Learning-Adaptive Control for Autonomous Robotics

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I. Current Status of the Project

Learning-Adaptive Control in the repetition domain offers significant advantages for systems performing repetitive tasks, as it enables parameter optimization across iterations rather than within a single execution. Beigi developed the theoretical foundations of learning and learning-adaptive control [1]–[7] and demonstrate the potential for substantial error reduction in trajectory tracking through iterative learning. Although the above references did apply these techniques to some very challenging physical systems [4] with great succes, some of the practical implementation of these approaches on modern robotic platforms present unique challenges that remain unaddressed in the current literature.

Our team of students has developed two projects: an autonomous robot car (See Poster) and a quadcopter (See Poster). Both projects were recently showcased at the Northeastern Systems and Controls Workshop (NESCW-2025) at Columbia University. The proposed funding will further support the development of the project's sensor suite and accelerate the implementation of the control frameworks from Beigi's work. A brief description of the current status of each project can be found here:

A. Autonomous Car

Under the Mechanical Engineering Projects course MECEE4998, MS student Onur Calisir has worked on building a four-wheeled autonomous vehicle (Figure 1) using ROS2, equipped with sensors including IMU, stereo-depth camera, and motor encoders. The robot car can be accurately teleoperated with velocity PID control, showcasing complete hardware and sensor interfacing. Each DC motor can be independently controlled and each sensor can provide accurate readings.

B. Quadcopter

Under the Electrical Engineering Projects course ELENE6002, MS student Anne Rose Sankar Raj has worked on building a 1.5kg payload quadcopter equipped with a Raspberry Pi 5 (Figure 2). It has a PixHawk flight controller with a built-in triple IMU, dual barometers, magnetometer, integrated temperature control, power, and current sensors. The drone is also equipped with a stereo-depth camera and ultrasonic sensors. Currently working on hardware and software integration.

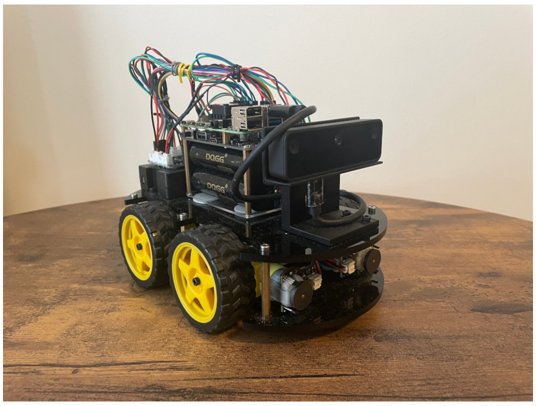

Fig. 1. Autonomous Vehicle NESCW-2005 Poster

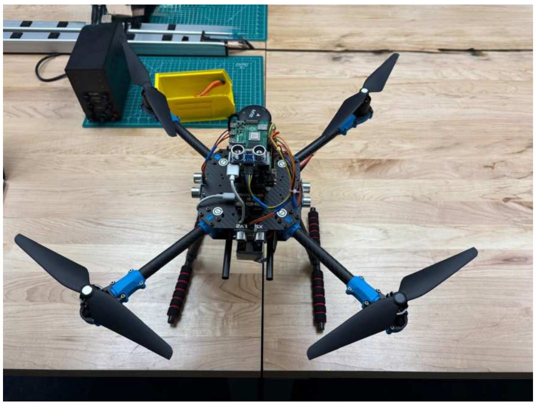

Fig. 2. Autonomous Quadcopter NESCW-2005 Poster

II. Future Directions of the Project

Our project aims to advance learning-adaptive control through practical implementation on complex robotic platforms while introducing innovative sensing capabilities. Learning adaptive control allows for minimizing error across repetitions of a repetitive task.

- **Hardware Validation:** We will implement Beigi's learning-adaptive control methodology [1]–[7] on three distinct non-linear robotic platforms (autonomous car, quadcopter, and robotic arm), validating the theoretical concepts in real-world hardware and identifying practical limitations not apparent in simulation
- **Advanced Parameter Estimation:** We will further enhance the original LAC framework with Mamba state-space models (S4) [9] to capture temporal dependencies in system dynamics better, addressing fundamental limitations in the original linear estimation techniques
- **Neural Network Integration:** By developing neural network alternatives to the generalized secant method, we will investigate whether modern deep learning approaches can accelerate convergence and improve adaptation robustness

A. *Sensing Innovation*

- **Acoustic Proximity Detection:** We are looking to implement the Leaky Surface Wave phenomenon on our robotic platforms, enabling 360° proximity detection using minimal hardware—just two piezoelectric sensors—while avoiding the blind spots inherent in traditional sensor arrangements
- **Signal Processing Advancement:** We will apply cepstral analysis techniques, which will transform complex acoustic signals into actionable proximity information, developing algorithms optimized for real-time operation on resource-constrained platforms

Integrating advanced control theory with novel sensing technologies significantly advances robotics research. By implementing these capabilities on practical platforms, we will establish new methodologies for robots that learn from experience while perceiving their environments in fundamentally new ways, potentially transforming robotic operations in manufacturing, delivery, and transportation industries.

III. Alignment with Sense, Collect, and Move Data

A. *Sensing*

- **Novel Piezoelectric Sensors:** We are looking to transform surfaces into active sensors through acoustic wave propagation, enabling omnidirectional collision detection with minimal hardware requirements while providing an economical alternative to expensive systems like LiDAR
- **"AuraSense" Implementation [8]:** Our adaptation of the Leaky Surface Wave phenomenon to mobile platforms using cepstral techniques explores fundamental signal properties across different structures, creating new sensing capabilities that detect objects traditional sensors might miss

B. *Data Collection*

- **Learning Control:** Our framework generates comprehensive datasets documenting how control parameters evolve across repetitions, capturing the relationship between sensory input, control adjustments, and performance improvements.
- **Educational Data:** We will develop standardized collection protocols and package our multisensory datasets for use in future research and project-based control classes, extending the impact beyond our research goals. The Nonlinear and Adaptive Control (MEEE E6610), as well as the Discrete Control Systems (EEME E4601) courses will be using the generated data for advancement of research projects.

C. *Data Movement*

- **Sensor-to-Control:** Our system implements direct connections from novel sensor data to adaptive control parameters, creating feedback loops where environmental perception directly influences robot motion strategies. In addition, it takes into account the repetitive nature of processes such as manufacturing and logistics.
- **Processing Framework:** We are developing optimized signal processing for resource-constrained platforms with accessible APIs, allowing future researchers to build based upon our sensing and control infrastructure.

These projects bridge mechanical and electrical engineering approaches through a comprehensive sensing and control framework, applying classical and modern techniques to challenging nonlinear robotics problems. This integrated approach embodies the SCMD center's mission by transforming how robots sense their environment, collect meaningful operational data, and translate this information into optimized motion, completing the entire sense-collect-move pipeline at the core of the center's vision.

IV. Nature of the Request for Funding

Access to funding to acquire the equipment listed below would be highly desirable to implement the research work we envision successfully. This would drive the research forward over the summer and allow us to contribute to the center's vision.

- **LiDAR Sensors:** An RPLIDAR A1M8 2D 360-degree scanning sensor is essential for providing ground-truth measurements to validate our novel active acoustic sensing system. This will enable us to quantitatively assess our proposed system's detection accuracy and range limitations across various environmental conditions.
  Link to RPLIDAR: https://a.co/d/4Lbl5nN
- **Robotic Arm Platform:** Acquisition of a 7-DOF collaborative robot arm (Yahboom MyCobot280) will extend our research to an additional widely used non-linear system, allowing us to validate our learning-adaptive control approach across multiple robotics domains. This addition will strengthen the generalizability of our research to

many robotics systems and provide a platform specifically designed for repetitive tasks.
Link to Robot Arm: https://a.co/d/1EiRMBP

- **Electronic Components and Signal Processing Hardware:** We require specialized electronic components for:
  - Signal conditioning circuits for piezoelectric sensor integration
  - Data acquisition modules to capture high-resolution acoustic signals
  - Interface adapters for multi-sensor integration with our computing platform

V. Further Details on the Request Amount

This project will only be possible with the generous support of the Sense, Collect, and Move Data center. To implement our research vision and align with the center's mission, we are seeking funding for the following essential components:

Item	**Count**	**Item**	**Subtotal**
RPLIDAR A1M8 sensors	2	100	$200
Yahboom MyCobot280 robotic arm	1	$1,400	$1,400
Circuitry, tools and components	1	$500	$500
Transportation and meals for students in the project*	3	$500	$1500
Total Funding Requested			$**3,600**

* – Three students ($500 per student for the whole summer)

TABLE I
Funding Request Breakdown

The requested funding will enable our team to implement the innovative sensing modalities and learning-adaptive control frameworks described in this proposal. These resources are critical for validating our approaches on real hardware systems and generating the valuable datasets that align directly with the center's mission of advancing novel approaches to sensing, collecting, and moving data in robotic systems.

References

[1] Homayoon Beigi, "New adaptive and learning-adaptive control techniques based on an extension of the generalized secant method," *Intelligent Automation and Soft Computing*, vol. 3, no. 2, pp. 171–184, 1997.
[2] Konstantin Avrachenkov, Homayoon Beigi, and Richard Longman, "Updating Procedures for Iterative Learning Control in Hilbert Space," Invited Paper, Intelligent Automation and Soft Computing Journal (Special Issue on Learning and Repetitive Control), Vol. 8, No. 2, 2002.
[3] Homayoon Beigi, "Adaptive and Learning-Adaptive Control Techniques based on an Extension of the Generalized Secant Method," Intelligent Automation and Soft Computing Journal, Vol. 3, No. 2, 1997, pp. 171–184.
[4] C. James Li, Homayoon Beigi, Shengyi Li, Jiancheng Liang, "Nonlinear Piezo-Actuator Control by Learning Self-Tuning Regulator," ASME Transactions, Journal of Dynamic Systems, Measurement, and Control, Vol. 115, No.4, December 1993, pp. 720–723.
[5] Konstantin E. Avrachenkov, Homayoon Beigi, and Richard W. Longman, "Operator-Updating Procedures for Quasi-Newton Iterative Learning Control in Hilbert Space," Invited Paper, IEEE Conference on Decision and Control (CDC'99), Phoenix, AZ, December 3-7, 1999.
[6] Homayoon Beigi, "A Parallel Network Implementation of The Generalized Secant Learning-Adaptive Controller," Proceedings of the Canadian Conference on Electrical and Computer Engineering, Toronto, Canada, Sep. 13–16, 1992, Vol. II, pp. MM10.1.1–4.
[7] Homayoon Beigi, "Neural Network Learning and Learning Control Through Optimization Techniques," Doctoral Thesis, School of Engineering and Applied Science, Columbia University, New York City, New York, 1991.
[8] X. Fan, R. Simmons-Edler, D. Lee, L. Jackel, R. Howard, and D. Lee, "AuraSense: Robot collision avoidance by full surface proximity detection," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2021, pp. 1763-1770.
[9] A. Gu and T. Dao, "Mamba: Linear-time sequence modeling with selective state spaces," *arXiv preprint arXiv:2312.00752*, 2023.

Supporting Documents

See the following pages for the Curriculum Vitae of project members.

Onur Calisir

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EDUCATION

Columbia University New York, NY
M.S. in Mechanical Engineering [GPA: 4.08] Expected Dec 2025

- Concentration: Robotics and Controls
- Relevant Coursework: Robot Learning, Model Predictive and Optimal Control, Reinforcement Learning, Applied Robotics Algorithms, Data Science & Machine Learning, Probabilistic Robotics, Advanced Manufacturing Processes, Kinematics of Robots and Machines
- Teaching Assistant: Kinematics of Machines and Robots by Dr. Lin (Spring '25), Introduction to Control Theory by Dr. Chbat (Fall '24)

University of California, Los Angeles (UCLA) Los Angeles, CA
B.S. in Mechanical Engineering [GPA: 3.72] Jun 2024

- Technical Breadth: Computer Science
- Relevant Coursework: Data Structures and Algorithms in C++, Digital Control Systems & Design, Computer-Aided Design, Manufacturing Processes, Linear Algebra, Discrete Mathematics, Electrical Circuits Analysis, Thermodynamics, Heat Transfer, Fluid Dynamics

EXPERIENCE

Columbia University New York, NY
Graduate Research on Learning-Adaptive Control Jan 2025 - Present

- Researching Learning-Adaptive Control methods based on Dr. Homayoon Beigi's work, with the goal of implementing and potentially modernizing these algorithms using contemporary neural network approaches
- Designed and built a four-wheeled autonomous robot platform powered by Raspberry Pi and ROS2, establishing the hardware foundation necessary for implementing and testing various autonomous algorithms
- Developed sensor integration framework combining depth camera data with quadrature motor encoders for state estimation, creating a modular architecture supporting plug-and-play experimentation with different sensor configurations
- Formulated implementation strategies for learning-adaptive controllers and prepared comparative analysis frameworks to benchmark performance against traditional PID controllers for trajectory tracking and error minimizing

+90 3D Digital Factory Istanbul, TR
Research&Development Intern Jul 2023 - Sep 2023

- Designed and led end-to-end production of innovative keychains with movable components using SolidWorks and SLS technology on Stratasys H350, coordinating with the Rapid Prototyping team for client demonstrations
- Initiated design of an automated SLA post-processing machine, devising prototype separation mechanisms and modeling key components projected to increase production efficiency
- Conducted comprehensive market research on SLA post-processing systems to support R&D strategy for presentation to the Scientific and Technological Research Council of Turkiye (TUBITAK)

PricewaterhouseCoopers (PwC) Istanbul, TR
ERP Assurance Intern Jun 2023 - Jul 2023

- Collaborated with ERP Sales team on digital transformation for a leading Turkish automotive parts manufacturer, applying engineering optimization methods to complex business processes
- Analyzed client's multi-channel sales operations and implemented SAP modules streamlining order processing and improved operational efficiency
- Facilitated and documented daily client meetings to align ERP transformation strategies with business goals, contributing to a proposal for an automated warehouse management model utilizing smart barcodes

Tur-Bo Jet Products Rosemead, CA
Mechanical Engineering Intern Jun 2022 - Aug 2022

- Created CAD designs for a mechanical butterfly check valve and assisted with its production and assembly, learning quality control processes and engineering specification implementation
- Migrated over 1,000 company design files to SolidWorks PDM cloud system, performing data integrity checks and organizing technical documentation

SKILLS

- Programming Languages: Python, C++, MATLAB & Simulink, SQL | Engineering Software: SolidWorks, Creo, AutoCAD, Catia
- Robotics: ROS/ROS2, SLAM, Gazebo, OpenCV | Systems: Linux, Git, SAP ERP | AI/ML: PyTorch, TensorFlow/Keras
- Manufacturing: Additive (FDM, SLA, SLS), CNC Programming, Manual Machining (Mill, Lathe), Laser Cutting, Soldering

PROJECTS

Automated Pill Dispenser - UCLA Capstone

- Led 6-person team in building and prototyping an automated pill dispenser achieving 95% dispensing reliability across varied pill sizes, while managing $500 budget
- Integrated Arduino/Raspberry Pi systems to manage 16 servo motors with redundant failure mechanisms, developing a modular design with user-friendly interface
- Developed multi-iteration hopper system with vibration motors and IR sensors, enabling precise single-pill dispensing through iterative design and testing