research in ad-hoc localization is pivoted upon the two factors I emphasize while designing algorithms for basic services, namely,a sound theoretical basis and practical deployability. A thorough exploration of ad-hoc localization schemes [1] revealed that ranging based ad-hoc localization techniques demand very high deployment densities (an average degree of 10 or more) for their success [1]. Such deployment densities may not only be economically impractical, but often extremely hard to guarantee in real deployments. To circumvent this problem I developed a novel *range-sector based localization scheme* that relies on nodes to estimate the approximate bearing information to their neighbors within a sector of 30-60 degrees in addition to the range measurements. This can be achieved by using sonar, directional antennae or a circular array of LEDs. The algorithm takes an iterative distributed optimization approach to minimizing a weighted mean square sum of localization errors that only requires a node to communicate with its single hop neighbors. Simulations suggested that the algorithm dramatically reduces deployment density requirements (an average degree of about 5-6 nodes). Implementing and deploying the algorithm on Pioneer P3-DX8 robots that carry a sonar belt array, gave me hands-on experience with tackling several real-world problems such as filtering outliers in range measurement.

Edge and Contour Estimation

My ability to draw ideas from various disciplines to arrive at practical solutions to sensor network problems is exemplified by my work on Edge detection. Data visualization aids such as contours or edges will become crucial as sensor networks begin to span vast geographical regions. The challenge is to estimate edges and contours of phenomena without incurring the communication overhead of having to relay all the collected data to a central location. I developed light weight localized edge detection [2] schemes wherein nodes rely on local communication (within 2-3 hops) to determine whether or not they lie on the edge of a phenomenon in a completely distributed manner. The schemes build on concepts from statistics (identifying bimodality in data), image processing (high pass filtering) and pattern recognition (constructing linear classifiers) and can be used to detect edges with up to 99% reliability in the face of sensor errors and random deployments. Some of the algorithms have been implemented on platforms such as Mica2 indicating their amenability to actual deployments.

My vision and future work

While NetSHM is complete in itself as a generic architecture with an existing prototype for a programmable SHM system that can be used by civil engineers today, it is but a beginning and an encouraging example for programmable sensor networks. Besides SHM applications, I believe that three other classes of applications will have a profound impact over the next few years; namely - *sensing coupled with control*, *data summarization*, and *tracking applications. Identifying and implementing appropriate sensor network services, designing algorithms that are amenable to practical deployments, and developing abstractions that enable easy application-level programmability will be the focus of my research over the next few years.* My diverse background and practical sensor network experience make me well suited for designing such systems.

SHM applications beyond NetSHM: There exists a challenging set of algorithms and basic services that remain unexplored in the space of SHM algorithms. In our NetSHM deployments we have observed severe congestion due to high data rates. While NetSHM uses a pre-configured rate control, congestion control mechanisms as a primitive are essential for SHM systems. As an extreme measure to avoid interference and losses due to collisions, data can be requested from each node one at a time; however this does not utilize the network capacity efficiently. How is it possible to design congestion control algorithms that use the wireless network capacity efficiently? Another interesting problem that needs to be tackled is group addressing and routing primitives for reliably communicating commands to a group of nodes, *e.g.,* "all sensors on the 4th floor." I believe that my knowledge of existing wired, wireless and sensor network protocols, coupled with my strong understanding of optimization will help me design and implement algorithms that address the above problems. An entirely new and unexplored approach to SHM could involve wireless controlled mobile sensor nodes (running on tracks in the structure) equipped with cameras that can automate this process. I believe that I can leverage my background in image processing and pattern recognition to develop and implement algorithms that detect cracks or evidence of corrosion, which can be implemented locally on the nodes, so that decisions, rather than images, are transmitted.

Sensing coupled with control : Several industries require automated monitoring and control for their manufacturing processes. Flexible dense deployments using wireless sensor networks can potentially lead to much better control of the manufacturing processes. Time-delay sensitive routing as a primitive will be crucial to such systems. How do we design routing schemes and reliable messaging that conform to time constraints, despite the variability in link characteristics and system constraints such as small queue sizes? Novel mechanisms to reduce communication overhead sensor nodes can be explored; for example, a sensor could send data to the controller only when the sensed data deviates "significantly" from a prediction model. The design of programmable sensor network-based control systems will bring forth a host of exciting challenges and research opportunities. I believe my expertise in the design aspects of control systems will enable me to pursue these efforts.

Data summarization : Data summaries such as spatio-temporal correlations, contour-maps, boundary descriptions, probabilistic compilations of phenomena, model based digests, statistics, *etc.* will prove crucial for visualization and analysis of vast amounts of sensed data generated across large geographical spaces. Practical localization, geographical addressing and routing mechanisms will be vital primitives in such systems. Smart resource management primitives that selectively sample and duty-cycle nodes may prove essential for long-term deployments. The experience I have gained from my work in edge estimation and image processing, has equipped me to explore these problems.

Tracking applications : Applications such as coordinated tracking require local collaboration among sensors. These applications will perhaps need a very different set of programming abstractions and addressing primitives based on local neighborhoods. I am confident that my understanding of estimation techniques such as Kalman filtering and other Bayesian schemes will help me design such systems.

In summary, I believe that I have both the knowledge and the ability to contribute practically and significantly to sensor network research by building programmable systems that enable a conducive environment for application development, spanning several disciplines.

References

[1] K. Chintalapudi, A. Dhariwal, R. Govindan, and G. Sukhatme, "Localization Using Ranging and Sectoring," in *INFOCOM*, Hong Kong, 2004.

[2] K. K. Chintalapudi and R. Govindan, "Localized Edge Detection in Sensor Fields," *AdHoc Networks Journal*, pp. 273–291, 2003.