

Research Vision

Current methodologies in robotics severely limit our abilities to create capable and efficient robots, even without practical computational constraints. Evidenced by the fact that even advanced robots still struggle with seemingly simple tasks like opening doors or achieving reliable locomotion. Even when seemingly working in simulation, they often fail to generalize when deployed in the real world. The challenge isn't just bridging simulation and reality—it's that our fundamental approaches to specifying and learning robotic behaviors are inherently inefficient and brittle. Modern control theory techniques which include learning, while powerful, often require roboticists to engage in the complex and error-prone task of designing objective functions that faithfully capture desired behaviors. My research aims to transform the field by developing principled methods that enable the **faithful translation of high-level objectives into robust learned behaviors**. Through my work combining programming languages, machine learning, and embedded systems, I develop techniques that help practitioners overcome these core limitations in robot design and implementation. This agenda introduces new foundations that make better use of available computational resources, enabling a new generation of robots that can achieve sophisticated capabilities while maintaining efficiency, and reliability in the real world.

Research Trajectory

My research program has made significant contributions to reliable and efficient robotic control, with over 100 citations across my publications demonstrating substantial impact in the field:

1. **Reliable Flight Control via Reinforcement Learning:** I developed a technique for composing reward functions that better captures the semantics of desired behaviors, this has influenced the design of subsequent works. I also developed a systematic framework (RE+AL) for learning controllers in simulated environments that preserves controller quality when transferred to real platforms. This work, published in ACM TCPS, demonstrated the first RL-based controllers trained in simulation to outperform well-tuned PID controllers on real racing quadrotors, achieving better tracking errors and reduced power consumption.
2. **Action Policy Smoothness:** Through my ICRA publication on CAPS (Conditioning for Action Policy Smoothness), I introduced a general regularization technique that mitigates a wide-spread issue in reinforcement learning for continuous control, namely the issue of unbounded action frequencies that cause numerous hardware failures upon deployment. When applied to real world control, this method achieved an 80% reduction in power consumption while maintaining reliable performance. This work has become a cornerstone reference in the field of efficient reinforcement learning, with adoptions in aerial, ground, and even underwater robots.
3. **Resource-Efficient Neural Architectures:** Published in IEEE CoG, we demonstrated that actor networks in reinforcement learning can be dramatically reduced in size (up to 99% reduction in weights) while maintaining satisfactory performance on common benchmark tasks. This breakthrough enables the deployment of learned controllers on heavily resource-constrained platforms.

Building on this notion of robust learning under resource constraints, my current work extends into several other directions:

4. **Sim-to-Real Adaptation:** By taking into account our capabilities in simulation and our limitations in reality, I’ve rethought how to frame the sim-to-real adaptation of RL policies as a multi-objective optimization problem. Without careful treatment of this issue, I’ve observed massive catastrophic forgetting problems in RL policies. Using what I term “anchor critics”, the work shows that such issues can be completely mitigated. Additionally, we’ve released SWANNFlight firmware, an open-source platform that enables researchers to test adaptation techniques on real robots.
5. **Expressive Reinforcement Learning:** I’m addressing fundamental limitations in how roboticists specify desired behaviors through Algebraic Q-Value Scalarization (**AQS**). This novel domain-specific language generalizes traditional linear reward composition by using the power-mean as a logical operator over normalized Q-values. This increases the expressiveness of policy specification. When integrated with our new Balanced Policy Gradient algorithm, AQS achieves up to 600% improvement in sample efficiency compared to state-of-the-art methods like Soft Actor Critic, while significantly reducing policy variability.

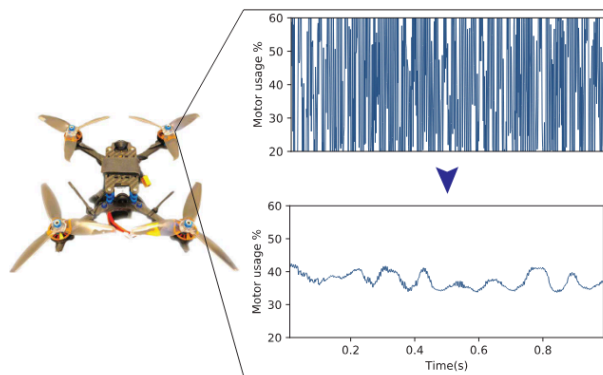


Figure 1: CAPS regularization significantly reduces control signal oscillations while maintaining performance, leading to 80% power reduction on real quadrotors.

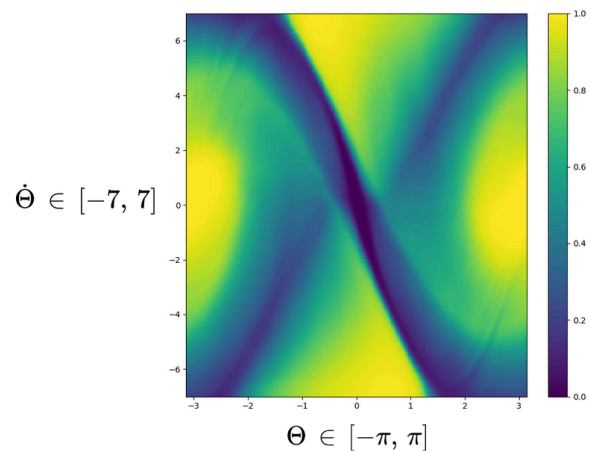


Figure 2: Quickly learned family of Lyapunov functions for a pendulum enabling stable control across multiple set points, improving sim-to-real transfer.

Past Achievements My research journey began at the American University of Beirut, where I first explored the intersection of neural networks and swarm control systems. As a researcher there, I developed a collection of experimental optimization algorithms for learning decentralized swarm control systems.

Future Research Program

Short-term Goals (2-5 years) Building on my current research achievements, I plan to pursue several interconnected research directions, supported by specific funding opportunities:

1. **Efficient Control for Resource-Constrained Robots:** I plan to advance the state-of-the-art in neural network control for under-instrumented limbed robots, focusing on:

- Developing HW/SW architectures for energy-efficient control
 - Creating efficient learned runtime adaptation techniques for constrained platforms
 - Enabling a new class of cost- and power-efficient robots
2. **Sustainable Robotics:** I will explore the intersection of eco-friendly robotics and efficient computing through:
- Design of power-aware neural networks that maximize efficiency
 - Integration of formal safety bounds with energy-efficient control
3. **Certified Survivability:** I intend on developing methods for certifiably safe and robust neural network-based controllers that can:
- Adapt to substantial system damages while maintaining safety guarantees
 - Transfer learned behaviors across different robot configurations
 - Provide formal verification of controller behavior

Long-term Vision (5+ years) My long-term research agenda aims to revolutionize how we develop and deploy reliable robotic systems:

1. **Theoretical Foundations:** Establish new theoretical foundations for:
- Provably safe adaptation in robotic systems
 - Resource-aware learning and control
 - Intuitive specification of robotic behaviors
 - Formal verification of learned behaviors
2. **Real-world Impact:** Drive the adoption of reliable robotic systems through:
- Development of open-source tools and frameworks
 - Industry collaborations for practical deployment
 - Creation of educational resources for the next generation of roboticists

Broader Impacts

My research program is deeply committed to broader impacts through education, mentorship, and technology transfer:

Educational Impact I have extensive experience in teaching and mentoring, having:

- Led courses in Distributed Systems, Embedded Systems, and Data Science at Boston University
- Developed innovative teaching materials, including a PyBullet simulation environment for teaching control fundamentals
- Created practical, industry-relevant projects that bridge theoretical concepts with real-world applications

Student Mentorship I've successfully mentored diverse groups of students in various contexts:

- Led the F1Tenth Racing Team of 11 students to second place in competition, developing novel approaches to autonomous racing
- Guided graduate students in research leading to publications at top venues (e.g., ECCV 2024)

- Supervised multiple successful projects through programs like RISE, Kilachand Honors College, and BU Spark
- Mentored students who have gone on to prestigious institutions like UC Berkeley

Industry and Technology Transfer My work bridges academia and industry through:

- Development of open-source tools and frameworks used in both research and practical applications
- Creation of startup ventures that demonstrate the commercial viability of research concepts
- Collaboration with industry partners on real-world applications of robotic systems

Diversity and Inclusion I am committed to fostering an inclusive research environment by:

- Mentoring students from diverse backgrounds and supporting their career development
- Creating accessible educational resources that democratize robotics education
- Designing projects that encourage participation from students with varied technical backgrounds

Through these activities, I aim to not only advance the field of robotics technically but also to build a diverse and skilled community of future roboticists.