Workshop W14

Control Barrier Functions: Recent Developments and Future Directions

Monday, December 12, 2023

Rm. Orchid Main 4301A

Organized by Gennaro Notomista and Yorai Wardi

List of abstracts

Magnus Egerstedt. Stacey Nicholas Dean of Engineering, Samueli School of Engineering, University of California, Irvine, USA.

Mutualistic Interactions in Heterogeneous Multi-Robot Systems.

Abstract. The typical approach to multi-robot systems is to divide the team-level tasks into suitable building blocks and have the robots solve their respective subtasks in a coordinated manner. However, by bringing together robots with different capabilities, it should be possible to arrive at completely new capabilities and skill sets. In other words, the whole becomes greater than the sum of its parts. In this talk, we will formalize this idea through the composition of barrier functions for encoding the collaborative arrangements in terms of expanding and contracting reachable and safe sets. Inspired by the ecological concept of a mutualism, i.e., the interaction between two or more species that benefit everyone involved, the formalism is contextualized in a long-duration setting, i.e., for robots deployed over long time scales where optimality has to take a backseat to “survivability”.

Ryan Cosner. Ph.D. student, California Institute of Technology, USA.

CBF-based Safety for Real-World Robotic Systems.

Abstract. Safety is paramount for the wide-scale deployment of modern robotics. However, ensuring safety for these systems becomes increasingly complex as robots leave the laboratory and venture into the outside world. In this work we show promising methods for generating safety guarantees for systems with real-world uncertainties such as bounded and unbounded state estimation error, model mismatch, and dynamics disturbances. In particular, we consider control barrier functions (CBFs) as a tool for guaranteeing safety and we propose methods for extending their guarantees to uncertain systems. We propose several methods for handling uncertainties and apply these methods in conjunction with machine learning tools such as preference-based learning and generative modeling to produce systems which are both robust and performant in the real-world. To verify the practical efficacy of our theoretical guarantees, we deploy our methods on a variety of bipedal, quadrupedal, wheeled, and flying robot platforms.

Erlend A. Basso and Aurora Haraldsen. Post-doctoral Fellows, Department of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Guidance schemes for underactuated marine vehicles with safety guarantees using control barrier functions.

Abstract. Uncrewed marine vehicles play an increasingly vital role in diverse operational scenarios such as mapping, exploration, transportation, surveillance, intervention, and maintenance. As the reliance on these vehicles grows, the imperative to ensure their safety, both formally and in practice, becomes increasingly critical. This presentation addresses the escalating demand for safety-critical controllers, where Control Barrier Functions (CBFs) have been introduced as a promising solution. While CBFs have shown considerable success in holonomic systems, challenges emerge in the presence of nonholonomic constraints. The focus of this talk is on dynamic guidance schemes for underactuated marine vehicles operating at transit speeds, and it explores the utilization of CBFs to reactively devise safe trajectories amidst obstacles. These vehicles are characterized by second-order nonholonomic constraints, along with additional speed requirements. In this context, a key innovation lies in the implementation of safety constraints at a kinematic guidance level rather than the traditional lower-level control layer. This strategy eliminates the necessity for an exact vessel model, providing a practical solution for real-world applications. Furthermore, for marine vehicles equipped with proven and resilient control systems, the guidance level serves as an apt interface without requiring modifications to the low-level feedback control. The proposed methodology considers a virtual vessel, modeled as a unicycle, to generate the desired trajectories. Guidance schemes for both trajectory tracking among unknown, static obstacles and collision avoidance of dynamic obstacles are presented.

Christos Cassandras. Distinguished Professor of Engineering. Head, Division of Systems Engineering, and Professor of Electrical and Computer Engineering. Center for Information and Systems Engineering (CISE). Boston University, USA.

Guaranteed Safe Autonomous Cooperative and Uncooperative Multi-agent Systems with Control Barrier Functions.

Abstract. We address the problem of combining the optimality of autonomous multi-agent systems with the guaranteed satisfaction of hard safety constraints at all times. We will review the basic theory of Control Barrier Functions (CBFs) and present a real-time control framework that combines trajectories generated through optimal control with the computationally efficient CBF method providing safety guarantees. A tractable optimal solution is first obtained for a linear or linearized system, and then this solution is optimally tracked while using CBFs to guarantee the satisfaction of all state and control constraints. This Optimal Control and CBF (OCBF) framework can be adapted to allow complex objective functions, noise, and nonlinear dynamics, possibly unknown. We will discuss how to overcome the issue of unknown system dynamics using event-driven controllers.

In this framework, it is assumed that all agents cooperate with each other. When some of the agents are uncooperative, we study how the risk introduced by this lack of full cooperation can still be managed through the partial collaboration of the cooperative agents. This approach is applied to autonomous vehicles in transportation systems where human driven vehicles are also present and where the objective is to jointly minimize the travel time and energy consumption of each vehicle subject to speed, acceleration, and speed-dependent safety constraints.

Takeshi Hatanaka. Associate Professor, Tokyo Institute of Technology, Tokyo, Japan.

Constraint-based control of multi-drone systems towards smarter agriculture.

Abstract. The decline and ageing of the farming population has made the smartening and automation of agriculture an urgent social issue, and robot technology is undoubtedly an important piece of the puzzle to solve the problem. In particular, the concept of Agriculture 4.0 emphasizes the needs for coordinated control of robotic swarm for scaling up to larger farmlands. In this talk, we address coordinated image sampling for multi-drone systems specialized to 3D model reconstruction of farmlands/crops from aerial images, and present a series of our research outcomes on the issue. We reveal how the concept of constraint-based control contributes to completing the mission and demonstrate the present solution through simulation, indoor experiments and field experiments on a real vineyard. We finally present a hierarchical control approach combining the constraint-based control and model predictive scheduler as a solution to the problem of geographical dispersal of multiple small-scale farmlands, where the constraint-based control plays a key role in ensuring real-time feasibility of model predictive control.

Kyriakos Vamvoudakis. Dutton-Ducoffe Professor of Aerospace Engineering, Georgia Institute of Technology, Atlanta, USA.

Fixed-Time Convergent Safe Reinforcement Learning.

Abstract. Exploiting the benefits of learning and Control Barrier Functions can enhance the performance and ensure the safety of autonomous systems in complex and unknown environments. Nonetheless, existing safe learning architectures lack finite time convergence guarantees, rendering these algorithms impractical for real-world applications. First, we will talk

about a safe pursuit-evasion game for enabling finite-time capture, optimal performance, and adaptation to an unknown cluttered environment. Then, we construct a learning-based target assignment algorithm to address the problem of multiple pursuers against multiple targets, wherein the assignment is performed based on the agent rationality level. Finally, we will address a safety-critical control problem using reachability analysis and design an online reinforcement learning-based mechanism for learning the solution to the safety-critical control problem in a fixed time.

Yorai Wardi. Professor of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, USA.

Integral CBF for dynamic controllers and tracking applications.

Abstract. This presentation focuses on an application of Control Barrier Functions (CBF) to feedback systems with dynamic controllers. Such systems directly control the time-derivative of the input to the plant, which is then integrated to result in the input itself. Thus the controller contains an integrator, albeit with variable gain, which may result in fast convergence on the one hand, but in large input oscillations and state overshoots at early stages of a controller's runs. These undesirable transient phenomena can be reduced or eliminated by applications of CBF.

The motivation for the work presented in this talk is derived from a new tracking controller which is designed for efficiency through implementation at low levels of the control hierarchy. The talk will first describe this controller, then focus on the application of CBF to smooth out a system's dynamics while maintaining safety. Moreover, it will show that the applications of CBF to dynamic controllers can be optimized by dynamic programs in situations where the plant's dynamics are not control affine.