Research Summary and Agenda

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OVERVIEW

I have focused my research interests on an emerging area of computer science called Cyber-Physical Systems (CPSs) where the cyber- and the physical-worlds intersect. The proliferation of inexpensive devices with computing, communication, and sensing capabilities is giving rise to a world of "smart objects" with tremendous potential to influence our lives. Harnessing these capabilities to obtain safe, controllable, and predictable operation, and produce "smart environments" is the core theme of my research. My research often involves building systems in order to evaluate their performance and analyze their effectiveness at solving problems.

My research thus far has taken two paths. In one, I have attempted to build abstractions and programming environments to tame the chaos that ensues when the cyber- and the physical-worlds meet and the system must obey the laws of physics in addition to following algorithms and procedures [SenSys '08, SenSys '09, SESENA '10]. The Department of Defense Information Science and Technology (ISAT) study on future directions for ensemble programming invited some of this work for presentation. In the second, I have attempted to utilize CPSs to solve real-world problems, from environmental monitoring [SenSys '07] and energy conservation [SenSys '10, SenSys '11, SIGBED Rev. '12, IEEE Des. Test '12, IGCC '12, CONET '12, ICCPS '13, SUSCOM '13] to battlefield situational awareness. The University of Virginia has filed a provisional patent application for some of my work on energy conservation. The sections below provide more details.

RESEARCH PHILOSOPHY

A desire to address real-world problems motivates my research. Thus, I focus on implementing real, working systems, which I can evaluate in realistic environments. System building, and deploying them in the real world, forces you to face issues that you can easily miss or gloss over when working at an abstract or theoretical level. Real implementations also give greater validity to results than obtaining them analytically or through simulation.

While I ground my research in implementation, I believe simulation and theory are critical for a complete evaluation of a system. This is especially true when building CPS applications, since the environment in which the system is tested heavily influences performance. Thus, in addition to implementing and evaluating a working system, researchers can use simulations to evaluate its performance in different environments and at scale. Having a solid grasp of the computer science theory behind the system gives greater confidence in any results obtained through experimentation.

Many researchers write and document software very poorly because their only goal is the generation of data necessary for the targeted publication. I believe that researchers should follow good software engineering principles and generate clean, well-documented code. This has a number of benefits, including the easing of code sharing within the research group and collaborating with others, easing the reproducibility and verification of results, and easing technology transfer if a project matures to that stage.

RESEARCH EXPERIENCE

Tools for Cyber-Physical System Application Development

The first path my research has taken so far is the development of systems to ease the CPS application implementation process. My desire to see CPS technology used by non-Computer Scientists and domain experts, just as they use computers as tools of their trade, motivated this project. This requires the handling of a number of challenges concurrently, including the coordination of heterogeneous devices, the robustness in the face of unreliable wireless links, and the managing of highly constrained resources.

My earlier work at the University of Virginia focused on the implementation of the MacroLab macroprogramming environment that provided a single-machine abstraction to a collection of networked smart objects. This allows the application developer to write a single application describing the global behavior of the system, and the MacroLab compiler automatically decomposes it into programs for each smart object. In addition, MacroLab is able to reconfigure the network dynamically by reprogramming the smart objects with a different decomposition of the application in response to changes in network topology, device energy availability, or physical stimuli sensed.

MacroLab provides a vector programming abstraction based on the Matlab programming language. We chose this abstraction since Matlab is one of the most commonly used programming languages among scientists. Thus, we hoped this would pave the way for scientists to use CPSs for their research. In order to provide MacroLab with a more complete application development tool-chain, for my master's thesis, I implemented the MDB macro-debugger. MDB allows programmers to debug MacroLab programs at the global application level without being concerned with the lower-level details such as wireless communication. The Department of Defense's ISAT study on future directions for ensemble programming invited this project for presentation.

Implementing Cyber-Physical System Applications

The second research path I have pursued over the last few years is the utilization of CPSs to solve real world problems. I have implemented CPSs for environmental research and energy conservation, and I am now in the process of implementing a system for situational awareness on the battlefield.

My first project at the University of Virginia was as part of a team that implemented and deployed a CPS to allow a group of environmental scientists to monitor sunlight under shrub thickets on an island off the coast of Virginia. An environmental scientist at the University of Virginia and a biologist at Virginia Commonwealth University who wanted to study the link between shoot architecture and light absorption characteristics of shrubs initiated the project. This project motivated my research philosophy of building and deploying systems in their target environments. It provided me first-hand experience in the challenges that arise when building real systems. This project also piqued my interest in designing tools to help scientists use CPSs themselves; instead of requiring CPS experts to build and deploy the systems for them.

Next, I used CPSs to tackle the issue of energy conservation. Based on the observation that homes account for 22% of all energy used in the United States, and the Heating, Ventilation, and Air Conditioning (HVAC) system consumes the majority of this energy, my research focused on optimizing the control of the HVAC system based on the usage patterns of homes. Our first approach, Smart Thermostat, attempted to retrofit traditional programmable thermostats to react to house occupancy. Smart Thermostat turns off the system when the house is unoccupied, turns on the system before the occupants return so that the house is at a comfortable temperature when they arrive, and turns back the temperature when the occupants are asleep. Studies that demonstrated the inefficient use of programmable thermostats motivated this project. In fact, on December 31, 2009, Energy Star stopped certifying programmable thermostats due to observations that incorrectly programmed thermostats actually waste more energy than manual thermostats. Thus, we attempted to automate the thermostat control in order to reduce the burden on residents to program their thermostats accurately. Experiments demonstrated that this system, the Smart Thermostat, could decrease the total energy consumed for heating and cooling by 28% with only $25 of extra hardware per home.

After implementing the Smart Thermostat, in order to see how far we could optimize HVAC control, we attempted to retrofit an existing centralized HVAC system for room-level zoning. Instead of responding to the whole house being occupied or vacant, the aim of this system was to react to occupancy at the room-level and condition only occupied rooms. Following my philosophy of building and deploying systems in the real world proved very valuable in this project since it uncovered a number of physical constraints that we may have overlooked if we evaluated the system analytically or in simulation. One of these constraints is the minimum number of rooms that the system can condition, so that even if there is only one occupied room, the system has to select other rooms to condition along with it. This is necessary to prevent damage to the HVAC system due to pressure buildup in the ducts when the airflow is constrained.

At the U.S. Army Research Lab, I am working on a CPS to increase the situational awareness of soldiers in the battlefield. I was motivated to start this project by the observation that more soldiers are carrying smartphones into battle. Soldiers could use these devices to collect and process data. Thus, we set about to utilize these resources to build a battlefield computation network in order to provide soldiers with mission critical information. As part of this project, we are collaborating with Prof. Stoleru from Texas A&M to tackle security and reliability in these networks. We are also collaborating with Professors Ammar and Zegura from Georgia Tech to research computation-offloading strategies to enable these smartphones to conserve energy.

FUTURE AGENDA

Based on my experience, I am confident that the following research directions have significant potential:

Predictive Room-Level Zoning of a Centralized HVAC System

In the near term, I am interested in exploring the impact of using room-level occupancy prediction to control an HVAC zoning system. For my Ph.D. dissertation, I implemented a reactive room-level zoning system, and proposed an algorithm to predict room level occupancy. I am interested in combining these two ideas to design a room-level zoning algorithm that predicts room-level occupancy when making control decisions. Such a system will increase occupant comfort by ensuring a room is at a comfortable temperature before the occupant enters and save energy by not conditioning soon to be vacant rooms.

Individualized HVAC Zoning

Another near term goal of mine is to incorporate my room-level zoning experience with the recent research in occupant tracking in homes. Many researchers have implemented systems over the last few years, using technologies such as doorway height sensors and RFID tags that can distinguish occupants as they move about a house. I am interested in investigating the possibility to condition rooms to differing temperatures depending on their occupants. This could be a very challenging problem due to frequent occupant movement between rooms, multiple occupants in a room, and the flow of air between rooms making it difficult to maintain a temperature. Yet, it would be interesting if such a level of customization were achievable by using CPSs.

Exploiting Natural Ventilation for Building Cooling

Beyond the optimized control of HVAC systems, I would like to explore the possibility of utilizing natural ventilation for cooling buildings. I envision a system that learns the airflow patterns through a house for different combinations of open windows, and using weather predictions and real-time weather data. Then it will decide if it can cool the house to its target temperature by opening windows instead of turning on the air conditioner. This could result in significant energy savings, especially in moderate climates. Yet a number of challenges, including security, humidity, and dust have to be considered when implementing such a system.

Seamless Integration of Heterogeneous Smart Objects

Finally, I would like to return to my experience with macroprogramming and tackle the problem of efficiently integrating disparate smart objects to give rise to intelligent systems. A simple application to demonstrate this concept is the interfacing of a smart refrigerator with a smart phone to build an application that suggests a store where the total cost of all items that are running out in the refrigerator is the lowest. In addition to an application-level programming interface, such a system would require drivers, and possibly hardware, in order to enable devices from different manufacturers to interoperate. The issue of interfacing devices that span geographic areas, yet are connected via the Internet, will drive the development of the Internet of Things and promote further research into privacy and security.