Research Statement

Rahul Mangharam

Foundations of Cyber-Physical Systems: Modeling, Architectures, Algorithms and Platforms

My research develops the foundations of Cyber-Physical Systems (CPS). CPS are the new 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 for predictability, in current CPS, the plants are difficult to model precisely because they are non-deterministic, interactive and often scale to thousands of controllers. My research addresses these structural concerns in the design of future Cyber-Physical Systems through closed loop modeling, architectures, algorithms and platforms. My aim has been to develop CPS to transform how we interact with and manipulate the physical world, just as the Internet transformed how we interact with information systems.

My work bridges scheduling theory and control systems for CPS. I have developed new techniques to *model* the interaction between controllers and complex messy plants such as the pacemaker and the heart (whose dynamics are not fully definable or understood). My work re-thinks 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. I have designed and synthesized scheduling *algorithms* for coordinating plants as they scale to thousands of controllers, such that the system as a whole operates within constraints while individual plants are always safe. Finally, I have developed new CPS *platforms* that capture non-determinism, interactivity, and scale to demonstrate the safety and efficacy of the proposed approaches.

My research on these four themes: Modeling, Architectures, Algorithms and Platforms has addressed the foundations of CPS across four domains spanning Medical Devices, Control over Wireless, Energy-Efficient Buildings and Automotive Systems.

- **CPS Modeling:** *From Verified Models to Verified Code for Life-Critical Systems.* I have focused on the formal modeling, synthesis and certification of high-confidence medical device software and systems. I have concentrated on both implantable medical devices and physiological control systems to ensure that both the functional and formal aspects are verified, validated and tested within the closed-loop context of their physiological systems. This theme is published in [1–16].
- **CPS Architectures:** *Distributed Control over Wireless Networks.* I have focused on radical architectural approaches for completely in-network computation for robust, optimal and secure control over inherently unreliable infrastructure. This theme is published in [17-37].
- **CPS Algorithms:** *Green Scheduling of Control Systems.* I have developed a new class of scheduling for CPS, called Green Scheduling, which incorporates the dynamics of the plant in the scheduling scheme. This is used for coordinated control of building automation systems to minimize peak energy consumption across a campus while satisfying dynamic occupant demand. This theme is published in [38-48].
- **CPS Platforms and Test-beds:** I have developed several platforms and tools for medical devices and physiological systems, wireless networks and protocols, energy-efficient buildings and automotive systems [49-64] to validate and demonstrate modeling and theoretical efforts.

Research Impact

In each theme, my lab has won national and international recognition in the form of the Intel Early Faculty Career Award'12, NSF CAREER Award'13, ACM SIGBED Frank Anger Memorial Award'11, IEEE RTAS Best Student Paper Award'12, National Academy of Engineers - Frontiers of Engineering'12 (for Top-15 engineers under 45), 1st Prize in the World Embedded Systems Competition, Seoul, Korea in 2010 *and* 2012, Intel/Cornell Cup Embedded Systems Award'12, SEAS Best Senior Design Award'12, Google Zeitgeist Award'12, ACM IPSN Best Presentation Award'12, Honeywell Industrial Wireless Innovation Award'11, Joseph and Rosaline Wolf Best Dissertation Award'12, etc.

Reflecting the cross cutting nature of my work, my research findings over the past 5.5 years have been published in the areas of ***Real-Time Systems*** [11, 40, 45, 46, 52, 53, 54], ***Embedded Systems*** [2, 5, 19, 29, 30, 31, 32, 41, 49, 55, 59], ***Control Systems*** [17, 18, 20, 21, 22, 23, 24, 25, 26, 27, 33, 39, 43, 44], ***Formal Methods*** [1, 3, 12, 13, 14], ***Medical* Systems** [4, 6, 10, 15, 16] and ***Automotive Systems*** [50, 51, 56-58, 60, 61, 63, 64].

I have served as co-chair of IEEE RTAS'12, the top Real-Time and Embedded Systems conference. I have co-chaired the Medical CPS Workshop at CPSweek in 2011, 2013 and 2014, which has established itself as a destination for clinicians, computer scientists, government regulators and industry experts for medical devices (http://medcps.org). I have also co-chaired the Analytical Virtual Integration for CPS workshop and have served on the organizing committee of Cyber-Physical Systems Week, host to the 5 premier conferences on controls, real-time systems and formal methods.

In recognition of this cross cutting research, I have been invited for talks in multiple formal methods venues such as CAV and NSV, the NY/NJ/PA transportation research centers, the US Food and Drug Administration (FDA), NAMUR Industrial Automation Working Group in EU, Honeywell Technical Symposium, Dagsthul Seminar, ARPA-Energy and multiple NSF and inter-agency joint workshops. I currently serve as guest editor on the Journal of Real-Time Systems, IEEE Design & Test, IEEE Transaction on Emerging Topics in Computing and IEEE Transactions on Embedded Systems. I have been invited to give Distinguished Lectures at UIUC, UCSD and Kansas State University. Popular media outlets such as The Economist, The Philadelphia Inquirer, NAE Bridge, and The Discovery Channel, have captured the lab's broad impact.

The National Science Foundation (NSF), US Department of Energy (DoE), US Department of Transportation (DoT), Semiconductor Research Corporation (SRC), DARPA and industry have recognized the productive inter-disciplinary flavor of the overall research. My lab has won several NSF grants in the form of single-PI grants, NSF CAREER award, NSF Major Research Instrumentation (Development, not Acquisition), NSF-Medium and NSF-Large awards. In the NSF CPS program, the budget has grown to $65 million, of which projects that I was PI or Co-PI for accounted for approximately $8.5 million. My work is also funded by the DoE HUB for Energy Efficient Buildings ($2.25 Million over 5 years), SRC/DoD TerraSwarm for Networked CPS (a $27 million multi-university 5-year project) and the DoT University Transportation Center ($5.9 million between CMU-Penn). Additionally, my lab receives significant funding from industry partners such as Honeywell Process Solutions, L3 Communications, and Intel. From January 2014, Comcast has funded a new MediaLab@Penn under my direction to explore the next generation of Cyber-Physical technology.

In the rest of this statement, I will summarize the past and current work in my group, and discuss future research extensions, broadly classified under four CPS domains of Medical CPS, Network CPS, Energy CPS and Automotive CPS.

1. Medical Cyber-Physical Systems - Implantable Devices & Physiological Control Systems

In this thrust, I have focused on the development of high-confidence medical device software and systems where the device interacts directly with the patient (e.g. implantable cardiac pacemakers) or works in coordination with the patient-in-the-loop (e.g. patient-controlled infusion pumps). In medical devices, the design of bug-free and safe software is challenging, especially in complex implantable devices that control and actuate organs whose response is not fully understood. For example, safety recalls of pacemakers and implantable cardioverter defibrillators between 1990-2000 affected over 600,000 devices. Of these, 200,000 or 41%, were due to *software issues* that continue to increase in frequency.

To address this problem, I have developed an integrated approach to functional and formal modeling such that the devices could be tested, validated and verified within the clinically-relevant and closed-loop context of the patient's condition. My aim has been to develop the foundations of formal modeling, synthesis and development *from verified closed-loop models* to *verified medical device software* and systems. This effort has involved successful collaborations with cardiologists in the Penn Hospital, Philadelphia VA Hospital and John's Hopkins Hospital. The results are published in [1–16].

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

My work has recognized the need for closed-loop evaluation between the device and the physiological system (i.e. the heart) instead of the current open loop evaluation where test signals are input into the device (i.e. the pacemaker) to evaluate its response to stimulus. This change ensures that devices do not adversely affect the state of the heart, as in my investigation of multiple clinical cases, including Pacemaker Mediated Tachycardia [4, 5, 7, 10]. I have developed an end-to-end approach for pacemaker formal verification (using Timed Automata), automated formal model translation for simulation-based testing (in Stateflow/Simulink), and finally automatic code-generation for platform testing – all within the closed-loop context of the heart.

My research has produced a real-time Virtual Heart Model (VHM) to model the electrophysiological operation of the normal and malfunctioning (i.e. during arrhythmia) heart [1, 2, 4, 8, 9, 11]. Based on a common kernel, the VHM exposes both functional (i.e. clinically relevant signals to interact in real-time with pacemakers) and formal interfaces (i.e. event timing) for validation and verification of implantable cardiac devices. By connecting the VHM with a pacemaker model (based on Boston Scientific's pacemaker specifications), my lab and I have been able to pace and synchronize the heart during the onset of the most common arrhythmias. The development of this VHM has addressed the challenge of developing environment models (i.e. heart models) that are both complex enough to express the physiological requirements, and general enough to cover all possible inputs to the device. I have adapted a Counter-Example-Guided Abstraction and Refinement (CEGAR) framework to refine the heart model to verify the simplest up to the most complex closed-loop safety properties [3, 13].

Along with our tools for code generation from UPPAAL models [2, 12], this effort enables model-driven design and certification of software for medical devices. The VHM has also been implemented on a "Heart-on-a-Chip" hardware platform [6, 16] for closed-loop experimentation with real pacemakers. My lab's integrated functional and formal device design approach is a step toward a rapid certification toolchain to help expedite the development of safe medical device software. With the 2013 NSF CAREER Award for *Foundations of Medical Cyber-Physical Systems*, my lab has embarked on the next phase of medical device research. This includes: (a) Quantative Verification to not just evaluate binary safety properties but the tradeoff between performance properties such as efficacy of therapy and device energy consumption; (b) Patient-specific heart modeling and device parameter optimization based on signal data from real patients; and (c) Development of a Rapid Certification Toolchain in collaboration with the US FDA.

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

My research studies the safety of medical device systems for the physiologic closed-loop control of drug infusion where an overdose or under dose causes adverse effects such as respiratory arrest. My main solution to this problem has been developing a verification approach for the safety properties of closed-loop medical device systems [2, 12]. I have demonstrated, using a case study of a Patient Controlled Analgesic (PCA) pump, that the approach can be applied to a system of clinical importance. My lab's 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. This research shows that the relationship between the two models preserves the crucial aspect of the timing behavior that ensures the conservativeness of the safety analysis [14, 15]. My lab and I have also developed and evaluated system designs that can provide open-loop safety under network failure. Such a technique can be applied to other tightly integrated medical systems in which fail-safe is essential, allowing for the construction of safety cases for regulatory approval of closed-loop medical systems. Together with partners from the Massachusetts General Hospital we are developing our research into an open and standardized physiological systems platform for an Intensive Care Unit *ICU-in-a-Bag*. This will allow for competitive design and evaluation of new approaches for safe and effective automatic control of physiological systems with the patient model in the loop. Such platforms help integrate research findings and are a step toward integration within hospitals.

Research Impact of Medical CPS

For the direction of this effort, I was awarded the NSF CAREER Award in March 2013 and my team was awarded the IEEE RTAS Best Student Paper Award in 2012. I have been invited to present this project at the US Food and Drug Administration (FDA) to establish a rapid certification toolchain for future medical devices. My efforts have been highlighted by Mathworks, who also created it into a webinar for the broader modeling community. I have been invited to the Dagsthul Seminar on *The Pacemaker Formal Methods Challenge* in Feb, 2014. The results and models of this work have been used by Prof. Marta Kwiatkowska, Oxford University;

Prof. Sanjit Seshia, UC Berkeley; Prof. Wang Yi, Uppsala University; Prof. Ashutosh Trivedi, Indian Institute of Technology; Prof. Sayan Mitra, UIUC; Prof. Kevin Fu, U. Michigan; among over 30 research groups. I have helped established the Medical CPS Workshop (now in its 5th year), at CPSWeek, which has become a premier destination for clinicians, scientists, regulators and industry experts for medical devices.

The *Heart-on-a-Chip* platform [6, 16] won the 1st Prize in the 2012 World Embedded Systems Competition in Seoul, Korea, the 2012 Penn SEAS Best Senior Design Competition and the Honorable Harold Berger Award for Best ESE Senior Design Project (http://pvs.medcps.org)

2. Networked Cyber-Physical Systems - Distributed Control over Wireless Networks

In 2009, my lab was invited by multiple industry partners (Honeywell, Siemens and Intel) to develop Networked CPS, an effort to address the loss of an average of $22,000 per minute of downtime during system faults on automotive assembly lines. My research aimed to create Wireless Plug-n-Play Automation Systems that can be swapped in and efficiently reconnect hundreds of I/O lines. My approach involves building communication architectures and protocols for robust and optimal control over wireless. This rethinks traditional embedded wireless networks that have largely focused on open loop sensing and monitoring and cannot provide closed loop guarantees.

My lab has developed two complementary approaches for robust, optimal and composable control over networks: (a) Embedded Virtual Machines (EVM) where controller tasks migrate across physical nodes at runtime to maintain stability and performance and (b) Wireless Control Network (WCN), a distributed in-network approach where the network itself acts as a controller. This effort has been published in [17-37].

1) Embedded Virtual Machines: Robust Architectures Network Control and Actuation

My research develops programming abstractions and runtime systems (EVM) to provide robust control over the inherently unreliable links, nodes and topology of wireless systems [17, 19, 28, 30, 35]. 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. EVMs work by assigning tasks to a set of controllers as a single component rather than statically mapping tasks to a specific physical node at design time. By decoupling the functionality from the unreliable physical substrate, EVMs maintain control and timing properties. This creates a powerful and flexible programming abstraction where virtual components are capable of migrating to the most competent set of physical controllers. EVM-based algorithms allow network control algorithms to operate seamlessly over less reliable wireless networks with topological changes. Through case studies in process control, my lab and I have demonstrated EVM's capabilities such as predictable outcomes during sensor/actuator failure, adaptation to mode changes and runtime optimization of resource consumption.

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

My research has developed a radical distributed scheme for control over wireless networks. This WCN approach treats the network *itself* as the controller as opposed to traditional networked control schemes where the nodes simply route information to and from a dedicated controller [17, 18, 20, 22, 23, 24, 25, 26, 27, 33, 34, 36, 37]. In other words, this approach computes the control law in a fully distributed way inside the network. Specifically, WCN formulates a strategy for every node in the network to follow; at each time-step, each node updates its internal state to be a linear combination of the states of the nodes in its neighborhood. My research shows that this causes the entire network to behave as a linear dynamical system, with sparsity constraints imposed by the network topology. Using a numerical design procedure (based on linear matrix inequalities), WCN determines 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. WCN also shows how the design procedure can be modified to maintain mean square stability for packet drop rates *up to 20%* for a specific network topology and plant. This is very close to the theoretical upper bound (25% for wired networks) of robustness to packet drops. My lab and I have also developed a method to *synthesize robust and optimal WCN* for control of discrete and continuous-time plants [18].

We demonstrate the use of the WCN on a real-world industrial case study for control of a distillation column [36]. WCN introduces very low computational and communication overhead on 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 for wireless industrial automation.

Our current and future efforts involve developing a design process that automatically translates control models to platform-independent Domain Specific Languages (executing EVM and WCN specific interpreter-based code), to platform dependent binaries. These binaries are assigned to physical nodes within a control network using the EVM and WCN distributed assignment and scheduling algorithms. This design process for *Control-as-a-Service* helps translate our efforts from theory to industrial implementations and is supported by the newly formed TerraSwarm project.

Research Impact of Networked CPS

My lab and I were awarded the 1st Prize in Honeywell's Wireless Innovation Competition, 2011. My doctoral student, Miroslav Pajic, was awarded the 2011 ACM SIGBED Frank Anger Memorial Award (highest award in the Embedded Systems and Modeling research communities), the 2012 Joseph and Rosaline Wolf Best Dissertation Award, and 2012 ACM IPSN Best Presentation Award. This effort also won a $2.1 Million NSF MRI research award, multi-year sponsorship from Honeywell and was demonstrated at the NAMUR Industrial Automation Working Group in the EU. My lab and I implemented EVM and WCN on the ISA100.11a industry standard wireless protocol, as open source systems (http://mlab.seas.upenn.edu/openisa).

3. Energy Cyber-Physical Systems – Green Scheduling of Energy Control Systems

In this effort, I have developed a new class of scheduling for CPS, called Green Scheduling, which incorporates the dynamics of the plant in the scheduling scheme. Green Scheduling is an approach to schedule multiple interacting control systems within a constrained peak demand envelope while ensuring that safety and operational conditions are facilitated for each control system. This is published in [38-48].

I apply this approach to buildings energy systems, in which heating, cooling, and air quality control systems operate independently of each other and frequently result in temporally correlated power demand surges. As peak power prices are 200-400 times that of the nominal rate, this uncoordinated activity is both expensive and operationally inefficient. Consequently, reducing peaks in electricity demand is desirable for both economic and reliability reasons. Green Scheduling formulates the peak demand envelope as a constraint on the number of binary control inputs that can be activated simultaneously for the general class of linear systems [39, 40, 44, 45, 46]. For example, out of m zone controllers, Green Scheduling limits the number of concurrently operating controllers to $k \leq m$. Given the interactions and environmental disturbances, we find the minimum feasible k controllers to enforce a peak power envelope *while* ensuring each of the m zones operate in their safe region (e.g. temperature deadband).

I have shown that these schedulability analysis methods are scalable for large-scale systems consisting of up to 1000 subsystems. Using a feedback control approach based on attracting sets and robust control Lyapunov functions, my lab and I have developed event-triggered and self-triggered scheduling algorithms that can handle large disturbances affecting the system [38, 43]. These algorithms can also exploit prediction of the disturbances to improve their performance. Finally, my lab and I have produced a scheduling method for discrete-time systems (such as supply-side chiller plants) based on backward reachability analysis [40].

These control/scheduling algorithms: (1) effectively reduce the peak demand for the demand and supply side, while maintaining certain operational or safety constraints of the system; (2) do not require highly accurate system model and forecasts; and (3) do not require high computational capability (particularly for systems with fast dynamics).

Research Impact of Energy CPS

This project won the 2012 ACM Building Systems Symposium (BuildSys) Award for best demonstration. It resulted in Truong X. Nghiem's doctoral thesis and was awarded a $2.25 Million DoE grant. My lab and I developed MLE+ [41, 42, 47] a toolbox for integrated modeling and control for energy-efficient buildings (using Matlab and DoE's EnergyPlus). MLE+ has been featured on the DoE's EnergyPlus website. It has been downloaded over 600 times and is actively used by over 36 institutions. (http://mlab.seas.upenn.edu/mlep). Our current efforts are on (a) Optimal Design of Experiments in the development of low-cost building model capture for model-based control; (b) Demand-Response strategies for coordinated supply-side and demand –side scheduling/control across campus wide networks; and (c) Peak-power management in hybrid energy storage systems with fast dynamics, such as battery-supercapacitor powered electric vehicles. This is supported by the DoE Energy-Efficient Buildings HUB program and with Siemens Corporate Research, Princeton, NJ.

4. Automotive Cyber-Physical Systems

In this thrust, I have explored multiple ideas related to approximate computing for low-cost autonomous driving and have developed several future vehicle platforms: *AutoPlug* for remote diagnostics of vehicle control software, *ProtoDrive* for hybrid energy scheduling and control in electric vehicles [57] and *AutoMatrix* for large-scale traffic simulation. This effort has been published in [49-64].

1) Anytime Algorithms for Real-Time Parallel Computing

My research in this area investigates imprecise and approximate real-time computation on parallel architectures for time-bounded applications with overloaded compute elements [52, 53, 54, 62]. For example, in future computer vision based autonomous driving systems, the processor receives gigabits of high-order video data but must compute the input to the vehicle controller by a deadline. Most algorithms we currently use 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. My research focuses on the development of time-bounded anytime algorithms on Graphics Processing Units (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, and selects system resources required to maximize the quality of the result. Current and future efforts in this direction involve exploiting the quality-time trade-off to construct and instrument the on-line measurement and decision making of anytime algorithms capable of efficiently managing GPU resources.

To explore real-time computation and control using GPUs, my lab and I have developed *AutoMatrix* [50, 52, 64], a traffic congestion simulation platform for large-scale traffic modeling, routing and congestion management. AutoMatrix is currently capable of simulating over 210 million vehicles on any US street map and executing traffic estimation, prediction and route assignment algorithms with high-throughput. I am currently working on future developments of this project within the newly endowed $5.9 Million DoT University Transportation Center. My lab and I aim to *co-design control and computation for anytime and approximate operation* with applications in low-cost autonomous driving.

2) *AutoPlug: Architecture for Remote Vehicle Electronic Controller Unit Diagnostics, Testing and Updates*

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 (>13%) of the overall vehicles recalled. As software verification and testing is done entirely at design time and the vehicle condition changes over the long lifetime, my research addresses the need for post-market remote diagnostics. For this thrust, my lab and I have developed AutoPlug [50, 51, 58, 60], an automotive Electronic Controller Unit (ECU) architecture between the vehicle and a Remote Diagnostics Center. The AutoPlug architecture diagnoses post market control system faults, applies system identification to reformulate the controller to the changed plant model, executes firmware over air updates, and conducts runtime verification of the updated controls software. Current and future efforts involve using this AutoPlug research to address the high rate of recall in General Motor's Diesel Aftertreatment system [56]. I am developing a new direction for remote diagnostics and runtime verification for control systems across plants with evolving uncertainty.

Research Impact of Automotive CPS

My AutoPlug project won the 1st Prize in the World Embedded Systems Competition held in Korea in November 2010. I was awarded the 2012 Intel Early Faculty Career Honor for efforts on Automotive CPS. I was invited to present these results at the National Academy of Engineers, Frontiers of Engineering (15 engineers under 45 years are selected nationwide). The ProtoDrive Electric Vehicle project won the 3rd Prize in the 2012 World Embedded Systems Competition, Korea (http://mlab.seas.upenn.edu/protodrive). This research effort is funded by the newly awarded $5.9 million DoT University Transportation Center between Penn and CMU (2013-1015) for safe and effective future vehicle architectures.

Summary of My Research Approach:

I try to ensure that my 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.* While finding the right contacts is non-trivial and time-consuming, I try to make this is a key priority because it ensures high impact.

I particularly enjoy using theoretical insights and approaches from diverse areas as the basis for the systems and protocols I build. I find such "cross-domain" work exciting (and educational). Students who join my group quickly diversify and become adept at a variety of skills for system building, modeling and theory.

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

References

(Only while at Penn; my students are underlined. Select papers marked in bold)

Theme 1: Medical CPS [1-16]

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Theme 2: Network CPS [17-37]

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53. R. Mangharam. "Profiling Anytime Algorithms for Real-Time Computing" *Workshop on Benchmarking of Embedded Systems, ESWeek, Montreal*, Canada, October 2013.

54. A. A. Saba and R. Mangharam, "Anytime Algorithms for GPU Architectures", *Analytic Virtual Integration of Cyber-Physical Systems Workshop*. Co-located with RTSS. December 2010.

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