mLAB
Real-Time & Embedded Systems Lab
http://mlab.seas.upenn.edu

Research Overview

Director: Rahul Mangharam

The broad goal of our research is to build the foundations of Cyber-Physical Systems (CPS). CPS is the next generation of time-critical and safety-critical Real-Time Embedded Systems where computation and communication are tightly coupled to control large, complex and "messy" plants. Unlike classical Real-Time Systems where the system is designed in a constrained manner to limit the complexity and non-determinism for modeling and scheduling, in current CPS, the plants are non-deterministic, interactive, scale to thousands of controllers and are often difficult to model precisely. Examples of these span implantable medical devices such as pacemakers which are responsible for safely controlling the human heart, wireless control-actuator networks for natural gas processing which scale to over 120,000 control-loops, and coordinated control of multiple building automation systems to minimize peak energy consumption across a campus while maintaining custom micro-environments in order to satisfy dynamic occupant demand. Our research focuses on the central needs for modeling, architectures, algorithms and platforms to systematically address these structural concerns in the design of future Cyber-Physical Systems.

Our work is motivated by the observation that, in bridging scheduling theory and control systems, merely extending classical real-time systems theory is both inadequate and overly restrictive. There is a strong need for new techniques to *model* the interaction between controllers and complex messy plants, such as the human body, so both the functional and formal aspects are tested, validated and verified within the closed-loop context of the overall system. There is a need to re-think the system *architectures* for control/actuation networks when wireless links are used such that irrespective of node, link and topology faults, the overall control stability and performance is maintained. As time-critical systems mature from classical Real-Time systems, there is a need to develop new *platforms* for Cyber-Physical Systems that capture the non-determinism, interactivity, and scale to demonstrate the safety and efficacy of the proposed approaches. *Just like the Internet transformed how we interact with information systems, Cyber-Physical Systems will transform how we interact with and manipulate the physical world.*

Based on these central themes, our research focuses on five Thrusts across the Cyber-Physical Systems domains of **Medical Devices**, **Industrial Control**, **Automotive Systems**, **Real-Time Parallel Computing** and **Energy-efficient Building Automation**. While these domains span a large spectrum of problems, they bring about a core set of generic challenges in modeling, architectures and evaluation of CPS. Each also introduces domain-specific issues which require significant effort from our research teams to learn from domain experts such as electro-physiologists in the Cardiac Operating Rooms and field engineers from Honeywell on-site at an oil refinery.

Reflecting the cross cutting nature of our work, our research findings have been published in selective venues in the areas of Real-Time Systems [4, 5, 6, 7, 22, 23, 18, 23, 26, 27, 28, 30], Embedded Systems [2, 15, 16, 17, 18, 20, 21], Control Systems [1, 2, 3, 14, 24, 25, 33] and Bio-Medical Engineering [8, 9, 10, 11, 12, 13, 29, 31, 36]. mLAB hosted the High-Confidence Medical Device Software & Systems workshop at CPSweek 2011. mLAB hosted the Analytic Virtual Integration of CPS workshop at IEEE RTSS 2011 in Vienna and will co-chair IEEE RTAS in Beijing in 2012. Popular media outlets such as The Economist, The Philadelphia Inquirer and The Discovery Channel, highlighting the lab's research, have captured the research's broad impact.

Since joining Penn, Dr. Mangharam is a founding member of the new Penn Research in Embedded Computing and Integrated Systems (PRECISE Center) that has allowed us to pursue several Medium and Large collaborative grants. He is a founding member of the committee to develop the new Computer Engineering major between the Electrical Engineering and Computer Science departments. He is also a founding member of the Embedded

Medical Devices Software & Systems	Network CPS Industrial Control Nets	Automotive CPS Automotive Plug-n-Play	Real-Time Parallel Computing

Systems Masters Program. This is the first such program in the nation with a specific focus on next-generation embedded systems. The Real-Time and Embedded Systems Laboratory now houses 5 Ph.D. students, 6 MS students and 8 undergraduates. Several of the undergraduate students mentored in the lab have gone on to win prestigious awards such as the 1st place in the 2010 World Embedded Software Competition held in Korea, 1st prize in Honeywell's Industrial Wireless Design Competition, the Google Zeitgeist Young Minds award and the Harold Berger Award given to the best Senior Design team [34]. Both projects have evolved into newly funded research projects. Undergraduate students we have mentored for more than a year have gone on to pursue Ph.D's at Princeton, U. Minnesota and Virginia Tech.

Thrust 1: Medical Cyber-Physical Systems

Project website: http://mlab.seas.upenn.edu/vhm

In the 20-year period from 1985 to 2005, the US Food and Drug Administration's (FDA) Maude database records nearly 30,000 deaths and 600,000 injuries due to medical device failures. This thrust focuses on the development of high-confidence medical device software and systems where the device may interact directly with the patient (e.g. implantable cardiac pacemakers) or work in coordination with the patient-in-the-loop (e.g. patient-controlled infusion pumps). The goal of this thrust is to develop an integrated approach to functional and formal modeling such that the devices may be tested, validated and verified within the clinically-relevant and closed-loop context of the patient's condition. This project contributes toward the Generic Pacemaker Project for the FDA.

1) Real-time Heart Model for Implantable Cardiac Device Validation and Verification

Designing bug-free medical device software is challenging, especially in complex implantable devices that may be used in unanticipated contexts. Safety recalls of pacemakers and implantable cardioverter defibrillators due to firmware problems between 1990 and 2000 affected over 200,000 devices. This encompasses 41% of the devices recalled and continues to increase in frequency. There is currently no formal methodology or open experimental platform to validate and verify the correct operation of medical device software. To this effect, a real-time Virtual Heart Model (VHM) has been developed to model the electrophysiological operation of the functioning (i.e. during normal sinus rhythm) and malfunctioning (i.e. during arrhythmia) heart. We have developed a methodology to construct a timed-automata model by extracting timing properties of the heart. The platform employs functional and formal interfaces for validation and verification of implantable cardiac devices. In [8, 9, 10, 11], we demonstrate that the VHM is capable of generating physiologically-relevant response to intrinsic (i.e. premature stimuli) and external (i.e. artificial pacemaker) signals for a variety of common arrhythmias. By connecting the VHM with a pacemaker model, we are able to pace and synchronize the heart during the onset of irregular heart rhythms. The VHM has also been implemented on a hardware platform for closed-loop experimentation with existing and virtual medical devices. This integrated functional and formal device design approach has potential to help expedite medical device certification for safe operation.

2) Model-Driven Safety Analysis of Closed-Loop Medical Systems

In modern hospitals, patients are treated using a wide array of medical devices that are increasingly interacting with each other over the network, thus offering a perfect example of a cyber-physical system. We are studying the safety of a medical device system for the physiologic closed-loop control of drug infusion. The main contribution of this effort is the verification approach for the safety properties of closed-loop medical device systems [12, 13]. We demonstrate, using a case study, that the approach can be applied to a system of clinical importance. Our method combines simulation-based analysis of a detailed model of the system that contains continuous patient dynamics with model checking of a more abstract timed automata model and the UPPAAL tool. We show that the relationship between the two models preserves the crucial aspect of the timing behavior that ensures the conservativeness of the safety analysis. We have also developed and evaluated system designs that can provide open-loop safety under network failure. We believe that such a technique can be applied to other tightly integrated medical systems in which fail-safe is essential. Our approach allows us to construct safety cases for regulatory approval of closed-loop medical systems.

Thrust 2: Wireless Industrial Automation

Project website: http://mlab.seas.upenn.edu/evm

This thrust focuses on the design of new architectures for wireless control and actuation in industrial plants. Time-critical and safety-critical automation systems are at the heart of essential infrastructures such as oil refineries, automated factories, logistics and power generation systems. While there are significant economic

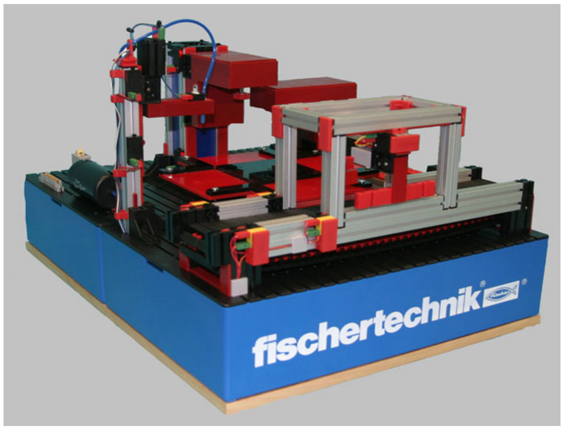
arguments for using wireless in closed-loop control systems, current approaches do not guarantee stability or performance of the control system. We are exploring both flexible network system architectures and radically new distributed approaches for control over wireless networks. To this end, we introduce two new approaches for robust wireless control/actuation: (a) Embedded Virtual Machines [4, 5, 6, 7] where controller tasks migrate across physical nodes at runtime to maintain stability and performance and (b) Wireless Control Network [1, 2, 3, 14, 24, 25, 33], a distributed in-network approach where the network acts as a wireless controller cloud. This project contributes toward Honeywell's OneWireless wireless industrial automation systems.

1) Robust Architectures for Embedded Wireless Network Control and Actuation

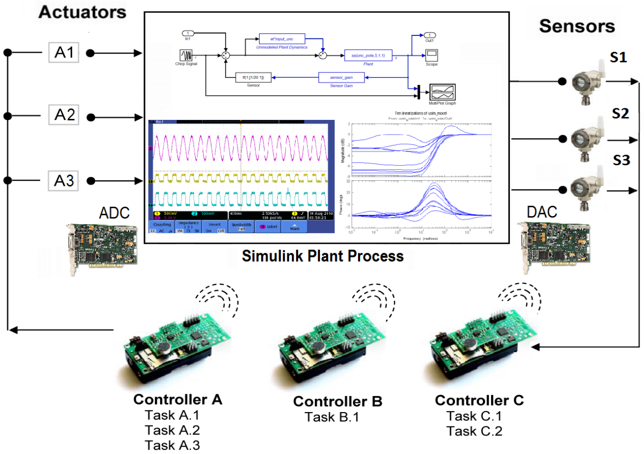
Embedded wireless networks have largely focused on open loop sensing and monitoring. To address actuation in such closed-loop wireless control systems there is a strong need to re-think the communication architectures and protocols for reliability, coordination and control. As the links, nodes and topology of wireless systems are inherently unreliable, such time-critical and safety-critical applications require programming abstractions and runtime systems where the tasks are assigned to a set of controllers as a single component rather than being statically mapped to a specific physical node at design time. To this end, we developed the Embedded Virtual Machine (EVM), a powerful and flexible programming abstraction where virtual components with their control and timing properties are maintained across node boundaries and functionality is capable of migrating to the most competent set of physical controllers. In the context of process and discrete control, an EVM is the distributed runtime system that dynamically selects primary-backup sets of controllers to guarantee QoS given spatial and temporal constraints of the underlying wireless network. EVM-based algorithms allow network control algorithms to operate seamlessly over less reliable wireless networks with topological changes. They introduce new capabilities such as predictable outcomes during sensor/actuator failure, adaptation to mode changes and runtime optimization of resource consumption. Through case studies in process control we are now able to demonstrate the preliminary capabilities of EVM-based wireless networks.

2) The Wireless Control Network: A New Approach for Control over Networks

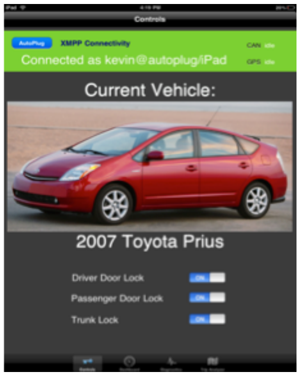
We have developed a radically different method to stabilize a plant with a network of resource constrained wireless nodes. As opposed to traditional networked control schemes where the nodes simply route information to and from a dedicated controller, our approach treats the network *itself* as the controller. This concept, called the Wireless Control Network (WCN), is one where the entire network itself acts as a distributed controller. Specifically, we have formulated a strategy for each node in the network to follow where at each time-step, each node updates its internal state to be a linear combination of the states of the nodes in its neighborhood. We have shown that this causes the entire network to behave as a linear dynamical system, with sparsity constraints imposed by the network topology. We provide a numerical design procedure (based on linear matrix inequalities) to determine the appropriate linear combinations to be applied by each node so that the transmissions of the nodes closest to the actuators will stabilize the plant. We also show how our design procedure can be modified to maintain mean square stability under packet drops in the network, and present a distributed scheme that can handle node failures while preserving stability. WCN introduces very low computational and communication overhead to the nodes in the network, allows the use of simple transmission scheduling algorithms, and enables compositional design (where the existing wireless control infrastructure can be easily extended to handle new plants that are brought online in the vicinity of the network). This work leads to new approaches to wireless industrial automation.

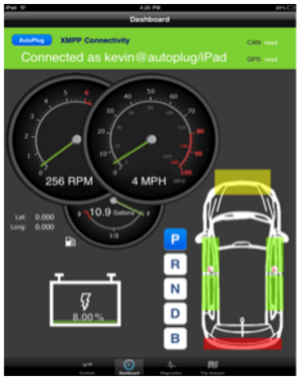


Wireless Factory of the Future



Wireless Control Network with hardware-in-loop test-bed

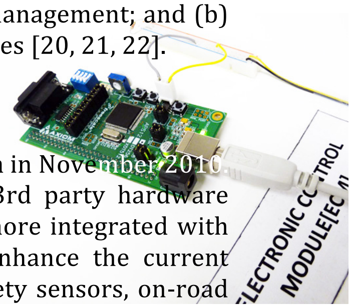




Thrust 3: Automotive Cyber-Physical Systems

Project website: http://mlab.seas.upenn.edu/research

In 2010, 20.3 million vehicles were recalled in the United States. Of those, General Motors recalled 1.3 million due to software issues alone, costing the firm $136 million. This thrust focuses on future automotive electronics architectures for remote diagnostics, software updates and traffic congestion management. Our early work has focused on (a) The specific need for new methods for remote vehicle warranty and recalls management; and (b) New infrastructure-less methods to increase traffic throughput by alleviating traffic shockwaves [20, 21, 22].



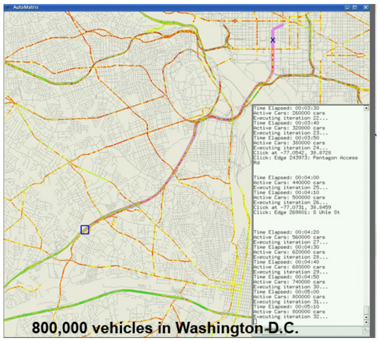
1) AutoPlug - Open Architecture for Plug-n-Play Automotive Services

Project website: http://www.autoplug.org

This project won the 1st Prize in the World Embedded Software Competition held in Korea in November 2010. AutoPlug is an open middleware and network architecture for Plug-n-Play services for 3rd party hardware devices and software modules. It allows vehicles to become extensible, customizable, and more integrated with evolving technology over the lifetime of the vehicle. AutoPlug enables car owners to enhance the current capabilities (e.g. engine performance, infotainment), add on new functionality (e.g. new safety sensors, on-road diagnostics), and personalize their vehicle via an “Automotive AppStore”.

2) AutoNet - Automotive Test-bed for Electronic Controller Unit Testing and Verification

In 2010, over 20.3 million vehicles were recalled. Software issues related to automotive controls such as cruise control, anti-lock braking system, traction control and stability control, account for an increasingly large percentage of the overall vehicles recalled. There is a need for new and scalable methods to evaluate automotive controls in a realistic and open setting. We have developed AutoNet [32, 35], an automotive Electronic Controller Unit (ECU) test-bed to diagnose, test, update and verify controls software. AutoNet consists of multiple ECUs interconnected by a CAN bus, a racecar driving simulator which behaves as the plant model and a vehicle controls monitor in Matlab. As the ECUs drive the simulated vehicle, the physics-based simulation provides feedback to the controllers in terms of acceleration, yaw, friction and vehicle stability. This closed-loop platform is then used to evaluate multiple vehicle control software modules such as traction, stability and cruise control. With this test-bed we highlight approaches for runtime ECU software diagnosis and testing of the stability and performance of the vehicle. Code updates can be executed via a smart phone so drivers may remotely ``patch" their vehicle. This closed-loop automotive control test-bed allows the automotive research community to explore the capabilities and challenges of safe and secure remote code updates for vehicle recalls management.



Thrust 4: Real-Time Parallel Computing

Project website: http://mlab.seas.upenn.edu/automatrix

This thrust focuses on the application of imprecise and approximate computation techniques for real-time systems *where the raw data feed cannot be processed in time for the real-time controller*. The goal of this effort is to investigate algorithms for real-time computation on multicore architectures such as Graphics Processing Units (GPUs) [18, 19]. Algorithms for such applications must therefore adaptively allocate resources appropriate to the goals/loads and evaluate their progress with execution time to deliver intermediate results.

Anytime Algorithms for GPU Architectures

Most algorithms are run-to-completion and provide one answer upon completion and no answer if interrupted before completion. On the other hand, anytime algorithms have a monotonic increasing utility with the length of execution time. Our investigation focuses on the development of time-bounded anytime algorithms on GPUs to trade-off the quality of output with execution time. Given a time-varying workload, the algorithm continually measures its progress and the remaining contract time to decide its execution pathway as well as the system resources required to maximize the quality of the result. To exploit the quality-time trade-off, the focus is on the construction, instrumentation, on-line measurement and decision making of algorithms capable of efficiently managing GPU resources. We have initially demonstrated this with a Parallel A* routing algorithm on a CUDA-enabled GPU. The algorithm execution time and resource usage is described in terms of CUDA kernels constructed at design-time. At runtime, the algorithm selects a subset of kernels and composes them to maximize the quality for the remaining contract time. This is an early effort to enable imprecise and approximate real-time computation on parallel architectures for stream-based time-bounded applications such as traffic congestion prediction and route allocation for large transportation networks.

In order to investigate a wider spectrum of anytime algorithms, we have designed AutoMatrix, a traffic congestion simulation platform on the Nvidia CUDA-enabled GPU. AutoMatrix is capable of stream processing over 16 million vehicles on any US street map and executing traffic estimation, prediction and route assignment algorithms with high-throughput. This research has the potential to extend real-time scheduling on parallel GPU architectures to attack a variety of data-driven, interactive and dynamical algorithms with timely operation.

Thrust 5: Scheduling Foundations for Cyber-Physical Systems

The focus of this final thrust is on the development of a new class of scheduling algorithms for CPS such as energy-efficient building automation [23, 26, 28, 30]. There is a fundamental difference between how traditional real-time theory treats timing constraints of a system and the timings restrictions that exist in a cyber physical system. In traditional real-time scheduling theory, the concept of periods, release times, execution time and deadlines of tasks is well specified as system-centric functional and timing requirements (i.e. a fixed worst case execution time) and is usually applied to CPU tasks. In a cyber-physical system, the execution time is a function of the system dynamics (i.e. control law) and the environment (weather, heating/cooling gradients, etc.) and may be applied to CPS resource scheduling (i.e. energy scheduling from a finite power source). This subtle difference results in a significant departure from classic fixed period/priority scheduling as the task's execution time is not constant. Not only do the control and scheduling decisions influence the physical parameters of the system (e.g. room temperature) but the physical parameters can also influence the scheduling parameters. The fact that scheduling parameters are no longer determined by system specifications alone, suggests that we cannot use traditional real time scheduling algorithms to schedule such systems.

Our goal is to explore alternate task execution models to better address generic CPS scheduling problems. To illustrate the models, we focus on the problem of coordinating multiple control loops (i.e. energy sinks such as heating ventilation and air conditioning (HVAC) systems) in a building to provide for a more energy-efficient operation under the constraint of minimizing the peak energy demand. In order to achieve this goal we define task models for energy scheduling such that the execution time is a function of the initial operation point, response time, weather, time of day, human occupancy, and other plant dynamics. We provide the conditions for feasibility, optimality and admissibility for a set of tasks [23]. We have built a physical building platform with several zones such that the temperature and humidity must be maintained in a dead-band. We are currently able to maintain comfort levels in all zones while applying elastic execution-time scheduling algorithms for minimizing peak energy demands. This effort is a step towards developing a general scheduling theory for CPS.

Summary of mLAB's Research Approach:

We try to ensure that our research ideas begin with a grounding in theory, are systematically modeled for both functional and formal analysis, are architected for efficiency across the control, computation and communication dimensions and are finally vetted by solid platform implementations. Each domain requires interacting with the respective domain experts *outside of EE and CS* and finding the right contacts is non-trivial and time-consuming. Nevertheless, we try to make this is a key priority because it ensures high impact.

We particularly enjoy using theoretical insights and approaches from other diverse areas as the basis for the systems and protocols we build. Such "cross-domain" work is both exciting (and educational). Students who join our group quickly diversify to become adept at a variety of skills including system building, modeling and theory.

We enjoy working on deep, challenging and multi-faceted problems that take a few years to address thoroughly. Rather than follow someone else's lead, our goal is to *define* the next hot area and make early contributions.

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PRECISE

PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING