RESEARCH STATEMENT

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

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My research develops the foundations of Safe Autonomous Systems. As vehicles, drones and medical devices gain greater autonomy and become life-critical, it is necessary to guarantee their safety. 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 provides guarantees for the safety and performance of autonomous life-critical Cyber-Physical Systems (CPS) and has evolved along the following themes:

1. **Safe Autonomous Vehicles:** *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 as a search engine for finding unsafe AV driving instances.

   For Aerial AVs, we ask the question: *How can we control hundreds of autonomous drones performing complex missions in urban airspaces?* 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. These efforts are part of the $14MM DoT Mobility21 National University Transportation Center, 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. It is published in [1-23].

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. 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 [24-44].

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 and adaptive production planning. 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. This has been demonstrated for demand-side energy management across large commercial buildings, making them adaptive to electricity prices by synthesizing control strategies with 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. It is published in [45-64].

4. **Autonomous System Platforms and Testbeds**: *How do we build the Department of Autonomy?*
   In order evaluate the safety of machine learning engineering for AVs at the limits of perception, planning and control, we developed the F1/10 Autonomous Racing community [http://f1tenth.org]. F1/10 produces open-source platforms, courses and international competitions using 1/10th scale Formula-1 autonomous racing cars. This effort spans 60 universities 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**) in 2016 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.

My team's efforts have been recognized through numerous awards including the 2018 ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS) Best Paper Award, 2017 American Control Conference (ACC) Best Paper Award (Energy Systems), 2016 ACM BUILDSYS Best Presentation Award, 2015 & 2014 SRC TECHCON Best in Session award, IEEE RTAS 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.

Reflecting the cross-cutting nature of my work, my research findings, *after tenure in 2014,* have been published in the areas of ***Formal Methods*** [8, 9, 10, 11, 12, 17, 18, 19, 21, 43, 44], ***Control Systems*** [2, 3, 4, 5, 14, 15, 16, 20, 22, 23, 57, 58, 62, 63, 64], ***Learning for Control*** [50, 51, 52, 53, 54, 55, 56, 59, 60, 61], ***Medical* Systems** [24, 25, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41] and **Autonomous Systems Education** [1, 6, 7, 13].

Since tenure, I have served as conference co-chair for ICCPS, RTSS, 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 and/or CDC controls conferences 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 and IEEE Transactions on Embedded Systems.

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 3rd 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. Published in [10, 16, 17, 19, 21].

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 Metric Temporal Logic (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. Published in [3, 4, 5, 8, 9, 11, 12, 14, 15, 18].

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 [2, 19, 20, 21, 22].

Impact: My Safe AV efforts have resulted in 3 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. As part of this, 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 PI, CPSweek, ESWeek, etc. conferences.

Research Agenda:

1) 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 Intel/MobilEye, GM, Ford, LG and StoneRidge, 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.

2) Formally-Constrained Machine Learning: I will develop a safety framework which incorporates constraints into the training, pruning and inferencing stages of data-driven algorithms to guarantee operations satisfy the desired properties. This has the potential of radically expanding the domain of application of Machine Learning into safety-critical areas.

3) 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, in order 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.

4) *Learning to Fly: Learning-based Decentralized Collision Avoidance for Scalable Urban Air Mobility* - Collision avoidance problems are notoriously complex and often resort to mixed integer linear programming which prevents real-time execution. My team is designing safe and efficient learning-based collision avoidance and related control approaches for scalable real-time operation.

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. In 2018, software was 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 Penn Hospital, Philadelphia VA Hospital, Georgia Tech, SUNY Stony Brook and FDA.

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 [24, 25, 28, 32, 33, 34, 35, 39].

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) [36, 37, 40], better algorithms for detecting fatal arrhythmias [30, 31, 43, 44], and predictable-performance programming languages for ICDs [26, 27, 29, 38, 41]. 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 [30, 31]. 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 [27, 29]. 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 Assistant Professors at Duke and Shanghai Tech universities.

Research Agenda: *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 has also developed 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 [45, 46, 47, 48, 49, 50, 51, 52, 53, 55, 56, 59, 60, 61]

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 [54, 57, 58, 62, 63, 64]

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. F1/10 [http://f1tenth.org/] enables a wide range of machine learning engineering with perception, planning, control and coordination modules. 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 5 international autonomous racing competitions for multi-vehicle racing with a variety of perception, planning and control algorithms including object detection, reactive and map-based local planners, advanced planners including Rapidly exploring Random Trees, pure pursuit trajectory followers and model- predictive control. We have developed a course for autonomous racing that is being taught at Oregon State University, UVA, N. Arizona University, Clemson University, etc. By driving at the limits of vehicle performance, we hope to accelerate the development of safe autonomous vehicles. F1/10 has over 59+ 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, Nvidia, Intel, etc. We aim to grow the community to further research in building better autonomous systems.

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. Matthew O'Kelly, Abhijeet Agnihotri, Houssam Abbas and **R. Mangharam**, "Building Responsible Autonomous Systems at 1/10th-scale: A project-based course and community" *ACM Special Interest Group on Computer Science Education (SIGCSE)*. February 2020.
2. 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. 2020.
3. **Y. V. Pant, A. Rodionova, H. Abbas, Kuk Jang, R. A. Quaye, R. Mangharam, "Learning-to-Fly: Learning-based Collision Avoidance for Scalable Urban Air Mobility". Under review. 2019.**
4. Y. V. Pant, H. Abbas, R. A. Quaye, **R. Mangharam**. "Distributed planning for multi-drone fleets with Signal Temporal Logic objectives". Under review. 2019.
5. Y. V. Pant , M. Z. Li, R. A. Quaye, H. Abbas, M. Ryerson, **R. Mangharam**. "FADS: Framework for Autonomous Drone Safety". Under review. 2019
6. J. Auckley, A. Jain, K. Luong, **R. Mangharam**, M. O'Kelly and H. Zheng, "TunerCar: A Superoptimization Toolchain for Autonomous Racing". Under review. 2019.
7. 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", Under review. 2019.
8. 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.
9. 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 (MTCPS), CPS Week*, 2019.
10. **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.**
11. **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.**
12. 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.
13. **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.
14. 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.
15. Yash Pant, Houssam Abbas, and **Rahul Mangharam**, "Control with Temporal Logic Requirements", in *Semiconductor Research Corporation TECHCON.* 2017.
16. Matthew O'Kelly, Houssam Abbas, and Rahul Mangharam, "Computer-Aided Design for Safe Autonomous Vehicles", IEEE International Symposium on Resilient Control Systems. September 2017
17. 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.

18. 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
19. 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
20. 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
21. 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.
22. 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.
23. 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

24. 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.
25. **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.**
26. 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.
27. **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**
28. 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.
29. 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.
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