RESEARCH STATEMENT

Foundations of Safe Autonomous Systems: Modeling, Architectures, Algorithms and Platforms

Rahul Mangharam
University of Pennsylvania

The central thread of my research in life-critical Cyber-Physical systems is to prove and demonstrate the safety of the autonomous agents that make life and death decisions on our behalf. As implantable medical devices, autonomous vehicles, and infrastructure control systems gain greater autonomy, it is necessary to guarantee safety within the closed-loop context of the controller, environment, and plant. By working at the intersection of applied formal methods, control systems and machine learning, I focus on the creation of mathematical models, fast verification algorithms, robust controllers and autonomous system platforms. My research interfaces with physiological systems such as the human heart for therapy of complex arrhythmias, autonomous machines which must safety operate in chaotic environments, and the built infrastructure which need to coordinate 10K+ controllers. Over the past decade, my research has evolved along these themes:

1. **Safe Autonomous Machines:** *What is a driver's license test for driverless vehicles?* Autonomous vehicles (AVs) have driven millions of miles, but even simple maneuvers like a lane change have not been verified for safety. The vehicles' complex decision logic and machine learning components exceed the capabilities of current verification tools. Moreover, they operate in a highly uncertain environment, making it impossible to model it realistically. My team develops scalable verification algorithms for the whole vehicle with its perception, planning and control stack. For ground AVs, we have constructed robustness-guided test and verification algorithms for AVs which behave as a search engine for unsafe AV driving instances.

   How can we generate the most competent agents in multi-agent dynamic games? In civilian driving, while safety is well specified, performance is not. Here we focus on autonomous racing as a domain that penalizes safe but conservative policies, highlighting the need for robust, adaptive strategies. However, the goal of generating competitive strategies and performing continuous motion planning simultaneously in an adversarial setting is a challenging problem. Existing approaches either discretize agent action by grouping similar control inputs, sacrificing performance in motion planning, or plan in uninterpretable latent spaces, producing hard-to-understand agent behaviors. Furthermore, the most popular policy optimization frameworks do not recognize the long-term effect of actions and become myopic. Our work on distributionally robust online adaptation via offline population synthesis and on game-theoretic objective space planning make algorithmic contributions to both challenges to deliver safety through agility.

   How can we control hundreds of autonomous drones performing complex missions in urban airspaces? For aerial AVs we developed Fly-by-Logic, a scalable multi-drone mission planner which is correct-by-construction and guarantees continuous-time and –space satisfaction of complex spatio-temporal constraints. We have also developed, Learning-to-Fly, learning-based collision avoidance algorithms.

   These efforts are part of the $14MM Mobility21 and $20MM Safety21 DoT National University Transportation Centers, which I direct at Penn. We also evaluate how to design Robot Safety Laws which bound and minimize risk in autonomous systems as part of our Intel Science & Technology Center for Connected Autonomous Systems. This theme is published in [1-50].

2. **Safe Autonomous Medical Devices:** *How can computer modeling and simulation be used as regulatory-grade evidence to improve the design and execution of clinical trials?* Bringing an implantable medical device to market requires a clinical trial that costs millions of dollars, takes several years and has a high chance of failure. Today, bench testing, animal trials and human trials are the predominant approach to evaluating the safety and efficacy of medical devices. Computer models of the human physiology might be used to test the device in the lab, but they do nothing to reduce the burden of the clinical trial. My team develops data-driven physiological and closed-loop device models, algorithms, and programming languages for robust Computer-Aided Clinical Trials (CACTs). Our focus has been to develop a statistical framework for the evaluation of implantable cardiac device algorithms with virtual cohorts generated from

physiological models. CACTs can be used to reduce the necessary cohort size, increase trial power, and reduce the probability of failure.

For complex arrhythmias such as Atrial Fibrillation, how can we guide the physician in real-time to make safer and faster surgical decisions? An ablation procedure for atrial fibrillation therapy often lasts 6 to 8 hours, and arrhythmia recurrence within 12 months after first ablation is about 45%. To address this, we developed an integrated computational heart model to guide left atrium arrhythmia ablation. Our system takes in the left atrium geometry and electrograms, processes them to extract regional tissue properties, which are used to tune a heart model, creating a patient-specific whole-atrium model. With this model, we can simulate and detect arrhythmia sources, and provide ablation assistance.

This effort is a collaboration with the US Food & Drug Administration (FDA) and is part of my $4.2MM NSF Frontiers *CyberCardia* project on Compositional, Approximate, & Quantitative Reasoning for Medical CPS. It is published in [51-77].

3. **Bridging Machine Learning and Control Systems:** *How can we use data-driven methods for optimal control of complex physical plants with safety and performance guarantees?* Building physics-based models of complex physical systems like buildings and chemical plants is extremely cost and time prohibitive for applications such as real-time optimal control, production planning and supply chain logistics. While data-driven algorithms can reduce this complexity, they are unable to control the plant with safety and performance guarantees. My team has developed an ensemble of data-driven algorithms for model capture, prediction, and control for complex physical plants. We demonstrated price-aware adaptive demand-side energy management across large commercial buildings by synthesizing control strategies with peak power and comfort guarantees. This effort began with the $169MM DoE HUB, based in Philadelphia, and Semiconductor Research Corporation's (SRC) $27MM *TerraSwarm* project. It was then commercialized in an NSF SBIR and is published in [78-103].

4. **Autonomous System Platforms and Testbeds:** *How do we build the Department of Autonomy?*
In order to evaluate the safety of machine learning engineering for AVs at the limits of perception, planning and control, we developed the F1Tenth Autonomous Racing community [http://f1tenth.org]. F1Tenth produces open-source platforms, courses and international competitions using 1/10th scale Formula-1 autonomous racing cars that are 10X the fun as students learn the entire autonomy stack in competitive settings. This effort has grown to **80 universities** which have participated in over 15 international autonomous racing competitions and is supported by the $1.5MM NSF CISE Community Research Infrastructure award. This was part of a $2.3MM NSF MRI for developing resilient networked-CPS platforms. This effort resulted in over $500K industrial gift funding from Toyota, Denso and Comcast.

Research Impact (Post-tenure)

In each theme, I have won national and international recognition and have had direct impact with the DoT, FDA, FAA and industry. For my work on life-critical Medical CPS, I was awarded the US Presidential Early Career Award for Scientists and Engineers (**PECASE**) and NSF CAREER Award. For work on Energy CPS, I was awarded the Department of Energy CLEANTECH $50K Prize (Regional) and an NSF SBIR to commercialize it. For work on Autonomous Vehicles and safety-critical CPS, I was awarded the IEEE Benjamin Franklin Key Award, Intel Early Faculty Career Award and invited to speak at the National Academy of Engineers - Frontiers of Engineering (for Top-15 engineers under 45) twice.

Awards: My team's efforts have been recognized through numerous awards including the ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS'18) Best Paper Award, American Control Conference (ACC'17) Best Paper Award (Energy Systems), ACM BUILDSYS'16 Best Presentation Award, 2015 & 2014 SRC TECHCON Best in Session award, IEEE RTAS'12 Best Student Paper Award, 1st Prize in the World Embedded Systems Competition, Korea (twice), Intel/Cornell Cup Embedded Systems Award, SEAS Best Senior Design Award, Google Zeitgeist Award, ACM IPSN Best Presentation Award, Honeywell Industrial Wireless Innovation Award, ACM SIGBED Frank Anger Memorial Award, Joseph and Rosaline Wolf Best Dissertation

Award, etc. Recent awards with students include 1^{st} Prize in the Autonomous Electric Go-karting Competition'23, Winner of the 14^{th} International F1Tenth Autonomous Racing Competition at IROS'23, Winner of 10^{th} International F1Tenth Autonomous Racing Competition at ICRA'22, Winner International JSAE'22 Autonomous Driving Competition, DASD'20 Best of Session Award, SIGCSE'20 2nd Best Paper Award for Curricula Initiatives, NeurIPS'19 Best Demonstration Award (Runner-up).

Distinguished Lab Alumni: Reflecting the cross-cutting nature of my work, my research findings have been published evenly across the areas of Formal Methods, Control Systems, Medical journals, and Autonomous Systems Education. Most importantly, my students have been heavily recruited at top institutions:

Johannes Betz'22 : Asst. Professor at Technical Uni, Munich.
Matthew O'Kelly'21 : Trustworthy.AI acquired by Waymo/Google
Yash V. Pant'19 : Asst. Professor at University of Waterloo.
Houssam Abbas'18 : Asst. Professor at Oregon State University.
Max Li'18 : Asst. Professor at University of Michigan.
Zhihao Jiang'17 : Asst. Professor at ShanghaiTech U..
Madhur Behl'16 : Assoc. Professor (Tenured) at U. of Virginia
Truong X. Nghiem'12: Assoc. Professor (Tenured) at N. Arizona U.
Miroslav Pajic'12 : Assoc. Professor (Tenured) at Duke U.

Research Community Leadership: Since tenure, I have served as conference co-chair for the major CPS/Embedded Systems/Real-Time Systems conferences such as ICCPS, RTSS, RTAS, EMSOFT, BuildSys, and COMSNETS, and on the Steering Committee for EMSOFT and BuildSys. I have co-chaired the Medical CPS Workshop in 2011, 2013, 2014 and 2019, which has established itself as a destination for clinicians, computer scientists, government regulators and industry experts for medical devices (http://medcps.org). I have been invited to talk at ACC, CDC and/or DAC conferences almost every year since 2014, at formal methods venues such as CAV and NSV, the NY/NJ/PA/USDoT transportation research centers, FDA, DoE, Honeywell Technical Symposium, GE Control Systems Symposium, Dagsthul, ARPA-Energy and multiple NSF and inter-agency joint workshops. I have served as guest editor on the Journal of Real-Time Systems, IEEE Design & Test, IEEE Transaction on Emerging Topics in Computing, IEEE Transactions on Embedded Systems and on the organizing committee for IEEE Trans. Intelligent Vehicles Steering Committee, RAS Voting Member.

Community and Industry Impact: Autoware is a non-profit for the world's leading open-source autonomous vehicle software system that runs on busses in Turkey, robotaxis in Japan, cargo vehicles in Estonia, shuttles in Taiwan, etc. and is a consortium of over 70+ companies. I serve on the Board of Directors and as Director of the Autoware Centers of Excellence which is a partnership of over 25+ international universities who collaborate on autonomous driving for future electric vehicle platforms. This offers a dedicated lab and staff in Pennovation for development of next generation AVs. I lead the F1Tenth autonomous racing community which has grown to over 80+ universities that teach the course I developed, use the platform for over 50+ publications since 2016 and have hosted 17 international competitions. The last competition in ICRA'23 had 150+ participants from over 23 countries. F1Tenth has started regional competitions – the last one was in South Korea in October 2023 and had over 33 teams.

In the rest of this statement, I will summarize my post-tenure work and future research agenda:

1. Building Safe Autonomous Systems - on the ground and in the air

In this thrust, I focus on three research vectors to test and verify autonomous systems: (1) Search for unsafe driving instances by integration of testing and verification for 3^{rd} party perception, planning and control modules within complex driving environments. (2) Scalable and on-board synthesis of AV control trajectories with spatial, temporal and reactive properties. (3) Anytime verification algorithms that can be used to trade-off runtime vs. strength of guarantee, and on the design of anytime controllers that can leverage the trade-off.

1) Robustness-Guided Verification: Search Engine for Unsafe AV Driving Instances

For systems with perception, planning and control pipelines, my team developed *Robustness Guided Verification* (RGV) which is the first theoretically-sound integration of robustness-guided temporal logic testing and approximate reachability analysis. This integration leverages falsification to quickly locate operating regions of a hybrid dynamical system where incorrect or marginally correct behavior could be exhibited, and then deploys expensive reachability analysis only in these regions. By expressing requirements in Metric or Signal Temporal Logic (MTL/STL), we formally and efficiently capture complex system, traffic and environments such as weather, road topology, vehicle dynamics and interactions with other agents. We developed test harnesses for full algorithmic pipelines operating in synthetic driving environments such as CARLA, Unreal Engine, Unity and Grand Theft Auto V, to search for low robustness instances where safety and performance properties are partially violated. This fast testing is then complemented with reachability analysis of just the low-robustness instances (i.e. near accidents) to speed up AV safety verification. Using this approach, we have been able to find complex bugs at the interface of perception/planning and planning/control in the AV software stack for a variety of driving scenarios. In collaboration with Toyota this work is published in [37, 43, 44, 46, 48].

2) Safe Autonomous Air-Traffic Control

As we transition to Urban Air Mobility (UAM) where 500-1,000 drones will operate in dense urban airspaces, the two fundamental safety challenges are with urban air traffic management and airborne collision avoidance. My team has developed Fly-by-Logic, a robustness-maximizing controller for fleets of drones, and it is currently the fastest and most reliable controller of its kind. By describing drone missions in MTL, we can synthesize mission trajectories for hundreds of drones, each with spatial, temporal and reactive guarantees. As weather and mission disturbances are difficult to predict, we maximize MTL robustness, a mathematically rigorous way of measuring the amount of disturbance that the controlled system can withstand without failing its mission, across the fleets. We demonstrated the computational tractability, scalability and guaranteed continuous-time satisfaction of the resulting trajectories on-board real drones and over long-range multi-drone missions. Collision avoidance problems are notoriously complex and often resort to mixed integer linear programming which prevents real-time execution. My team has designed safe and efficient Learning-based decentralized collision avoidance for scalable urban air mobility. Published in [14, 20, 23, 28, 29, 35,36, 38, 39, 41, 42].

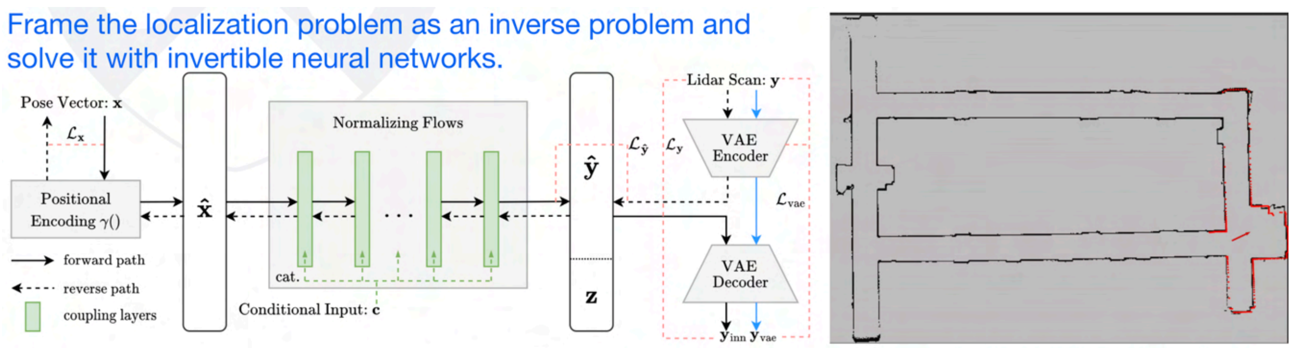
3) Anytime Perception and Control for Energy-efficient AVs

Most perception algorithms are run-to-completion, operate independently of the control subsystem and dominate the energy footprint of autonomous systems. To achieve safe long-term autonomy, it is essential to have energy-efficient on-board operations by co-designing perception and control algorithms. In this effort, my team designed a variety of Robust Anytime Model Predictive Controllers that instruct the perception pipeline how long to run based on what quality of estimate is needed, thus saving computation energy when a low-quality estimate suffices (say, an autonomous car driving on an empty road), and cranking up the computation when a high-quality estimate is needed quickly, e.g., in a near-miss. Anytime AV architectures have been demonstrated to outperform regular MPC and significantly reduced energy consumption on drones running visual odometry for perception. Published in [32, 45, 47, 49, 50].

Impact: My Safe AV efforts have resulted in 4 consecutive DoT University Transportation Centers (UTC) from 2011 onwards with CMU. I serve as the Penn Director for the $14MM DoT Mobility21 National UTC – this is the largest size UTC and only four exist in the nation. Starting November 2023, we were awarded a $20MM Safety21 UTC (2023-2028). I hosted the DoT Mobility21 Transportation Summit (2017), DoT Mobility21 Next-Generation Truck Freight Summit (2018) and co-hosted the Safe AI Industry Day (2019) in Philadelphia. Our efforts have resulted in multi-year funding from Toyota, Denso, L3, Comcast, Honeywell, Nvidia and Intel. At the national stage, I have been invited to present at forums such as the National Academy of Engineers, Computing Research Association, NASA/FAA, at NSF-EU, NSF-Germany, NSF Automated Freight Vehicles workshops and demonstrations at NSF CPS & CSR PI, CPSweek, ESWeek, ICRA, IROS, IEEE IV, etc.

Building Safe Autonomous Systems - Research Agenda:

1) Learning-based localization, planning and control: To develop a more explainable autonomous system stack we have developed new techniques in implicit map representation and *localization using invertible neural networks* (see figure below) and *differentiable trajectory generation* approaches for accurate and fast (>150Hz) autonomy stacks which operate on low-cost edge hardware. We will also explore *physics-constrained motion prediction* which uses a surrogate dynamical model to ensure that predicted trajectories are dynamically feasible. We achieve this via a two-step integration consisting of intent and trajectory prediction subject to dynamics constraints. We can construct prediction regions that quantify uncertainty and are tailored for autonomous driving by using conformal prediction. Finally, we will explore *imitation learning with multiple imperfect experts*, an approach for interactive learning with multiple imperfect experts. We will show that policy learned can outperform both experts and policies learned from other interactive imitation learning algorithms. This research contributes to our MAD Games: Multi-Agent Dynamic Games project for agile collaborative teams in competitive games like autonomous racing where all agents operate at the limits of their vehicle's dynamics. This preliminary research is published in [1-13, 15-19]



Network Structure ***Live Localization on F1tenth Car***

2) Learning Adaptive Safety for Multi-Agent Systems: Ensuring safety in dynamic multi-agent systems is challenging due to limited information about the other agents. Control Barrier Functions (CBFs) show promise for safety assurance but current methods make strong assumptions about other agents and often rely on manual tuning to balance safety, feasibility, and performance. In this work, we will delve into the problem of adaptive safe learning for multi-agent systems with CBF. We will show how emergent behavior can be profoundly influenced by the CBF configuration, highlighting the necessity for a responsive and dynamic approach to CBF design. So far, we have developed ASRL, a novel adaptive safe RL framework, to fully automate the optimization of policy and CBF coefficients, to enhance safety and long-term performance through reinforcement learning. By directly interacting with the other agents, ASRL learns to cope with diverse agent behaviors and maintains the cost violations below a desired limit. We will evaluate ASRL in a multi-robot system and a competitive multi-agent racing scenario, against learning-based and control-theoretic approaches. We will build upon CBF-based control to formulate a theory for safe control synthesis for hybrid dynamical systems. Preliminary research published in [78, 79. 8, 81, 82].

3) Robot Safety Laws for Autonomous Systems: I will explore what Robot Safety Laws are necessary to ensure the safety, assign blame and limit liability in the form of safety benchmarks prior to an AV driving on the streets. By extending Robustness-Guided Verification to evaluate these laws, we establish the parametric boundaries for such frameworks. In collaboration with Autoware partners, we are developing test harnesses for AV simulators to explore the trade-off between conservative and assertive behavior for naturalistic driving across a canonical set of driving scenarios.

4) On-Board Verification: What GPUs did for graphics processing, Verification Processing Units will do for On-Board Verification (OBV). I will develop OBV ASICs for continual online execution of verification code by the system to take corrective action if an unsafe situation is imminent. Unlike runtime verification, which only checks one execution at a time, with OBV we conduct exhaustive verification for a receding horizon to ensure all possible actions have probabilistic safety and performance guarantees.

2. Medical Devices: From verified models to verified code for implantable devices

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 and defibrillators) 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. Medical device recalls due to software has risen from 10% in 1996 to 24% in 2011, with at least 1.8 million devices recalled since 2011. Since 2018, software has been the leading cause of medical device recalls.

To address this problem, in the first five years at Penn, I 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. Since tenure, this effort has been accelerated with the NSF Frontiers project – CyberCardia, to develop the formal models and tools for synthesis of verified closed-loop models to verified medical device software and systems. This effort involves successful collaborations with cardiologists in the Hospital of the University of Pennsylvania, Penn Presbyterian Medical Center, Philadelphia VA Hospital, Georgia Tech, SUNY Stony Brook and the US FDA. See https://medcps.org for demonstrations.

1) Computer-Aided Clinical Trials

Clinical trials are the major bottleneck in getting new devices to market: they take several years, cost millions of dollars, and expose consenting patients to yet-unproven devices. My team is developing Computer-Aided Clinical Trials (CACT) as a formal and statistical framework that rigorously incorporates evidence generated from computer simulations and model-checking into the design of clinical trials. This can be used to reduce the necessary cohort size, increase trial power, and reduce the probability of failure. A major obstacle to acceptance in-silico pre-clinical trials as regulatory-grade evidence is the lack of a framework for explicitly modeling sources of uncertainty in simulation results and quantifying the effect on trial outcomes. By formulating a CACT within a Bayesian statistical framework we can quantify the uncertainty propagation from modeling and simulation to capture the robustness of the across all stages of the trial. CACTs have been validated in retrospective clinical trials and in hardware testbeds where our heart models directly interact with commercial implantable cardiac devices. Published in [57, 58, 61, 65, 66, 67, 68, 72].

2) Models, Algorithms and Languages for Medical CPS

a) Closed-loop Formal Models: To develop safer medical device software, my team has demonstrated the first model-checkable models for the interaction between the human heart and Implantable Cardioverter Defibrillators (ICD) [69, 70, 73], better algorithms for detecting fatal arrhythmias [63, 64, 76, 77], and predictable-performance programming languages for ICDs [59, 60, 62, 71, 74]. My team defined these problems and approached them through close collaboration with physicians at the Hospital of the University of Pennsylvania and in the FDA. The use of formal models marks a sharp break with current practice, where the ICD was viewed as being too complex for exhaustive verification, and where open-loop testing was still the norm. This forms the basis for a recent collaboration with the FDA on closed-loop physiological control.

b) Arrhythmia detection algorithms: My team demonstrated that on the space of cardiac signals, distance between functions is best measured using a 2-parameter measure based on the study of stochastic processes [63, 64]. This can have far-reaching consequences, as measuring distance is a fundamental operation in many arrhythmia detection tasks. As an example, we applied this new measure to develop an arrhythmia detector and demonstrated its superiority to state-of-the-art algorithms on real patient data. These findings were presented at the Scientific Sessions of the Heart Rhythm Society, the world's leading society of electrophysiologists.

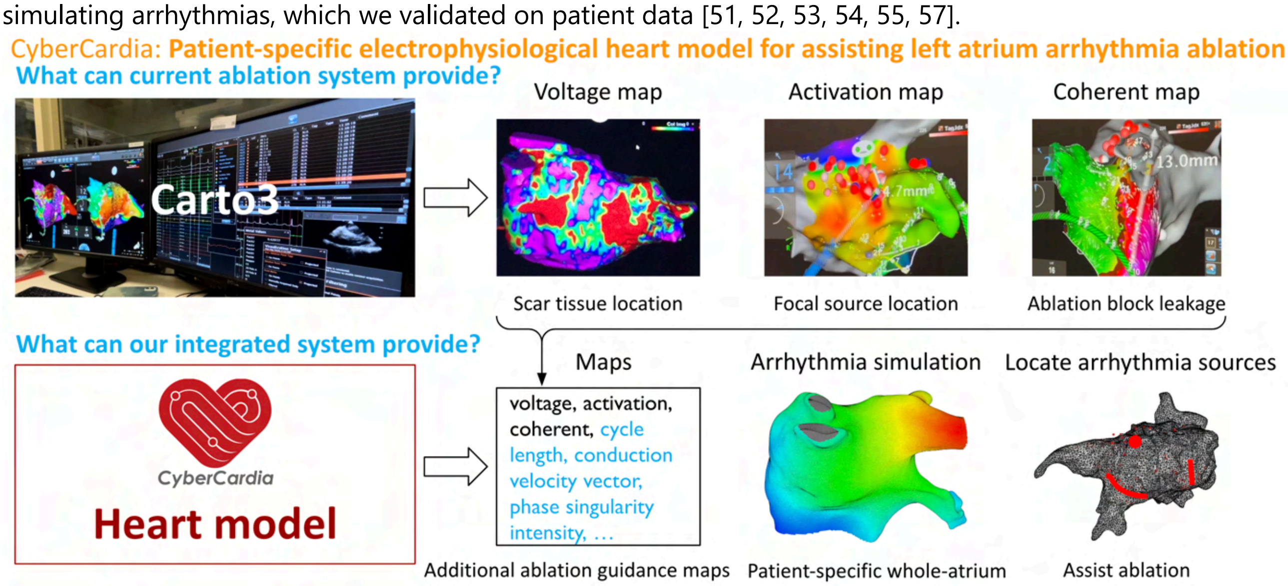
c) Predictable-performance programming languages: My team demonstrated that Quantitative Regular Expressions (QREs) are a better programming language for ICDs in terms of power profiling and efficacy, early in the design cycle, than general purpose languages like C [60, 62]. As QREs provide a declarative language that relieves the user from worrying about low-level implementation details, we demonstrated rigorous early design exploration in computing static upper bounds on power consumption and efficacy of ICD algorithms.

Impact: For the direction of this effort, I was awarded the PECASE in 2016, NSF CAREER Award and my students won the best paper awards in RTAS, and SRC TECHCON. I have been invited to present this project at the US FDA on several occasions to establish a rapid certification toolchain for medical devices. My efforts have been highlighted by Mathworks, who also created a webinar for the broader modeling community. I have been invited to the Dagsthul Seminar on *The Pacemaker Formal Methods Challenge*. 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, CU Bolder; Prof. Sayan Mitra, UIUC; Prof. Kevin Fu, U. Michigan; among over 40 research groups. I have helped established the Medical CPS Workshop (now in its 9th year), and my students have become tenure-track professors at Duke, UVA, Oregon State and Shanghai Tech.

Medical Devices - Research Agenda:

1. Patient-specific Electrophysiological heart model for assisting left atrium arrhythmia ablation.

Atrial arrhythmia is a prevalent heart disease that results in weak and irregular contractions of the atria. It affects millions of people worldwide. Cardiac ablation is among the most successful treatment options. During the procedure, catheters are inserted into the left atrium to map the atrium geometry and record endocardium electrograms that are then converted into electro anatomical maps to pinpoint the arrhythmia source locations. However, identifying arrhythmia sources is challenging. The electrograms are asynchronous and can be susceptible to noise. The spatial distribution of sampling sites is non-uniform, which leads to inaccurate maps. Identifying arrhythmia source locations is not a trivial task. Therefore, an ablation procedure often lasts from 3 to 6 hours, and arrhythmia recurrence within 12 months after first ablation is about 45%.
To address these challenges, we are developing an integrated computational heart model to guide left atrium arrhythmia ablation. Our system takes in the left atrium geometry and electrograms, processes them to extract regional tissue properties, which are used to tune a heart model, creating a patient-specific whole-atrium model. With this model, we can simulate and detect arrhythmia sources, and provide ablation assistance. To build such a system, we investigated the fiber effects on atrial activation patterns. So far, we developed a fast heart model tuning method which takes only a few seconds of computation time on a personal computer, enabling real-time assistance during the ablation procedure. Current results show we achieve high accuracy in simulating arrhythmias, which we validated on patient data [51, 52, 53, 54, 55, 57].



2. Data-driven Algorithms for implantable cardiac devices

The ultimate goal of my research in medical devices is to provide a safer, faster and least burdensome route to regulatory approval for new life-critical medical devices, a goal that has been identified as a priority by the FDA, the National Institute of Biomedical Imaging and Bioengineering, and the Medical Device Innovation Consortium. While continuing the current exciting research trajectory, I will develop (1) a complete compiler tool-chain that produces low-level code from programs written in formal streaming languages. This will lead to an entirely new way of programming medical devices, where high-level guarantees on runtime and power consumption are preserved at the code-level, without the need to develop auxiliary and unreliable models of power consumption. (2) My team is also developing data-driven and personalized implementations of ICD algorithms for anti-tachycardia pacing and shock discrimination with significantly improved specificity. We are investigating the mapping of CNNs to Spiking Neural Networks for energy-efficient personalized algorithms for implantable cardiac devices. (3) Finally, we are developing high-definition heart models for real-time guidance to cardiac electrophysiologists to reduce the time and effort in cardiac ablation therapy procedures.

3. Bridging Machine Learning and Control for Physical Systems

Decisions on how to best optimize energy systems operations for complex plants, such as buildings and chillers, are becoming ever so complex and conflicting, that model-based predictive control (MPC) algorithms must play an important role. However, a key factor prohibiting the widespread adoption of MPC in buildings, is the cost, time, and effort associated with learning first-principles based dynamical models of the underlying physical system. In this thrust, we developed control-oriented data-driven approaches for implementing finite-time receding horizon control for demand-side energy management across multiple buildings. These algorithms reduce the problem of capturing an accurate MPC-oriented model of a building from 6-7 months to 6-7 hours, without having to build white/grey box models of the systems dynamics. We also explored this problem from a scheduling theory perspective and extend real-time scheduling theory to operate on plants with dynamics.

1) Learning and Control for Plants with Complex Dynamics

We developed control-oriented models based on regression trees, random forests and Gaussian Processes to capture linear and non-linear models for buildings using only the building automation system's existing data. Along with available weather data and operation schedules, we are able to predict the power consumption of the building with 94-97% accuracy. These black-box models can be effectively applied for receding horizon optimal control with probabilistic guarantees on constraint satisfaction through chance constraints. This is used to suggest set point control strategies to maximize participation in demand response programs and peak power minimization. Using Gaussian Processes for learning control-oriented models, we developed methods for the optimal experiment design of functional tests to learn models of a physical system at the fastest rate. We further developed an optimal online learning method for continuously improving the data-driven model in closed-loop with a real-time controller. Our methods are demonstrated and validated across several building and chiller plant case studies. Published in [83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 95, 96, 99, 100, 101]

2) Scalable Scheduling of Energy Control Systems

Peak power consumption is a universal problem across energy control systems in electrical grids, buildings, and industrial automation where the uncoordinated operation of multiple controllers result in temporally correlated electricity demand surges. While there exist several different approaches to balance power consumption by load shifting and load shedding, they operate on coarse grained time scales and do not help in de-correlating energy sinks. The 'Energy System Scheduling Problem' is particularly hard due to its binary control variables. Its complexity grows exponentially with the scale of the system, making it impossible to handle systems with more than a few variables. We developed a scalable approach for fine-grained scheduling of energy control systems that combines techniques from control theory and computer science. For example, the original system with binary control variables are approximated by an averaged system whose inputs are the utilization values of the binary inputs within a given period. The error between the two systems can be bounded, which allows us to derive a safety constraint for the averaged system so that the original system's safety is guaranteed. These approaches were used to schedule hundreds of controllers and their associated plant dynamics, and were extended for (1) quantifying uncertainty propagation from sensing to modeling and control for buildings; (2) elastic real-time scheduling for plants with dynamics; and (3) campus-wide multi-building and chiller integrated simulation. Published in [93, 96, 97, 101, 102, 103].

Impact: This effort won an NSF SBIR commercialization grant towards AI for Smart Buildings. Our team won the IEEE/ACM ICCPS Best Paper Award (2018), ACC Best Paper Award for Energy Systems (2017), ACM BuildSys Best Presentation Award (2016) and SRC TECHCON Best in Session Award (2015). Graduates from this program went on to become tenure-track Assistant Professors in University of Virginia and University of N Arizona, and joined Amazon AI Labs. We developed MLE+, a toolbox for integrated modeling and control for energy-efficient buildings, which has been featured on the DoE's EnergyPlus website.

4. F1/10 Autonomous Racing: Safe, Ethical and Agile Autonomous Systems

In order to facilitate research and education in autonomous systems, my team developed an open-source research platform of high-performance autonomous racing cars that are 1/10th-scale of Formula-1 cars and can reach a top speed of 50mph. F1Tenth [http://f1tenth.org/] enables a wide range of machine learning engineering with perception, planning, control and coordination modules [24, 25,26,30, 31, 33, 34]. In addition to the platform hardware, we developed an AV software stack and a set of simulators as plug-and-play replacements for the 1/10th-scale platform itself. We have organized 15 international autonomous racing competitions for multi-vehicle racing with a variety of perception, planning and control algorithms including SLAM, model-predictive control, and advanced planners including Rapidly exploring Random Trees. We have developed a course for autonomous racing that is being taught at CMU, TU Vienna, TU Munich, Oregon State University, UVA, N. Arizona University, Clemson University, and over 2 dozen more universities. By driving at the limits of vehicle performance, we hope to accelerate the development of safe autonomous vehicles. F1Tenth has over 80+ university community partners for research and education. It is supported by a $1.5MM NSF CISE Community Research Infrastructure award and several industrial partners such as National Instruments, SICK, Nvidia, Intel, etc. We aim to grow the community to further research in building better autonomous systems.

In the past year, we have developed AV4EV Open-source AV software for Open-standards EV platforms [https://av4ev.org]. The first platform is an autonomous electric gokart for which we developed the drive/brake/steer-by-wire systems, mechanical design, electrical and power circuits, embedded software and autonomous navigation capabilities. This has been featured on Fox News and the open-source design is being replicated in Hungary, Japan, Clemson University, Poznan University and across 20 universities in South Korea. The goal of this platform is to demonstrate realistic autonomous driving with a full stack of sensors (3D lidars, GNSS, cameras, IMUs, etc.), sensor fusion and indoor-outdoor driving for applications in movement of people and goods. This project has engaged over 28 MS Robotics students. They won the 2023 Autonomous Karting Series Competition in Purdue University and have become expert platform architects.

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, and I try to spend 40% of my time understanding the problem. 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.

PUBLICATIONS

(Only post-tenure; my students are underlined. Select papers marked in bold)

Theme 1: Building Safe Autonomous Systems

1. Yang, Shuo; Pappas, George J; Mangharam, Rahul; Lindemann, Lars; "Safe Perception-Based Control under Stochastic Sensor Uncertainty using Conformal Prediction", IEEE Conference on Decision & Control (CDC), 2023

2. Nagy, Tomás; Amine, Ahmad; Nghiem, Truong X; Rosolia, Ugo; Zang, Zirui; Mangharam, Rahul; "Ensemble Gaussian Processes for Adaptive Autonomous Driving on Multi-friction Surfaces", 22nd World Congress of the International Federation of Automatic Control (IFAC), 2023.

3. Evans, Benjamin; Betz, Johannes; Zheng, Hongrui; Engelbrecht, Herman A; Mangharam, Rahul; Jordaan, Hendrik W; "Accelerating Online Reinforcement Learning via Supervisory Safety Systems", Proceedings of 2023 International Conference on Advanced Robotics (ICAR), December 5-8, 2023, Abu Dhabi, UAE.

4. Zheng, Hongrui; Zang, Zirui; Yang, Shuo; Mangharam, Rahul; "Towards Explainability in Modular Autonomous Vehicle Software," IEEE Intelligent Vehicles Symposium, 2023

5. Sun, Xiatao; Zhou, Mingyan; Zhuang, Zhijun; Yang, Shuo; Betz, Johannes; Mangharam, Rahul; "A Benchmark Comparison of Imitation Learning-based Control Policies for Autonomous Racing," IEEE Intelligent Vehicles Symposium, 2023

6. Tumu, Nandan; Lindemann, Lars; Nghiem, Truong, Mangharam, Rahul; "Physics constrained motion prediction with uncertainty quantification," IEEE Intelligent Vehicles Symposium, 2023
7. Qiao, Zhijie; Sun, Xiatao; Loeb, Helen; Mangharam, Rahul; "Drive Right: Shaping Public's Trust, Understanding, and Preference Towards Autonomous Vehicles Using a Virtual Reality Driving Simulator," IEEE Intelligent Vehicles Symposium, 2023
8. **Zang, Zirui; Zheng, Hongrui; Betz, Johannes; Mangharam, Rahul; "Local_INN: Implicit Map Representation and Localization with Invertible Neural Networks", International Conference on Robotics and Automation (ICRA) 2023**
9. Sun, Xiatao; Yang, Shuo; Mangharam, Rahul; "MEGA-DAgger: Imitation Learning with Multiple Imperfect Experts", Humans in Cyber-Physical Systems Workshop at CPS-IOT Week, 2023
10. Qiao, Zhijie; Sun, Xiatao; Loeb, Helen; Mangharam, Rahul; "Drive Right: Promoting Autonomous Vehicle Education Through an Integrated Simulation Platform", Humans in Cyber-Physical Systems Workshop at CPS-IOT Week, 2023
11. Zheng, Hongrui; **Mangharam, Rahul**; "Differentiable Trajectory Generation for Car-like Robots with Interpolating Radial Basis Function Networks", 2023 (under submission)
12. Zheng, Hongrui; Zhuang, Zhijun; Betz, Johannes; **Mangharam, Rahul**; "Game-theoretic Objective Space Planning", 2023 (under submission)
13. Loeb, Helen; **Mangharam, Rahul**; Leveraging the internet to drive a real car in the Virtual Reality Earth Model, 2023 (under submission)
14. Pant, Yash Vardhan; Abbas, Houssam; Mangharam, Rahul; "Distributed Trajectory Planning for Multi-rotor UAVs with Signal Temporal Logic Objectives." IEEE Conf. on Control Tech. & Applications (CCTA). 2022
15. Zang, Zirui; Tumu, Renukanandan; Betz, Johannes; Zheng, Hongrui; Mangharam, Rahul; "Winning the 3rd Japan Automotive AI Challenge-Autonomous Racing with the Autoware Auto Open Source Software Stack." IEEE Intelligent Vehicles Symposium (IV). 2022.
16. Stanley Bak; Johannes Betz; Abhinav Chawla; Hongrui Zheng; Rahul Mangharam; "Stress Testing Autonomous Racing Overtake Maneuvers with RRT," IEEE Intelligent Vehicles Symposium (IV). 2022.
17. Zheng, Hongrui; Betz, Johannes; Ramamurthy, Arun; Jin, Hyunjee; Mangharam, Rahul; "Combinatorial and Parametric Gradient-Free Optimization for Cyber-Physical System Design". IEEE Workshop on Design Automation for CPS and IoT (DESTION). 2022
18. Bhargav, Jayanth; Betz, Johannes; Zheng, Hongrui; Mangharam, Rahul; "Deriving spatial policies for overtaking maneuvers with autonomous vehicles".14th International Conference on COMmunication Systems & NETworkS (COMSNETS). 2022
19. Qiao, Zhijie; Loeb, Helen; Gurrla, Venkata; Lebermann, Matt; Betz, Johannes; Mangharam, Rahul; "Drive Right: Autonomous Vehicle Education through an Integrated Simulation Platform." SAE International Journal of Connected and Automated Vehicles. 2022
20. K. J. Jang, A. Rodionova, Y. V. Pant, and R. Mangharam, "Learning-to-Fly RL: Reinforcement Learning-based Collision Avoidance for Scalable Urban Air Mobility", AIAA/IEEE 39th Digital Avionics Systems Conference (DASC) 2020. **Best of Session Award!**
21. **M. O'Kelly, H. Zheng, R. Mangharam, et. al. "FormulaZero: Distributionally Robust Online Adaptation via Offline Population Synthesis". 37th International Conference on Machine Learning (ICML), 2020.**
22. A. Rodionova, I. Alvarez, M. S. Elli, F. Oboril, J. Quast, and R. Mangharam, "How Safe is Safe Enough? Automatic Safety Constraints Boundary Estimation for Decision-Making in Automated Vehicles". IEEE Intelligent Vehicles Symposium (IV), 2020.

23. A. Rodionova, Y. V. Pant, K. J. Jang, H. Abbas, R. Quaye, and R. Mangharam, "Learning-to-Fly: Learning-based Collision Avoidance for Scalable Urban Air Mobility", 23rd Intelligent Transportation Systems Conference (IEEE ITSC 2020).
24. **A. Agnihotri, M. O'Kelly, H. Abbas and R. Mangharam. "Teaching Autonomous Systems at 1/10th-scale: A project-based course and community". ACM Special Interest Group on Computer Science Education (SIGCSE). February 2020. 2nd Best Paper Award!**
25. Matthew O'Kelly, Hongrui Zheng, Achin Jain, Joseph Auckley, Kim Luong, Rahul Mangharam, "TunerCar: A Superoptimization Toolchain for Autonomous Racing", IEEE International Conference on Robotics and Automation (ICRA), 2020.
26. **Betz, Johannes; Zheng, Hongrui; Liniger, Alexander; Rosolia, Ugo; Karle, Phillip; Behl, Madhur; Krovi, Venkat; Mangharam, Rahul; "Autonomous vehicles on the edge: A survey on autonomous vehicle racing." *IEEE* Open *Journal of Intelligent Transportation Systems*, 2022.**
27. Qiao, Zhijie; Loeb, Helen; Gurrla, Venkata; Lebermann, Matt; Betz, Johannes; Mangharam, Rahul; "Drive Right: Promoting Autonomous Vehicle Education Through an Integrated Simulation Platform", *SAE International Journal of Connected Autonomous Vehicles* 5(4):357-366, 2022.
28. Y. V. Pant, M. Z. Li, A. Rodionova, R. A. Quaye, H. Abbas, M. Ryerson, **R. Mangharam**. "FADS: Framework for Autonomous Drone Safety." In *IEEE Transactions on Intelligent Transportation Systems, Special Issue on Unmanned Aircraft System Traffic Management.* Transportation Research Part C: Emerging Technologies, Volume 130, 2021, https://doi.org/10.1016/j.trc.2021.103275
29. A. Rodionova, Y. V. Pant, , C. Kurtz, K. J. Jang, **R. Mangharam**. Learning-'N-Flying: A Learning-based, Decentralized Mission Aware UAS Collision Avoidance Scheme. ACM Transactions on Cyber-Physical Systems (TCPS) 5 (2021): 1 - 26.
30. D. Karthik, M. O'Kelly, H. Zheng, S. Singh, and **R. Mangharam**, "Bridging the Sim-to-Real Gap for Reinforcement Learning with F1/10 Autonomous Racing". *Proceedings of Machine Learning Research (PMLR).* 2020.
31. F1Tenth website, https://f1tenth.org
32. Y. V. Pant, H. Abbas, K. Mohta, R. A. Quaye, T. X. Nghiem, J. Devietti, **R. Mangharam**. "Anytime Computation and Control for Autonomous Systems", in IEEE Transactions on Control Systems Technology. 2021.
33. H. Abbas, J. Auckley, M. Behl, M. Bertogna, P. Burgio, A. Jain, D. Karthik, K. Luong, **R. Mangharam**, M. O'Kelly and H. Zheng, "An Open-source 1/10th Scale Autonomous Racing Platform", 2019. https://arxiv.org/pdf/1901.08567.pdf
34. Matthew O'Kelly, Hongrui Zheng, Dhruv Karthik, **Rahul Mangharam**. F1TENTH: An Open-source Evaluation Environment for Continuous Control and Reinforcement Learning in Proceedings of the NeurIPS 2019 Competition and Demonstration Track, PMLR 123:77-89, 2020.
35. Yash V. Pant, Rhudii Quaye, Houssam Abbas, Akarsh Varre and **Rahul Mangharam**, "Fly-by-Logic: A Tool for Unmanned Aircraft System Fleet Planning using Temporal Logic", *Eleventh NASA Formal Methods Symposium*, Houston, TX. May 2019.
36. Y. V. Pant, H. Abbas, **R. Mangharam**. Distributed planning of Multi-rotor drone fleets using the Smooth Robustness of Signal Temporal Logic. *Monitoring and Testing of CPS Workshop, CPS Week*, 2019.
37. **Houssam Abbas, Yash V. Pant and Rahul Mangharam, "Temporal Logic Robustness for General Signal Classes", in *Proceedings of the 22nd ACM International Conference on Hybrid Systems: Computation and Control* (with CPS-IoT Week 2019) (HSCC '19), Montreal, QC, Canada. April 2019.**

38. **Yash V. Pant, Houssam Abbas, Rhudii A. Quaye, and Rahul Mangharam, "Fly-by-Logic: Control of Multi-Drone Fleets with Temporal Logic Objectives" in *Proceedings of the 9th ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS)*, April 2018.**

39. Yash V. Pant, Houssam Abbas and **Rahul Mangharam**, "Distributed planning of Multi-rotor drone fleets using the Smooth Robustness of Signal Temporal Logic" in *4th Workshop on Monitoring and Testing of Cyber-Physical Systems (CPS-IoT Week)*, Montreal, Canada. April 2019.

40. **Rahul Mangharam**, Megan Reyerson, Steve Viscelli, Hamsa Balakrishanan, Alexandre Bayen, Surabh Amin, Leslie Richards, Leo Bagley, George Pappas, "MOBILITY21: Strategic Investments for Transportation Infrastructure & Technology". *A Computing Community Consortium (CCC) white paper*. eprint arXiv:1705.01923. 2018.

41. Yash Pant, Houssam Abbas, and **Rahul Mangharam**, "Smooth Operator: Control Using the Smooth Robustness of Temporal Logic", *IEEE Conf. on Control Technology and Applications.* Dec 2017.

42. Yash Pant, Houssam Abbas, and **Rahul Mangharam**, "Control with Temporal Logic Requirements", in *Semiconductor Research Corporation TECHCON.* 2017.

43. Matthew O'Kelly, Houssam Abbas, and Rahul Mangharam, "Computer-Aided Design for Safe Autonomous Vehicles", IEEE International Symposium on Resilient Control Systems. September 2017

44. Rodionova, M. O'Kelly, H. Abbas, V. Pacelli, and R. Mangharam, "An Autonomous Vehicle Control Stack", in Workshop on *Applied Verification for Continuous and Hybrid Systems* (ARCH), 2017.

45. Y. V. Pant, H. Abbas, **R. Mangharam**. "Control using the Smooth Robustness of Temporal Logic", in *Monitoring and Testing of CPS Workshop (MTCPS), CPS Week*, 2017

46. Houssam Abbas, Matthew O'Kelly, and **Rahul Mangharam**, "Relaxed decidability and the robust semantics of Metric Temporal Logic", *Proceedings of the 20th ACM Intl. Conf. on Hybrid Systems: Computation and Control (HSCC)*. February 2017

47. Yash Pant, Houssam Abbas, and **Rahul Mangharam**, "Robust Model Predictive Control for Non-Linear Systems with Input and State Constraints Via Feedback Linearization", *IEEE Conference on Decision and Control (CDC).* Las Vegas, USA, Dec 2016

48. Matthew O'Kelly, Houssam Abbas, Sicun Gao, Shin'ichi Shiraishi, Shnipei Kato, and **Rahul Mangharam**, "APEX: Autonomous Vehicle Plan Verification and Execution", SAE World Congress, April 2016.

49. Yash Pant, Houssam Abbas, Kartik Motha, Joseph Divetti and **Rahul Mangharam**, "Co-design of Anytime Computation and Control Systems", IEEE Real-Time Systems Symposium (RTSS), December 2015.

50. Yash Vardhan Pant, Houssam Abbas, K. N. Nischal, Paritosh Kelkar, Dhruva Kumar, Joseph Devietti and **Rahul Mangharam**, "Power-efficient algorithms for autonomous navigation", *IEEE Complex Systems Engineering (ICCSE),* Nov 2016.

Theme 2: Building Safe Medical Devices

51. Jiyue He, Arkady Pertsov, John Bullinga, **Rahul Mangharam**, "Individualization of atrial tachycardia models for clinical applications: Performance of fiber-independent model", *IEEE Trans. on Biomedical Eng, 2023.*

52. He, Jiyue; Pertsov, Arkady M; Cherry, Elizabeth M; Fenton, Flavio H; Roney, Caroline H; Niederer, Steven A; Zang, Zirui; **Mangharam, Rahul**; "Fiber Organization has Little Effect on Electrical Activation Patterns during Focal Arrhythmias in the Left Atrium", *IEEE Transactions on Biomedical Engineering, 2023.*
Feature Article

53. Jiyue He, Arkady Pertsov, John Bullinga, Rahul Mangharam, "Tachycardia activation pattern predictivity of a fiber-independent left atrium model", Cardiac Physiome Society. 2023.

54. Jiyue He, Arkady Pertsov, Rahul Mangharam, "Real-time atrial tachycardia ablation guidance with a left atrium model", Heart Rhythm Society. 2023.

55. Jiyue He, A. Pertsov, S. Dixit, K. Walsh, E. Toolan and R. Mangharam, " Patient-specific heart model towards atrial fibrillation", Proceedings of the ACM/IEEE 12th International Conference on Cyber-Physical Systems (ICCPS). May 2021.

56. Huang, S., Diep, M., Jang, K., Cherry, E. M, Fenton, F. H, Cleaveland, R., Lindvall, M., Mangharam, R., & Porter, A "Towards Automated Comprehension and Alignment of Cardiac Models at the System Invariant Level" In CSBio'20: Proceedings of the Eleventh International Conference on Computational Systems-Biology and Bioinformatics, 2020.

57. Jiyue He, Kuk Jin Jang, Katie Walsh, Jackson Liang, Sanjay Dixit, and **R. Mangharam**, "Electroanatomic Mapping to Determine Scar Regions in Patients with Atrial Fibrillation", *41st International Engineering in Medicine and Biology Conference (IEEE EMBC)*. July 2019.

58. **Kuk Jin Jang, *Yash Vardhan,* Pant, Bo Zhang, James Weimer, and Rahul Mangharam, "Robustness Evaluation of Computer-aided Clinical Trials for Medical Devices", *10th ACM/IEEE International Conference on Cyber-Physical Systems* (with CPS-IoT Week 2019) (ICCPS '19), Montreal. April 2019.**

59. Nicola Paoletti, Zhihao Jiang, Md Ariful Islam, Houssam Abbas, **Rahul Mangharam**, Shan Lin, Zachary Gruber, and Scott A. Smolka. 2019. "Synthesizing stealthy reprogramming attacks on cardiac devices". *10th ACM/IEEE International Conference on Cyber-Physical Systems* (with CPS-IoT Week 2019) (ICCPS '19), Montreal, Canada. April 2019.

60. **Houssam Abbas, Rajeev Alur, Konstantinos Mamouras, Rahul Mangharam, and Alena Rodionova, "Real-time Decision Policies with Predictable Performance", *Proceedings of the IEEE* 106(9). August 2018**

61. Kuk Jin Jang, James Weimer, Houssam Abbas, Zhihao Jiang, Jackson Liang, Sanjay Dixit, **Rahul Mangharam**, "Computer Aided Clinical Trials for Implantable Cardiac Devices", *40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, July 2018.

62. Houssam Abbas, Konstantinos Mamouras, Alena Rodionova, Rajeev Alur, Jackson Liang, Sanjay Dixit, and **Rahul Mangharam**, "A novel programming language to reduce energy consumption by arrhythmia monitoring algorithms in implantable cardioverter-defibrillators", *Heart Rhythm Journal*. May 2018.

63. Houssam Abbas and **Rahul Mangharam**, "Generalized Robust MTL Semantics for Problems in Cardiac Electrophysiology", *American Control Conference*. March 2018.

64. Abbas, H., Jang K.J., Liang J., Dixit S., and **Mangharam R**. "A novel ICD morphology discriminator to improve discrimination between Ventricular and Supraventricular tachycardias" in *Heart Rhythm Society Scientific Sessions*, Chicago. May 2017

65. Islam, M.A., Lim, H., Paoletti, N., Abbas, H., Jiang, Z., Cyranka, J., Cleaveland, R., Gao, S., Clarke, E., Grosu, R. and **Mangharam, R.**, CyberCardia project: Modeling, verification and validation of implantable cardiac devices. In *IEEE Intl. Conference on Bioinformatics and Biomedicine (BIBM),* pp. 1445-1452. 2016.

66. Zhihao Jiang, Houssam Abbas, Kuk Jin Jang, Marco Beccani and **Rahul Mangharam**, " Computer aided clinical trials for implantable cardiac devices", *Modeling, Design and Safety Analysis in Physiological Closed-Loop Systems Symp. at 53rd Society of Eng. Science Annual Technical Meeting, U. Maryland.* Oct 2016.

67. Zhihao Jiang, Houssam Abbas, Kuk Jin Jang, Marco Beccani and **Rahul Mangharam**, "In-silico Pre-clinical Trials for Implantable Cardioverter Defibrillators", *38th International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. August 2016.

68. Zhihao Jiang, Houssam Abbas, Kuk Jin Jang, Marco Beccani and **Rahul Mangharam**, "Modeling and Simulation for In-silico Pre-clinical Trials for Implantable Cardiac Devices", *BMES/FDA Frontiers of Medical Devices Conference.* May 2016.
69. Houssam Abbas, Kuk Jin Jang, Zhihao Jiang, and **Rahul Mangharam**, "Towards Model Checking of Implantable Cardioverter Defibrillators", *19th ACM International Conference on Hybrid Systems: Computation and Control* (HSCC). March 2016.
70. Houssam Abbas, Kuk Jin Jang, and **Rahul Mangharam**, "Benchmark: Nonlinear Hybrid Automata Model of Excitable Cardiac Tissue", *Applied Verification for Continuous and Hybrid Systems, Cyber-Physical Systems Week.* April 2016.
71. Zhihao Jiang, Houssam Abbas, Pieter J. Mosterman, and **Rahul Mangharam**, " Automated Closed-Loop Model Checking of Implantable Pacemakers using Abstraction Trees ", *IEEE Medical Cyber-Physical Systems*, CPS Week. April 2016.
72. Zhihao Jiang, Houssam Abbas, Kuk Jin Jang, and **Rahul Mangharam**, "Towards high confidence medical device software", *IEEE Computer.* January 2016.
73. Z. Jiang and **R. Mangharam**. "High-Confidence Medical Device Software Development". *Foundations and Trends in Electronic Design Automation*, Vol. 9, No. 4 (2015) 309–391. December 2015
74. **M. Pajic, Z. Jiang, I. Lee, O. Sokolsky and R. Mangharam. "Safety-critical Medical Device Development using the UPP2SF Model Translation Tool"** ***ACM Transactions of Embedded Computing Systems*** **(TECS). Sp. issue containing the best papers from RTAS 2012. January 2015.**
75. Kuk Jang, Jungmin Ryoo, Orkan Telhan and **Rahul Mangharam**, "CloudMat: Context-aware Personalization of Fitness Content," *IEEE 12th Intl. Conf. on Services Computing (SCC),* June 2015.
76. Z. Jiang and **R. Mangharam** "Integrated Functional and Formal Modeling for Medical Device Software". *Semiconductor Research Corporation TECHCON.* September 2014. Best in Session Award
77. M. Pajic, **R. Mangharam**, O. Sokolsky, D. Arney, J. M. Goldman and I. Lee "Model-Driven Safety Analysis of Closed-Loop Medical Systems", *IEEE Transactions of Industrial Informatics* (TII), *Special Section on Cyber-Physical Systems.* Vol.10, Issue:1 Feb 2014.

Theme 3: Bridging Machine Learning and Control Systems

78. Chen, Yu; Yang, Shuo; **Mangharam, Rahul**; Yin, Xiang; "You Don't Know When I Will Arrive: Unpredictable Controller Synthesis for Temporal Logic Tasks," 22nd World Congress of the International Federation of Automatic Control (IFAC), 2023.
79. **Shuo Yang, Mitchell Black, Georgios Fainekos, Bardh Hoxha, Hideki Okamoto, Rahul Mangharam; "Safe Control Synthesis for Hybrid Systems through Local Control Barrier Functions", 2023 (under review)**
80. Luigi Berducci, Shuo Yang, **Rahul Mangharam**, Radu Grosu; "Learning Adaptive Safety for Multi-Agent Systems", 2023 (under review)
81. Jiangwei Wang, Shuo Yang, Ziyan An, Songyang Han, Zhili Zhang, Meiyi Ma, **Rahul Mangharam**, Fei Miao; "Multi-agent reinforcement learning guided by signal temporal logic specifications", 2023 (under review)
82. Yang, Shuo; Chen, Shaoru; Preciado, Victor M; **Mangharam, Rahul**; "Differentiable Safe Controller Design through Control Barrier Functions." *IEEE Control Systems Letters + IEEE Conf. on Decision & Control,* 2023
83. **F. Smarra, G. D. Di Girolamo, V. De Iuliis, A. Jain, R. Mangharam, and A. D'Innocenzo "Data-driven Switching Modeling for MPC using Regression Trees and Random Forests",** ***Nonlinear Analysis: Hybrid Systems, A journal of IFAC, the International Federation of Automatic Control.*** **2020**

84. **Achin Jain, Truong X. Nghiem, Manfred Morari, and Rahul Mangharam. "Learning and Control using Gaussian Processes" in *Proceedings of the 9th ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS)*, April 2018.** Best Paper Award

85. **Francesco Smarra, Achin Jain, Tullio de Rubeis, Dario Ambrosini, Alessandro D'Innocenzo and Rahul Mangharam. "Data-driven model predictive control using random forests for building energy optimization and climate control". *Journal of Applied Energy*, 2018.**

86. Jain, F. Smarra, M. Behl, **R. Mangharam**, "Data-driven Model Predictive Control with Regression Trees – An Application to Building Energy Management" *ACM Transactions on Cyber-Physical Systems*, Volume 2 Issue 1, February 2018.

87. Jain, D. Nong, T. X. Nghiem, **R. Mangharam**, "Digital Twins for Efficient Modeling and Control of Buildings – An Integrated Solution with SCADA Systems" *ASHRAE/IBPSA-USA Building Performance Analysis Conference and SimBuild*. September 2018.

88. Francesco Smarra, Achin Jain, **Rahul Mangharam** and Alessandro D'Innocenzo. Data-Driven Switched Affine Modeling for Model Predictive Control. In *Proceedings of the 6th IFAC Conference on Analysis and Design of Hybrid Systems*, 2018.

89. Jain, F. Smarra, **R. Mangharam**, "Data Predictive Control using Regression Trees and Ensemble Learning", 56th IEEE Conference on Decision and Control (CDC), 2017

90. Achin Jain, Madhur Behl, and **Rahul Mangharam**, "Data predictive control for building energy management". *American Control Conference (ACC)*. June 2017. **Best Paper Award (Energy Systems)**

91. Achin Jain, Madhur Behl, and **Rahul Mangharam**, "Data Predictive Control for Peak Power Reduction". *ACM International Conference on Embedded Systems for Energy-Efficient Built Environments (BUILDSYS)*. Nov 2016. **Best Presentation Award**

92. Madhur Behl, Achin Jain, and **Rahul Mangharam**, "Data-Driven Modeling, Control and Tools for Cyber-Physical Energy Systems", *ACM/IEEE 7th Intl. Conference on Cyber-Physical Systems (ICCPS)*. April 2016.

93. **Rahul Mangharam**, Houssam Abbas, Madhur Behl, Kuk Jang, Miroslav Pajic and Zhihao Jiang, " Three Challenges in Cyber-Physical Systems," *8th International Conference on Communication Systems and Networks (COMSNETS)*, 2016.

94. Achin Jain, Madhur Behl, and **Rahul Mangharam**, "Data Predictive Control for Cyber-Physical Energy Systems", *ACM Transactions on Cyber-Physical Systems*, Vol. 9, No. 4, Article 39. July 2017.

95. **Madhur Behl, Francesco Smarra, and Rahul Mangharam, "DR-Advisor: A Data-Driven Demand Response Recommender System", *Journal of Applied Energy*. January 2016.**

96. Madhur Behl, Truong Nghiem, Willy Bernal and Rahul Mangharam, "Campus-Wide Integrated Building Energy Simulation" 14th International Conference of the International Building Performance Simulation Association (*IBPSA*), Dec 2015.

97. Truong Nghiem and **Rahul Mangharam**, "Scalable Scheduling of Energy Control Systems," *Proceedings of the 12th International Conference on Embedded Software (EMSOFT)* , 137-146. October 2015.

98. Madhur Behl and **Rahul Mangharam**, "Sometimes money does grow on trees: Data Driven Demand Response with Regression Trees", *SRC TECHCON*. September 2015. Best in Session Award

99. Madhur Behl, Truong Nghiem and **Rahul Mangharam**, "DR-Advisor: A Data Driven Demand Response Recommender System". *CISBAT International Building Simulation Association IBPSA*, Sept 2015.

100. Madhur Behl and **Rahul Mangharam**, "Sometimes, Money Does Grow On Trees: Data-Driven Demand Response with DR-Advisor", *ACM International Conference on Embedded Systems for Energy-Efficient Built Environments (BUILDSYS)*. November 2015.

101. M. Behl, T. Nghiem and **R. Mangharam**. "IMpACT: Inverse Model Accuracy and Control Performance Toolbox for Buildings". *IEEE Intl. Conference on Automation Science and Engineering (CASE)*, 2014.
102. Y. Pant, T. Nghiem and **R. Mangharam**. "Peak Power Reduction in Hybrid Energy Systems with Limited Load Forecasts". *American Control Conference (ACC).* June 2014
103. M. Behl, T. Nghiem and **R. Mangharam**. "Model-IQ: Uncertainty Propagation from Sensing to Modeling and Control in Buildings". *ACM/IEEE Intl.l Conference on Cyber-Physical Systems* (ICCPS). April 2014.