USC Viterbi School of Engineering

CSCI 699: Foundations and Algorithms for Intelligent Autonomous Systems

Units: 4.0

Fall 2024 — MonWed — 5:00-6:50PM

Location: GFS 222

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Office: SAL 328
Office Hours: TBD
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Catalogue Description

Autonomous systems; stability and safety certificates via (1) sum-of-squares programming, and (2) learning; logic-constrained control synthesis via (1) feedback control, (2) smoothing-based optimization, (3) mixed integer linear programming, and (4) reinforcement learning

Course Description

Autonomous systems are engineered systems that operate in complex environments without human intervention. Applications can be found in self-driving cars, intelligent transportation, and robotics, e.g., to control mobile robot fleets to deliver food in Santa Monica. These applications require autonomous systems to exhibit intelligent behavior. Specifically, these systems have to satisfy complex performance requirements (e.g., delivering food in a pre-defined order), be reactive (e.g., react to traffic), and be safe (e.g., avoiding collisions with pedestrians). In this course, **we aim to understand how to design algorithms for intelligent autonomous systems** that provably result in the satisfaction of such requirements.

Autonomous systems research has its foundations in systems and control theory. Systems and control theory deals with control of dynamical systems but is limited in scope by only dealing with simple stability and invariance specifications. Formal methods are mathematical techniques for the specification, design, and verification of software and hardware systems. These techniques are formal as system specifications are grounded in mathematical logic that can express intelligent system behavior and that allow for a formal deduction of system correctness in that logic. Specifically, temporal logics are used as they extend Boolean logic with temporal modalities to express truly complex spatial and temporal system requirements. Over the past decade, a new community has formed that works at the intersection of formal methods and systems & control theory to design intelligent autonomous systems that satisfy temporal logic specifications.

In this course, we will study **foundations from the fields of systems and control theory (system models, stability, forward invariance, control theory, learning in control) and formal methods (system abstractions, temporal logics, temporal/spatial robustness, reactive synthesis)**. We will use tools from these two fields to develop formal control design techniques that result in intelligent behavior of autonomous systems. While we put a strong emphasis on the foundations of intelligent autonomy, we will put equal emphasis on computational aspects (using sum-of-squares programming, mixed integer programming, satisfiability modulo theory solvers, among others). The course will also contain lectures on **recent and emerging topics, such as the use of large language models**. The final part of the course will contain a **course project** in which students can implement the learned tools on an autonomous systems simulator of their choice.

Intended audience: any graduate student broadly interested in autonomous systems research, and more specifically with interests in control & dynamical systems, formal methods, and optimization.

Learning Objectives

After taking the course, students will know basic concepts related to analyzing and designing autonomous systems. Particularly, the students will learn basic concepts from systems and control theory (system models, stability, forward invariance, control theory, learning in control) and formal methods (system abstractions, temporal logics, temporal/spatial robustness, reactive synthesis). The students will further learn how to bridge ideas from these two fields and be able to design formal control algorithms using optimization techniques such as sum-of-squares programming, mixed integer linear programming, and satisfiable modulo theory solvers. Students will get the opportunity to apply these techniques to an autonomous system of their choice. Throughout the course, students will learn to critically assess limitations of the learned techniques.

Recommended Preparation

Due to the interdisciplinary nature of the topic, the course will provide introductions to the fields of systems & control theory and formal methods. As such, no strict prerequisites are required. After all, the most important prerequisite is the student's interest in the topic, motivation, and commitment to learning.

Nonetheless, some background in systems theory, optimization, and/or logic may be helpful, e.g., as (partially) taught in

- optimization for information and data sciences (EE 588),
- linear systems theory (EE 585) and/or nonlinear control systems (EE 587),
- introduction to artificial intelligence (CSCI 360).

Course Notes

The final grade will be determined based on attendance, three homeworks, and a course project. Lecture notes and slides will be posted online after each lecture. The lectures will not be recorded.

Technological Proficiency and Hardware/Software Required

Course homeworks and projects require standard computing software (Matlab, Python, C++).

Required Readings and Supplementary Materials

Required readings and supplementary materials will be announced during the course.

Description of Assignments and How They Will Be Assessed

The three homeworks will contain problem sets based on the given lectures. The course project is a research project, i.e., it is the students responsibility to i) define a problem with a scope aligned with the course topic, and ii) to propose a viable solution and illustrate its success. It is required that students implement their solution on an autonomous systems simulator of their choice (the course instructor will provide suggestions on suitable simulators). A final project report has to be submitted and a 10-15 minute research presentation has to be given in front of the class. The course project can be performed in teams of at most two students.

Grading Breakdown

Assignment	Points	% of Grade
Homework 1	20	20
Homework 2	20	20
Homework 3	20	20
Course Project	40	40
TOTAL	100	100

Assignment Submission Policy

Instructed in first lecture.

Attendance

Mandatory attendance.

Academic Integrity

This course will follow the expectations for academic integrity as stated in the USC Student Handbook. The general USC guidelines on Academic Integrity and Course Content Distribution are provided in the subsequent “Statement on Academic Conduct and Support Systems” section.

Please ask the instructor [and/or TA(s)] if you are unsure about what constitutes unauthorized assistance on an exam or assignment, or what information requires citation and/or attribution.

You may not record this class without the express permission of the instructor and all other students in the class. Distribution of any notes, recordings, exams, or other materials from a university class or lectures — other than for individual or class group study — is prohibited without the express permission of the instructor.

Use of Generative AI in this Course

Generative AI is not permitted: Since creating, analytical, and critical thinking skills are part of the learning outcomes of this course, all assignments should be prepared by the student working individually or in groups as described on each assignment. Students may not have another person or entity complete any portion of the assignment. Developing strong competencies in these areas will prepare you for a competitive workplace. Therefore, using AI-generated tools is prohibited in this course, will be identified as plagiarism, and will be reported to the Office of Academic Integrity.

Course Schedule: A Weekly Breakdown

	Topics/Daily Activities	**Readings and Homework**	**Deliverable/ Due Dates**

Week 1	Course Overview, Dynamical Systems (system models, system properties: stability and forward invariance)	[1], [2], [3]	
Week 2	Stability and Forward Invariance Certificates (discr./cont. time Lyapunov and barrier functions)	[1], [2], [3]	
Week 3	Computing Certificates via: (1) sum-of-squares programming, and (2) learn & verify with satisfiable modulo theory solver	[4], [5], [6], [7], [8], [9]	
Week 4	Nonlinear Feedback Control (control barrier and control Lyapunov functions)	[2], [3], [10], [11], [12] **Homework 1 out (on Friday)**	
Week 5	Introduction to Formal Methods: Linear Temporal Logic, Model Checking	[13], [14]	**Homework 1 (on Friday)**
Week 6	Signal Temporal Logic, spatial and temporal robustness	[15], [16], [17]	
Week 7	Formal Control Synthesis via: (1) Time-Varying Control Barrier Functions, and (2) Smoothing-based optimization	[3], [18], [19], [20]	
Week 8	Formal Control Synthesis via: (3) Mixed Integer Linear Programming	[21], [22], [23] **Homework 2 out (on Friday)**	
Week 9	Project Discussions		**Homework 2 (on Friday)**
Week 10	Formal Control Synthesis under Uncertainty	[24], [25], [26], [27]	
Week 11	Formal Control Synthesis for Multi-Agent Systems	[3], [28], [29], [30], [31], [32], [33], [34] **Homework 3 out (on Friday)**	
Week 12	Formal Control Synthesis via: (4) Reinforcement Learning	[35], [36], [37]	**Homework 3 (on Friday)**
Week 13	Recent and Emerging Topics (guest lectures)		
Week 14	Recent and Emerging Topics (large language models and formal methods)		
Week 15	Project Days		**Project Presentation**
FINAL	**Final Project Report**		Due on the university-scheduled date of the final exam.

References

[1] “Linear System Theory and Design” by Chi-Tsong Chen
[2] “Nonlinear Systems” by Hassan Khalil
[3] “Formal Methods for Multi-Agent Feedback Control Systems” by Lars Lindemann and Dimos V. Dimarogonas
[4] “Semidefinite Programming Relaxations for Semialgebraic Problems” by Pablo Parillo
[5] “Introducing SOSTOOLS: A General Purpose Sum Of Squares Programming Solver” by Stephen Prajna, Antonis Papachristodoulou, and Pablo Parillo
[6] “Safety Verification of Hybrid Systems using Barrier Certificates” by Stephen Prajna and Ali Jadbabaie
[7] “On the construction of Lyapunov functions using the sum of squares decomposition” by Antonis Papachristodoulou and Stephen Prajna
[8] “Formal Synthesis of Lyapunov Neural Networks” by Alessandro Abate, Daniele Ahmad, Mirco Giacobbe, and Andrea Peruffo
[9] “Simulation-guided Lyapunov Analysis for Hybrid Dynamical Systems” by James Kapinski, Jyotirmoy V. Deshmukh, Sriram Sankaranarayanan, and Nikos Aréchiga
[10] “A 'universal' construction of Artstein' s theorem on nonlinear stabilization” by Eduardo Sontag
[11] “Control Barrier Functions: Theory and Applications” by Aaron D. Ames, Samuel Coogan, Magnus Egerstedt, Gennaro Notomista, Koushil Sreenath, and Paulo Tabuada
[12] “Learning Control Barrier Functions from Expert Demonstrations” by Alexander Robey, Haimin Hu, Lars Lindemann, Hanwen Zhang, Dimos V Dimarogonas, Stephen Tu, and Nikolai Matni
[13] “Principles of Model Checking” by Christel Baier and Joest Pieter Katoen
[14] “Formal Methods for Discrete-Time Systems” by Calin Belta, Boyan Yordanov, and Ebru Gol
[15] “Robust Satisfaction of Temporal Logic over Real-Valued Signals” by Alexandre Donze and Oded Maler
[16] "Robustness of Temporal Logic Specifications for Continuous-Time Signals” by Georgios Fainekos and George Pappas
[17] “Temporal Robustness of Stochastic Signals” by Lars Lindemann, Alena Rodionova, and George Pappas
[18] “Control Barrier Functions for Signal Temporal Logic Tasks” by Lars Lindemann and Dimos Dimarogonas
[19] “Smooth operator: Control using the smooth robustness of temporal logic” by Yash Vardhan Pant, Houssam Abbas, and Rahul Mangharam
[20] “A Smooth Robustness Measure of Signal Temporal Logic for Symbolic Control” by Yann Gilpin, Vince Kurtz, and Hai Lin
[21] “Model Predictive Control for Signal Temporal Logic Specification” by Vasumathi Raman et al.
[22] “Time-robust control for STL Specifications” by Alena Rodionova, Lars Lindemann, Manfred Morari, and George Pappas

[23] “Formal Methods for Control Synthesis: An Optimization Perspective” by Calin Belta and Sadra Sadraddini
[24] “Reactive Synthesis from Signal Temporal Logic Specifications” by Vasumathi Raman, Alexandre Donzé, Dorsa Sadigh, Richard M. Murray, and Sanjit A. Seshia
[25] “Robust temporal logic model predictive control” by Sadra Sadraddini and Calin Belta
[26] “Control design for risk-based signal temporal logic specifications” by Sleiman Safaoui, Lars Lindemann, Dimos V Dimarogonas, Iman Shames, and Tyler H Summers
[27] “Safe control under uncertainty with probabilistic signal temporal logic” by Dorsa Sadigh and Ashish Kapoor
[28] “Control Barrier Functions for Multi-Agent Systems under Conflicting Local Signal Temporal Logic Tasks” by Lars Lindemann and Dimos Dimarogonas
[29] “Barrier Function Based Collaborative Control of Multiple Robots under Signal Temporal Logic Tasks" by Lars Lindemann and Dimos Dimarogonas
[30] “SpaTeL: a novel spatial-temporal logic and its applications to networked systems” by Iman Haghighi, Austin Jones, Zhaodan Kong, Ezio Bartocci, Radu Gros, and Calin Belta
[31] “Robotic Swarm Control from Spatio-Temporal Specifications” by Iman Haghighi, Sadra Sadraddini, and Calin Belta
[32] “Distributed Communication-aware Motion Planning for Multi-agent Systems from STL and SpaTeL Specifications” by Zhiyu Liu, Bo Wu, Jin Dai, and Hai Lin
[33] “Monitoring mobile and spatially distributed cyber-physical systems” by Ezio Bartocci, Luca Bortolussi, Michele Loreti, and Laura Nenzi
[34] “A Logic for Monitoring Dynamic Networks of Spatially-distributed Cyber-Physical Systems” by Laura Nenzi, Ezio Bartocci, Luca Bortolussi, and Michele Loreti
[35] “Q-learning for robust satisfaction of signal temporal logic specifications” by Derya Aksaray, Austin Jones, Zhaodan Kong, Mac Schwager, and Calin Belta
[36] “Tractable Reinforcement Learning of Signal Temporal Logic Objectives” by Harish Venkataraman, Derya Aksaray, and Peter Seiler
[37] “Model-Free Reinforcement Learning for Spatiotemporal Tasks Using Symbolic Automata” by Anand Balakrishnan, Stefan Jaksić, Edgar A. Aguilar, Dejan Nicković, and Jyotirmoy V. Deshmukh

Statement on Academic Conduct and Support Systems

Academic Integrity:
The University of Southern California is a learning community committed to developing successful scholars and researchers dedicated to the pursuit of knowledge and the dissemination of ideas. Academic misconduct, which includes any act of dishonesty in the production or submission of academic work, comprises the integrity of the person who commits the act and can impugn the perceived integrity of the entire university community. It stands in opposition to the university's mission to research, educate, and contribute productively to our community and the world.

All students are expected to submit assignments that represent their own original work, and that have been prepared specifically for the course or section for which they have been submitted. You may not submit work written by others or "recycle" work prepared for other courses without obtaining written permission from the instructor(s).

Other violations of academic integrity include, but are not limited to, cheating, plagiarism, fabrication (e.g., falsifying data), collusion, knowingly assisting others in acts of academic dishonesty, and any act that gains or is intended to gain an unfair academic advantage.

The impact of academic dishonesty is far-reaching and is considered a serious offense against the university. All incidences of academic misconduct will be reported to the Office of Academic Integrity and could result in outcomes such as failure on the assignment, failure in the course, suspension, or even expulsion from the university.

For more information about academic integrity see the student handbook or the Office of Academic Integrity's website, and university policies on Research and Scholarship Misconduct.

Please ask your instructor if you are unsure what constitutes unauthorized assistance on an exam or assignment, or what information requires citation and/or attribution.

Course Content Distribution and Synchronous Session Recordings Policies
USC has policies that prohibit recording and distribution of any synchronous and asynchronous course content outside of the learning environment.

Recording a university class without the express permission of the instructor and announcement to the class, or unless conducted pursuant to an Office of Student Accessibility Services (OSAS) accommodation. Recording can inhibit free discussion in the future, and thus infringe on the academic freedom of other students as well as the instructor. (Living our Unifying Values: The USC Student Handbook, page 13).

Distribution or use of notes, recordings, exams, or other intellectual property, based on university classes or lectures without the express permission of the instructor for purposes other than individual or group study. This includes but is not limited to providing materials for distribution by services publishing course materials. This restriction on unauthorized use also applies to all information, which had been distributed to students or in any way had been displayed for use in relationship to the class, whether obtained in class, via email, on the internet, or via any other media. (Living our Unifying Values: The USC Student Handbook, page 13).

Students and Disability Accommodations:
USC welcomes students with disabilities into all of the University's educational programs. The Office of Student Accessibility Services (OSAS) is responsible for the determination of appropriate accommodations for students who encounter disability-related barriers. Once a student has completed the OSAS process (registration, initial appointment, and submitted documentation) and accommodations are determined to be reasonable and appropriate, a Letter of Accommodation (LOA) will be available to generate for each course. The LOA must be given to each course instructor by the student and followed up with a discussion.

This should be done as early in the semester as possible as accommodations are not retroactive. More information can be found at osas.usc.edu. You may contact OSAS at (213) 740-0776 or via email at osasfrontdesk@usc.edu.

Support Systems:

Counseling and Mental Health - (213) 740-9355 – 24/7 on call
Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention.

988 Suicide and Crisis Lifeline - 988 for both calls and text messages – 24/7 on call
The 988 Suicide and Crisis Lifeline (formerly known as the National Suicide Prevention Lifeline) provides free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week, across the United States. The Lifeline is comprised of a national network of over 200 local crisis centers, combining custom local care and resources with national standards and best practices. The new, shorter phone number makes it easier for people to remember and access mental health crisis services (though the previous 1 (800) 273-8255 number will continue to function indefinitely) and represents a continued commitment to those in crisis.

Relationship and Sexual Violence Prevention Services (RSVP) - (213) 740-9355(WELL) – 24/7 on call
Free and confidential therapy services, workshops, and training for situations related to gender- and power-based harm (including sexual assault, intimate partner violence, and stalking).

Office for Equity, Equal Opportunity, and Title IX (EEO-TIX) - (213) 740-5086
Information about how to get help or help someone affected by harassment or discrimination, rights of protected classes, reporting options, and additional resources for students, faculty, staff, visitors, and applicants.

Reporting Incidents of Bias or Harassment - (213) 740-5086 or (213) 821-8298
Avenue to report incidents of bias, hate crimes, and microaggressions to the Office for Equity, Equal Opportunity, and Title for appropriate investigation, supportive measures, and response.

The Office of Student Accessibility Services (OSAS) - (213) 740-0776
OSAS ensures equal access for students with disabilities through providing academic accommodations and auxiliary aids in accordance with federal laws and university policy.

USC Campus Support and Intervention - (213) 740-0411
Assists students and families in resolving complex personal, financial, and academic issues adversely affecting their success as a student.

Diversity, Equity and Inclusion - (213) 740-2101
Information on events, programs and training, the Provost's Diversity and Inclusion Council, Diversity Liaisons for each academic school, chronology, participation, and various resources for students.

USC Emergency - UPC: (213) 740-4321, HSC: (323) 442-1000 – 24/7 on call
Emergency assistance and avenue to report a crime. Latest updates regarding safety, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible.

USC Department of Public Safety - UPC: (213) 740-6000, HSC: (323) 442-1200 – 24/7 on call
Non-emergency assistance or information.

Office of the Ombuds - (213) 821-9556 (UPC) / (323-442-0382 (HSC)
A safe and confidential place to share your USC-related issues with a University Ombuds who will work with you to explore options or paths to manage your concern.

Occupational Therapy Faculty Practice - *(323) 442-2850 or* otfp@med.usc.edu
Confidential Lifestyle Redesign services for USC students to support health promoting habits and routines that enhance quality of life and academic performance.