IEEE SMC 2023 Maui, Hawaii


# Tutorial

## Title
Planning and Control with Machine Learning for Autonomous and Robotic Systems

## Abstract
Many robotic systems involve highly nonlinear, complex, and large-scale decision-making problems in safety-critical situations. Stability and safety are often research problems of control theory, while conventional black-box AI approaches lack much-needed robustness, scalability, and interpretability, which are indispensable to designing control and autonomy engines for safety-critical aerospace and robotic systems. However, the existing performance guarantees of black-box AI approaches are inadequate and often times lead to safety compromises. This tutorial session gives a tutorial overview of machine learning control systems with safety and stability guarantees. We will present some recent results using contraction-based incremental stability tools for deriving formal robustness and stability guarantees of various learning-based and data-driven control problems, with some illustrative examples including learning-to-fly control with adaptive meta learning, learning-based swarm control and planning synthesis, and optimal motion planning with stochastic nonlinear dynamics and chance constraints. We will also present recent results on neural-network-based contraction metrics (NCMs) as a stability certificate for safe motion planning and control.

## Duration
2 hours

## Motivation –
Machine learning and AI have been used for achieving autonomy in various aerospace and robotic systems, with or without the presence of human interactions. Many research issues in Systems, Man, and Cybernetics could involve highly nonlinear, complicated, and large-scale decision-making problems in safety-critical situations. However, the existing performance guarantees of black-box AI approaches may not be sufficiently powerful. This talk gives a mathematical overview of our various mathematical tools for achieving safe ML-based control systems for autonomous robots. This is not to argue that these methods are always better than conventional approaches but to provide the SMC community with formal tools to investigate their enhancements with ML systems and limitations.

## Expected audience
Any researchers with some basic knowledge of control systems

**Outline of contents**

- Motivation and Introduction (10 minutes)
- Contraction-based incremental stability tools for deriving formal robustness and stability guarantees of various learning-based and data-driven control problems (30 minutes)
- Learning-to-fly control with adaptive meta learning (20 minutes)
- Learning-based swarm control and planning synthesis and Neural Tree Expansion with Monte Carlo Tree Search (20 minutes)
- Optimal motion planning with stochastic nonlinear dynamics and chance constraints (20 minutes)
- Neural-network-based contraction metrics (NCMs) as a stability certificate for safe motion planning and control (20 minutes)

**Key references**


- H. Tsukamoto, S.-J. Chung, and J.-J. E. Slotine, "**Contraction Theory for Nonlinear Stability Analysis and Learning-based Control: A Tutorial Overview**," *Annual Reviews in Control*, vol. 52, 2021, pp. 135-169. (PDF)
- M. O'Connell*, G. Shi*, X. Shi, K. Azizzadenesheli, A. Anandkumar, Y. Yue, and S.-J, Chung, **"Neural-Fly Enables Rapid Learning for Agile Flight in Strong Winds,"** *Science Robotics*, vol 7, No. 66, May 4, 2022. (Paper)
- G. Shi, W. Hoenig, X. Shi, Y. Yue, and S.-J. Chung, "**Neural-Swarm2: Planning and Control of Heterogeneous Multirotor Swarms using Learned Interactions**," *IEEE Transactions on Robotics*, vol. 38, no. 2, April 2022, pp. 1063-1079. (PDF)
- H. Tsukamoto and S.-J. Chung, "**Learning-based Robust Motion Planning with Guaranteed Stability: A Contraction Theory Approach**," *IEEE Robotics and Automation Letters*, vol. 6, no. 4, Oct. 2021, pp. 6164-6171. (PDF)
- H. Tsukamoto and S.-J. Chung, "**Neural Contraction Metrics for Robust Estimation and Control: A Convex Optimization Approach**," *IEEE Control Systems Letters*, vol. 5, no. 1, Jan. 2021, pp. 211-216. (PDF)
- **G. Shi*, X. Shi*, M. O'Connell***, R. Yu, K. Azizzadenesheli, A. Anandkumar, Y. Yue, and S.-J. Chung, "**Neural Lander: Stable Drone Landing Control using Learned Dynamics**," *Proc. 2019 IEEE International Conference on Robotics and Automation (ICRA)*, May 20-24, 2019, Montréal, Canada. (Extended version PDF)

*These authors contributed equally to this work.


**List of speakers**

**Soon-Jo Chung** is Bren Professor of Control and Dynamical Systems in the California Institute of Technology. Prof. Chung is also a Senior Research Scientist of the NASA Jet Propulsion Laboratory. Prof. Chung received the S.M. degree in Aeronautics and Astronautics and the Sc.D. degree in Estimation and Control with a minor in Optics from MIT in 2002 and 2007, respectively. He received the B.S. degree in Aerospace Engineering from KAIST in 1998 (school class rank 1/120). From 2009 to 2016, Prof. Chung was an associate professor and an assistant professor at the University of Illinois at Urbana-Champaign. Prof. Chung was a Member of the Guidance & Control Analysis Group in the Jet Propulsion Laboratory as a JPL Summer Faculty Research Fellow and Faculty Affiliate working on distributed small satellites during the summers of 2010-2014.

Professor Chung's research focuses on distributed spacecraft systems, space autonomous systems, and aerospace robotics, and in particular, on the theory and application of control, estimation, learning-based control and planning, and navigation of autonomous space and air vehicles. He is the recipient of the UIUC Engineering Dean's Award for Excellence in Research, the Arnold Beckman Faculty Fellowship of the U of Illinois Center for Advanced Study, the AFOSR Young Investigator Program (YIP) award, the NSF CAREER award, a 2020 Honorable Mention for the IEEE Robotics and Automation Letters Best Paper Award, three best conference paper awards (2015 AIAA GNC, 2009 AIAA Infotech, 2008 IEEE EIT), and five best student paper awards. He also received multiple teaching awards including the UIUC List of Teachers Ranked as Excellent and the instructor/advisor for the 1st place winning team of the AIAA International Student Conference and the AIAA Undergraduate Team Space Design Competition. The work and robots of Prof. Chung's and his colleagues have received extensive media coverage. The robotic bat, called Bat Bot, was placed in a special exhibit at the Museum of Arts and Crafts in Hamburg along with the work of virtuosos like Albrecht Dürer and Alexander von Humboldt. Prof. Chung is an Associate Editor of the IEEE Transactions on Automatic Control and the AIAA Journal of Guidance, Control, and Dynamics. He was an Associate Editor of the IEEE Transactions on Robotics, and the Guest Editor of a Special Section on Aerial Swarm Robotics published in the IEEE Transactions on Robotics. He is an Associate Fellow of AIAA.
Curriculum Vitae: https://caltech.app.box.com/s/atuettgqasypno6qcospa0juf4z80mtz

**Hiroyasu Tsukamoto** is an incoming assistant professor of Aerospace Engineering at the University of Illinois Urbana-Champaign and is currently a Ph.D. student at the Department of Aerospace, California Institute of Technology. His research interest includes deep learning-based robust optimal control, estimation, and motion planning for general nonlinear systems, aerial swarms, and general autonomous aerospace & robotic systems (Google Scholar: https://scholar.google.com/citations?user=G9iATfcAAAAJ&hl=ja). His work on contraction theory for machine learning is featured at the IEEE Conference on Decision and Control and summarized as an invited tutorial paper at the Annual Reviews in Control (https://sites.google.com/view/contractiontheory/). He has also worked on designing GNC schemes for the interstellar object exploration project (https://youtu.be/4KPaqSpFMEU) and the CASTOR project at NASA JPL. A two-minute visual summary of his research can be found here (https://youtu.be/upXKc7X5OZA). CV: https://drive.google.com/file/d/1XBAX-EY46RTgaOutegW8RmILrSiEt3q1/view?usp=sharing

**Guanya Shi** is an incoming (Fall 2023) Assistant Professor in the Robotics Institute and the School of Computer Science at Carnegie Mellon University (CMU). Dr. Shi completed his Ph.D. in 2022 from Caltech, advised by Soon-Jo Chung and Yisong Yue. Guanya Shi received a B.E. from Tsinghua University in 2017. He was awarded the Simoudis Discovery Prize and the Ben P.C. Chou Doctoral Prize at Caltech and was named a Rising Star in Data Science by the University of Chicago. Dr. Shi is currently a postdoctoral scholar in the Paul G. Allen School of Computer Science and Engineering (CSE) at the University of Washington with Byron Boots. Dr. Shi is broadly interested in the intersection of machine learning and control theory, spanning the entire spectrum from theory to real-world agile robotics. CV: https://drive.google.com/file/d/1zwjK26dgouy9diFvVhvJ1fTsoCzi87j_/view