1 RESEARCH PHILOSOPHY AND METHODOLOGY

We draw inspirations from real-world applications that present an opportunity for making breakthroughs, discover practical research problems through experimental studies and inter-disciplinary collaborations, develop fundamental theory principles and algorithms and implement real-world protocols and systems.

2 RESEARCH VISION AND THRUST

Our research primarily focuses on Cyber-Physical Systems and Security for geophysical imaging, smart grid and smart health, where sensing, computing, communication and security play a critical role and need a transformative study. It greatly impacts the society on environment, energy and health issues.

2.1 Real-time In-situ Geophysical Imaging

A sensor web system is often used in environment monitoring application to provide a high degree of visibility into environmental physical processes - capture the spatial and temporal environmental changes, essentially like a “video camera”. One of the niche is geophysical imaging, that use a network of geophysical sensors to image the subsurface and has critical application in hazard mitigation and oil/gas exploration. We are the leader of real-time in-situ geophysical imaging and have enormous collaborations with geophysics community, such as top researchers from U.S. Geological Survey, Jet Propulsion Laboratory, University of North Carolina, Georgia Tech, University of Utah, University of Texas, and etc.

- Collaborative sensing and computing. In volcano monitoring and oil/gas explorations, hundreds to thousands seismic sensors are needed to image a high-resolution seismic tomography. With such a large-scale and high data-fidelity, it is virtually impossible to collect raw real-time data through wireless networks, due to severe limitations of energy and bandwidth at current, battery-powered stations. In our NSF CDI project 1 (NSF-1125165, $1,833,608, 9/2011-8/2015), we are developing a large-scale sensor network system called Volcano Seismic Realtime Imaging (VolcanoSRI), that senses and processes seismic signals and computes real-time 3D volcano tomography within the network. Realizing such a VolcanoSRI system requires a transformative approach to tomography inversion, seismic signal sensing and processing, and the associated sensor network design. It is a sharp departure from traditional data collection paradigm, and the first attempt to invert seismic tomography in distributed networks to avoid costly data collection. The in-situ seismic tomography computing is formulated as a least-squares problem \( s^* \), i.e., \( s^* = \arg\min_s \| t - As \| \), where \( A \in \mathbb{R}^{Q \times m^3} \), \( s \in \mathbb{R}^{m^3 \times 1} \), and \( t \in \mathbb{R}^{Q \times 1} \). where each node only knows partial rows in \( A \) and \( t \) and they together need to compute \( s \) by exchanging limited amount of information through an unreliable wireless mesh network. Moreover, we expect a high degree of variability in the network’s

1. http://sensorweb.cs.gsu.edu/?q=VolcanoSRI
operating conditions over time. Node dropout and occasional reboot will result in variable sensor data availability and network topology. The in-network processing and computing algorithms have to operate robustly in the face of these fluctuations, a new approach must be created to deal with adverse conditions and partial, possibly temporary, system failure.

In our new **NSF CyberSEES** project \(^2\) (NSF-1442630, $1.2M, 1/2015-1/2019), we advance this effort and create a real-time Ambient Noise Seismic Imaging system that can autonomously perform in-network computing of the 3D shallow earth structure images based on ambient noise alone. The project will study the subsurface sustainability of Long Beach, California and Yellowstone using their existing seismic array datasets and design the real-time in-situ seismic imaging system accordingly. In the late stages of the project, a field demonstration of the prototype system in Yellowstone expects to image the subsurface of some geysers. The techniques developed find further utility in monitoring and understanding the dynamics of subsurface oil, mine and geothermal resources, alongside concomitant hazards in oil exploration, mining, hydrothermal eruption, and volcanic eruption.

- **Collaborative communication and storage.** In a challenging environment, a predictable and stable path may never exist, the network connectivity is intermittent, and a node could suddenly appear or disappear. The rare upload opportunity and unpredictable node disruptions often result in data loss. Those unpredictable network disruptions make the traditional communication protocols inefficient and particularly needs a collaborative resource coordination mechanism. In our **NSF CAREER** project \(^3\) (NSF-1066391, $422,955, 6/2010-5/2015), we are designing a collaborative communication and storage middleware - an integrated approach which cooperatively configures resources to increase disruption resilience, data persistence and network lifetime, and capture the fluctuating connectivity for data delivery. The proposed Collaborative Topology Control middleware \([5]\) systematically adjusts radio configurations to combat network disruptions, increase network reliability and disruption resilience, and prolong network lifetime in challenging environments. The Collaborative Data Delivery middleware \([6]\)–\([10]\) integrates collaborative routing, forwarding and network erasure coding protocols to capture the intermittent connectivity for disruption-resilient data delivery. The Collaborative Storage Management middleware \([11]\), \([12]\] collaboratively utilizes network storages to increase data persistence, so that the data more likely survives and eventually reaches a data sink, even as nodes fail. In this research, we are also proposing a holistic evaluation methodology that evaluates how well the global spatial and temporal environmental changes have been recorded, not just those low-level engineering criteria such as network throughput or delivery ratio.

- **Space in-situ integrations.** In our NASA-USGS funded project \(^4\) (NASA-NNX06AE42G, $1,628,979, and USGS-VHP, $500K, 1/2007-12/2009), we developed an Optimized Autonomous Space In-situ Sensorweb (OASIS) system. It has two-way communication capability between ground and space assets, uses both space and ground data for optimal allocation of limited bandwidth resources on the ground, and uses smart management of competing demands for limited space assets. The space and in-situ control components of the system are integrated such that each element is capable of autonomously tasking the other. The in-situ sensor network was deployed into the craters and around the flanks of Mount St. Helens in July 2009, and linked to the command and control of the EO-1 satellite. This is the first demonstration of space-in-situ sensor web \([13]\)–\([15]\) in the world. It has been later demonstrated in JPL’s Mars Yard. The in-situ sensor network \([16]\)–\([18]\) delivers volcano status (seismic, geodetic, space-born infra-red measurements, infrasound) in real time to central processing centers for volcanic monitoring and geophysical analysis, and optimizes use of limited power and bandwidth based on a volcano’s activity level. As an extension of our aforementioned OASIS and

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3. http://sensorweb.cs.gsu.edu/?q=NSFCareerAward
VolcanoSRI project, we are currently investigating an integration of ground seismic network and UAV Interferometric Synthetic Aperture Radar (InSAR) to improve accuracy of volcano tomography while generating volcano topography at the same time. Real-time seismic analysis provides epicenter location, fault parameters, and, given enough data, the geometry of magmatic intrusion with short latency. Geodetic measurements (InSAR, GPS, leveling, etc) on the other hand, reflect volume changes and surface strain more directly by tracking surface deformation. The deformation models provide detailed information on the dike/fault orientations and pressurized bodies within the volcano edifice following an injection event. The incorporation of strong structural constraints on the boundaries of 3D bodies will increase the spatial resolution of the tomographic imaging considerably.

2.2 Smart Grid Cyber-security and Testbed

Developing the Smart Grid is an urgent global priority as its economic, environmental, and societal benefit will be enjoyed by generations to come. Information and communication technologies are at the core of the Smart Grid vision as they will empower today’s power grid with the capability of supporting two-way energy and information flow, isolating and restoring power outages more quickly, facilitating the integration of renewable energy sources into the grid and empowering the consumer with tools for optimizing their energy consumption. In our NSF CPS project 5 (NSF-1135814, $1,871,453, 10/2011-9/2015), we study the foundational information and computation architectures for future smart grids, and a scalable experimental platforms for evaluations and validations. My collaborators in this project are Lang Tong (Cornell), Kenneth Birman (Cornell) Tim Mount (Cornell), Robert Thomas (Cornell), Pravin Varaiya (UC Berkeley). We are focusing on the following key research issues:

- **Smart grid emulators and testbed design.** We are developing an open and scalable experimental platform (SmartGridLab) for empirical investigations and testing of algorithms and concepts. To this end, we propose a software-hardware hybrid that integrates the hardware testbed with a software emulator. This allows a virtual node in the emulator to interact with a real node in the testbed. This innovative architecture allows researchers to examine real system performance under realistic communication and computation constraints in the hardware while evaluating algorithm scalability in software. Our Smart-Grid Common Open Research Emulator (SCORE) [19] is the first smart grid emulator that integrates both power and communication network. Comparing to the existing works of co-simulation of Smart Grid, SCORE (as an emulator) will significantly reduce the development and test time of new ideas, since the same application program running in SCORE can be directly ported to embedded devices with little or no modification. SCORE supports large-scale emulations across multiple computers in the Internet. In our SmartGridLab testbed [20], [21], each device is designed to emulate various real energy devices in power grid, such as smart appliances, energy storages, solar panels, wind turbines, power generators etc. Our final SmartGridLab platform will support online integration and interaction among multiple live smart emulations and testbed experiments. It may potentially enable integrated experiments with real smart grid. With our NSF SFS grant (NSF-1303359, $500K, 9/2013-8/2016), we will further incorporate an integrated simulation framework of smart grids for security educational purposes, design and implement a suite of course modules and handson exercises upon the system, and contribute to the establishment of an education and training pipeline for information security workforce in future power industry through carefully planned evaluation and dissemination activities.

- **Cyber-physical security and fault localization in smart grid** Cyber-physical security of the power grid C encompassing attack prevention, detection, mitigation, and resilience C is among the most important research needs for the emerging smart grid. One of the overarching goals of the future

5. http://sensorweb.cs.gsu.edu/?q=SmartGrid
research is to develop a comprehensive cyber security risk modeling framework that integrates the dynamics of the physical system as well as the operational aspects of the cyber-based control network. We have been studying the fault localization [28], topology attack problems [29]. With the growing penetration of renewable and demand response programs which lead to frequent flow reversals and substation reconfigurations, correct identification of the topology becomes an imperative task in future power grid management. However, due to insufficient measurements on transmission and distribution networks, the aforementioned task is inevitably challenging. In [28], we propose a framework for distributed line outage or more generally line change detection in smart grid system. In [29], we propose a maximum a posteriori based mechanism, which is capable of embedding prior information on the breaker status, to enhance the identification accuracy.

- **Demand response, hierarchical control, and location real time price.** A customer equipped with real-time price measurements and the ability to manage their demand over time would benefit from Location Real Time Price (LRTP) of the electricity purchased. Indeed, providing LRTP to customers ultimately benefits the network operators because these customers are likely to shift their demand from peak to off-peak periods, and as a result, the installed capacity of the peaking units needed to maintain reliability can be reduced significantly. Full demand-side participation [22], [23] in a future smart grid is, however, likely to require some form of hierarchical control to manage devices on distribution networks. It is essential for such a control hierarchy to have a spatial information hierarchy that manages the collection and distribution of information and provides the correct economic incentives to influence customer behavior. While the role of real-time pricing has been studied extensively, the spatial aspect of LRTP is less known but this is an essential issue for mitigating the variability of generation from renewable sources that are also spatially distributed on the grid.

2.3 **Activity Sensing and Tracking for Smart Health**

Although present day society is globally networked, the spaces that people occupy, specifically living environments, remain sedentary and disconnected. As technology advances, there is a growing interest in adding intelligence to human living environments. In a smart and connected health environment, highly interactive and embedded devices (sensors and actuators), in surrounding environments or on body, are used to sense and control in order to meet the demands of the environment and the health, safety, and productivity of its residents. In our [NSF NetSE project](http://sensorweb.cs.gsu.edu/?q=ActiSen) (NSF-0914371, $300,000, 10/2009-9/2013), our goal is to imbue wireless sensor networks with cognitive capabilities and context awareness. My collaborator of this project is Diane Cook (WSU).

- **Activity-aware sensing and networking.** In the literature, the feedback from environment context to the network resource allocation is almost unexplored. Therefore this missing link, if utilized in an intelligent manner, shall improve the sensor network performance and lifetime significantly. The operation of an activity-aware sensor network is conceptually different from typical sensor networks in a way that it retroactively optimizes the network operations using learned activity pattern. We study how to use historical behavioral pattern information to efficiently optimize performance and resource usage of the sensor network through activity aware sensing, routing, and transceiving. We have developed an ActiSen system [24], which utilizes activity patterns to make sleep and wake-up decisions [25], as well as influence the routing protocols [26]. Each sensor node is aware of the activities in which it plays a part (the activity sensor set). From the activity models the sensor node can determine when the activities typically occur as well as the triggers for the activity (the sensor events that typically occur before and at the beginning of the activity).
• **Activity tracking for interleaved and parallel activities.** Tracking and modeling the movements of users is a key step toward developing many applications of smart environment. However, users may often not want to reveal their identity thus video camera or other complex sensors are simply too privacy intrusive. We set up a testbed in GSU that is equipped with binary motion sensors (which detects motion or no-motion) only, with the goal of tracking people’s moving trajectory in the hallway. A key research challenge is how to simultaneously track multiple (unknown and variable number of) users from anonymous binary motion sensor data [27] in a crowded environment, where motion trajectories can overlap or crossover in all possible ways. We understand certain overlapped motion trajectory is impossible to separate from binary motion data only, thus are also further investigating how to integrate history patterns and a few low-cost radar sensors in corners to improve the tracking accuracy. Trajectory tracking is a key step toward activity recognition in smart environments.

**NOTE**

More details of our research projects can be found at http://sensorweb.cs.gsu.edu/?q=research.

**REFERENCES**


