USC Viterbi School of Engineering

EE 599, Learning and Control for Safety-Critical Robotic Systems

Units: 04

Term: Spring 2023
Day—Time: MW, 4-5:30pm
Location: TBD

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Course Description

Machine learning has led to tremendous progress in domains such as computer vision, speech recognition, and natural language processing. Fueled by these advances, machine learning approaches are now being explored to develop intelligent physical systems that can operate reliably in unpredictable environments. These include not only robotic systems such as autonomous cars and drones, but also large-scale transportation and energy systems. However, learning techniques widely used today are extremely data hungry and lack the necessary mathematical framework to provide guarantees on correctness, causing safety concerns as data-driven physical systems are integrated in our society.

The course covers the mathematical foundations of dynamical system safety analysis and modern algorithmic approaches for robotic decision making in safety-critical contexts. The focus is on safe robot learning, paying special attention to robot model uncertainty and ensuring robot safety under vision and perception-based sensors.

The course will start with an overview of background material from relevant subfields: control theory, machine learning, and robotics. This will be followed by advanced techniques (reachability analysis, Lyapunov and barrier functions, etc.) in this area. These advanced techniques will also be demonstrated via reviewing recent research papers that develop and validate them on a variety of robotic applications, including navigation and manipulation. The course will conclude with an overview of recent work in ensuring and updating safety guarantees while learning, especially in the presence of vision and perception sensors. Project work as part of the course will provide a flavor of research in this new emerging area. The course is primarily intended for MS and PhD students in Robotics, Controls, Machine Learning, and Communications and Signal Processing Areas.

Learning Objectives

1. Providing students a review of the current state of safe control of autonomous systems and robots.
2. To provide a platform for students to explore projects related to this area.
3. Providing students an overview of recent advances in safe learning for robotic systems.
4. To introduce students to new research directions for safety-critical control.

Prerequisite(s): Students are recommended to have some background in control theory and/or reinforcement learning.

Co-Requisite (s): N/A

Concurrent Enrollment: course(s) that must be taken simultaneously: N/A

Recommended Preparation: EE 445 (Introduction to robotics), EE 585 (Linear system theory)

Course Notes

Grading Type: letter grade

The course is Web-Enhanced **(Blackboard)**.

Syllabus, homeworks and other class information will be posted on Blackboard.

Technological Proficiency and Hardware/Software Required

Students will be assumed to have basic programming skills.

Required Readings and Supplementary Materials

Required textbook: There will be no required textbook. Course will be based on seminal papers from the past, recent papers on active areas of research, and technical reports. Lectures will cover selected material drawn from some of the additional texts listed below.

Additional recommended text:

1. *Control System Design: An Introduction to State-Space Methods* by B. Friedland 1986. [Friedland86]
2. *Dynamic Non-cooperative Game Theory* by T. Başar and G. J. Olsder. SIAM Series in Classics in Applied Mathematics Philadelphia,1999. [Basar99]
3. *Reinforcement Learning and Optimal Control* by *D. P. Bertsekas, Athena Scientific, 2019. [Bertsekas19]*

Description and Assessment of Assignments

- ***Programming Assignments:*** Students will be assigned four programming assignments. The assignments will consist of solving problems based on the lecture topics discussed at the beginning of the course and will sometimes include a "research-oriented" problem to stimulate and probe students' creativity. Programming assignments will contrast different methods for safely controlling autonomous systems on the same set of environments, and will enable students to understand the trade-offs between different techniques.
- ***Class Presentation:*** Students will present papers (after an overview provided by the instructor). Paper presentations will be followed by open discussions. Students will be graded based on their presentations.
- ***Paper Reviews:*** Students will write reviews for a subset of papers that are being read in the course.
- ***Course Project:*** In addition, students will be required to work on a course project in groups of 2-3. Projects will involve designing safety controllers in simulation (and possibly but not required to) on real-robot platforms. Students will write a project proposal, present their findings in an oral presentation, and write a conference style paper. There will be multiple project milestones along the way to guide progress. Instructor will provide feedback on the various project milestones.

Grading Breakdown

Assignment	**% of Grade**	
Programming Assignments	40%	
Class Presentation	15%	
Paper Reviews	15%	
Course Project	30%	
TOTAL	100%	

Assignment Submission Policy

Homework to be submitted in class on the due date. Late homeworks will not be accepted unless prior approval for late submission has been obtained.

Additional Policies

Attendance of the lectures is expected.

Course Schedule: A Weekly Breakdown

Week	Topic & Research Papers
1	Scope of the course, outline of topics to be covered. Autonomous Systems and Safety 101. Summary of recent trends in safety in robotics.
	Part 1: Background
2	Dynamical systems review: modeling robotic systems as dynamical systems. - Reference: Chapter 2 of [Friedland86]
	Homework#1 assigned.
3	Controller design for known dynamical systems: optimal control problem, overview of dynamic programming and model predictive control. - Reference: Chapter 1 of [Bertsekas 19]
4	Safety analysis of dynamical system: safety as a reachability problem, Hamilton-Jacobi reachability. - Reference: Chapter 8 of [Basar99]
	Homework#1 due. *Homework#2 assigned.*
5	Safety analysis of dynamical system: computation of reachable sets.
6	Case studies in safety-critical robotics: robust walking, autonomous driving, and safe airspace design.
7	Structured and unstructured uncertainty models. Introduction to learning-based control.
	Homework#2 due. *Project Ideas Due.*
	Part 2: Learning-based control of robotic systems
8	Model building for unknown systems: indirect and direct learning of models. Sample reading list: - PILCO: A Model-Based and Data-Efficient Approach to Policy Search, ICML 2011. - Deep Reinforcement Learning in a Handful of Trials using Probabilistic Dynamics Models, NIPS 2018. - Goal-Driven Dynamics Learning via Bayesian Optimization, CDC 2017. - A Survey of Iterative Learning Control, IEEE Control Systems Magazine, 2006.
	Homework#3 assigned.

9	Learning for environment constraints and perception: a case study in visual navigation. Sample reading list: - Cognitive Mapping and Planning for Visual Navigation, CVPR 2017 - Beauty and the Beast: Optimal Methods Meet Learning for Drone Racing, ICRA 2019 - Learning to Fly by Crashing, IROS 2018
10	Learning for environment constraints and perception: a case study in robotic manipulation. Sample reading list: - Learning Hand-Eye Coordination for Robotic Grasping with Deep Learning and Large-Scale Data Collection, ISER 2016 - Learning Dexterous In-Hand Manipulation, arXiv - Dex-Net 2.0: Deep Learning to Plan Robust Grasps with Synthetic Point Clouds and Analytic Grasp Metrics, RSS 2017
	Homework#3 due. *Homework#4 assigned.* *Project Proposal (conference-style submission with mock results) due.*
	Part 3: Safe learning for robotic systems.
11	Safety guarantees during learning. Handling unknown safety specifications. Sample reading list: - A General Safety Framework for Learning-Based Control in Uncertain Robotic Systems, TAC 2019. - End-to-End Safe Reinforcement Learning through Barrier Functions for Safety-Critical Continuous Control Tasks, arXiv 2019. - Safe Model-based Reinforcement Learning with Stability Guarantees, arXiv 2017.
12	Updating safety assurances online. Handling partially observable safety specifications. Sample reading list: - Reachability-Based Safety Guarantees Using Efficient Initializations, CDC 2019. - An Efficient Reachability-Based Framework for Provably Safe Autonomous Navigation in Unknown Environments, CDC 2019.
	Homework#4 due.
13	Safety assurances for perception-driven robotic systems. Sample reading list: - Compositional Falsification of Cyber-Physical Systems with Machine Learning Components, Journal of Automated Reasoning 2019 - Formal Specification for Deep Neural Networks, arXiv 2018 - Verification of Image-based Neural Network Controllers Using Generative Models, arXiv 2021
14	Conclusions and Future Outlook

15	*Final Project Presentations and Conference-style Paper Due.*

Statement on Academic Conduct and Support Systems

Academic Conduct

Plagiarism – presenting someone else's ideas as your own, either verbatim or recast in your own words – is a serious academic offense with serious consequences. Please familiarize yourself with the discussion of plagiarism in *SCampus* in Section 11, *Behavior Violating University Standards*https://scampus.usc.edu/1100-behavior-violating-university-standards-and-appropriate-sanctions/. Other forms of academic dishonesty are equally unacceptable. See additional information in *SCampus* and university policies on scientific misconduct, http://policy.usc.edu/scientific-misconduct/.

Discrimination, sexual assault, and harassment are not tolerated by the university. You are encouraged to report any incidents to the *Office of Equity and Diversity* http://equity.usc.edu/ or to the *Department of Public Safety* http://capsnet.usc.edu/department/department-public-safety/online-forms/contact-us. This is important for the safety whole USC community. Another member of the university community – such as a friend, classmate, advisor, or faculty member – can help initiate the report, or can initiate the report on behalf of another person. *The Center for Women and Men* http://www.usc.edu/student-affairs/cwm/ provides 24/7 confidential support, and the sexual assault resource center webpage sarc@usc.edu describes reporting options and other resources.

Support Systems

A number of USC's schools provide support for students who need help with scholarly writing. Check with your advisor or program staff to find out more. Students whose primary language is not English should check with the *American Language Institute* http://dornsife.usc.edu/ali, which sponsors courses and workshops specifically for international graduate students. *The Office of Disability Services and Programs* http://sait.usc.edu/academicsupport/centerprograms/dsp/home_index.htmlprovides certification for students with disabilities and helps arrange the relevant accommodations. If an officially declared emergency makes travel to campus infeasible, *USC Emergency Information* *http://emergency.usc.edu/*will provide safety and other updates, including ways in which instruction will be continued by means of blackboard, teleconferencing, and other technology.