FACULTY MENTOR
Yang Zheng

PROJECT TITLE
Predictive Control for Autonomous Vehicles in Mixed Traffic Systems

PROJECT DESCRIPTION
The emergence of connected and autonomous vehicles (CAVs) promises to revolutionize road transportation systems. In particular, the advancements of CAVs offer new opportunities for traffic control, where autonomous vehicles can receive information from other traffic participants and act as mobile actuators to influence traffic flow internally, thus increasing efficiency and safety on public roads. Both small-scale real-world experiments (e.g., https://youtu.be/2mBjYZTeaTc) and large-scale numerical simulations (e.g., https://soc-ucsd.github.io/mixed-traffic/) have shown promising results. Recent work has also started to build a solid theoretical understanding of the influence of CAVs in mixed traffic involving both autonomous vehicles and human-driven vehicles.

In this project, the student will begin by reading some existing analysis and control methods of autonomous vehicles in mixed traffic, e.g. [1]-[3], and the references therein. Then the student will need to explore new control methods, especially optimization-based predictive control, for regulating autonomous vehicles in mixed traffic. Another major focus will be the implementation of the analysis and control methods in Matlab or Python. A range of numerical demonstrations will be carried out in this project too.

This project will be in person.

INTERNS NEEDED
2 Students

PREREQUISITES
- A strong background in linear algebra and optimization and good programming skills (Python, Matlab, Julia, etc.) are required.

[1] Zheng, Yang, Jiawei Wang, and Keqiang Li. ""Smoothing traffic flow via control of autonomous vehicles."" IEEE Internet of Things Journal 7.5 (2020): 3882-3896.
[2] Wang, J., Zheng, Y., Chen, C., Xu, Q., & Li, K. (2021). Leading cruise control in mixed traffic flow: System modeling, controllability, and string stability. IEEE Transactions on Intelligent Transportation Systems.
[3] Wang, J., Zheng, Y., Li, K., & Xu, Q. (2022). DeeP-LCC: Data-enabled predictive leading cruise control in mixed traffic flow. arXiv preprint arXiv:2203.10639.
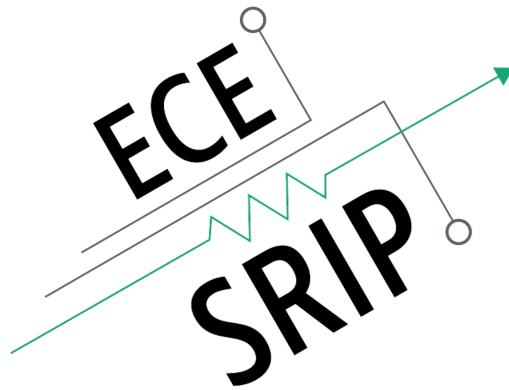
FACULTY MENTOR

Yang Zheng

PROJECT TITLE

Semidefinite Relaxation for Machine Learning Problems

PROJECT DESCRIPTION

Neural networks (NNs) have shown promising results in many applications, including image recognition, natural language processing, and robotic control. Some recent work has also incorporated Deep NNs (DNNs) into safety-critical systems, like autonomous driving. Although DNNs obtain unprecedented empirical success, their opacity poses significant challenges, especially in safety-critical systems. Therefore, it is desirable to provide rigorous analysis and guarantees about the behaviors of DNNs, either as a standalone component or as an integrated component in a feedback loop.

One interesting problem is the robustness verification of NNs, which aims to find adversarial examples that reveal ways NNs can fail or certify no adversarial examples exist. The input/output behavior of NNs is nonlinear and non-convex, making it hard to solve verification problems exactly. A variety of convex relaxation techniques, such as interval bound propagation, linear programs (LP) [1]-[3], and semidefinite programs [4], have been proposed to derive an approximated solution. It is shown empirically that semidefinite relaxation can offer much tighter bounds than LP relaxations [4], but semidefinite relaxation, in general, suffers from the scalability issue. Currently, the techniques in [4] can only deal with small NNs.
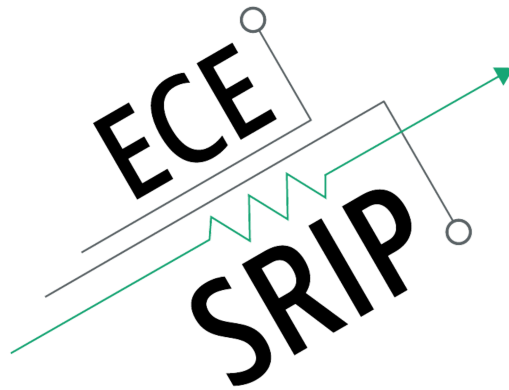
This project aims to develop efficient semidefinite relaxation for NN verification. The starting point is to exploit the inherent neural network structure (e.g., cascading structure) to develop layer-wise relaxations; a related topic is chordal decomposition (see [5][6]). Several possible objectives can be targeted, including

- The development of efficient methods for verifying NNs via semidefinite relaxation (layer-wise decomposition and tightening by LP cuts etc.)
- The development of strategies to balance relaxation quality and solution efficiency for semidefinite relaxation
- The implementation of a verification toolkit for the verification of NNs
- Numerical comparison with the existing toolkits.

This project will be in person.

INTERNS NEEDED
2 Students

PREREQUISITES
- A strong background in linear algebra and optimization and good programming skills (Python, Matlab, Julia, etc.) are required.

[1] Salman, H., Yang, G., Zhang, H., Hsieh, C. J., & Zhang, P. (2019). A convex relaxation barrier to tight robustness verification of neural networks. In Advances in Neural Information Processing Systems (pp. 9835-9846).
[2] Singh, G., Ganvir, R., Püschel, M., & Vechev, M. (2019). Beyond the single neuron convex barrier for neural network certification. In Advances in Neural Information Processing Systems (pp. 15098-15109).
[3] Tjandraatmadja, C., Anderson, R., Huchette, J., Ma, W., Patel, K., & Vielma, J. P. (2020). The convex relaxation barrier, revisited: Tightened single-neuron relaxations for neural network verification. arXiv preprint arXiv:2006.14076.
[4] A. Raghunathan, J. Steinhardt, and P. S. Liang, "Semidefinite relaxations for certifying robustness to adversarial examples," advances in Neural Information Processing Systems, pp. 10877–10887,2018.
[5] Vandenberghe, Lieven, and Martin S. Andersen. "Chordal graphs and semidefinite optimization." Foundations and Trends in Optimization 1.4 (2015): 241-433.
[6] Zheng, Y., Fantuzzi, G., Papachristodoulou, A., Goulart, P., & Wynn, A. (2020). Chordal decomposition in operator-splitting methods for sparse semidefinite programs. Mathematical Programming, 180(1), 489-532.
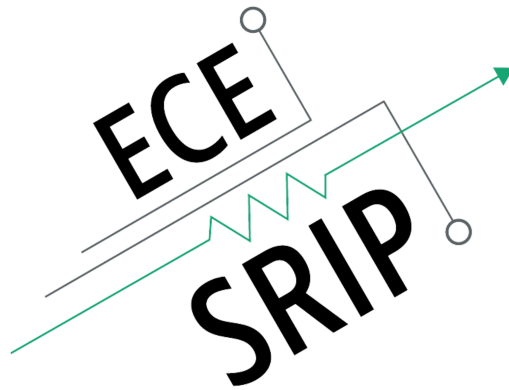
FACULTY MENTOR
Yang Zheng

PROJECT TITLE
Model-Free Learning in Non-Convex Control Problems

PROJECT DESCRIPTION
Many recent studies have started to apply machine learning techniques to the control of unknown dynamical systems. They have achieved impressive empirical results. However, the convergence behavior, statistical properties, and robustness performance of these approaches are often poorly understood due to the nonconvex nature of the underlying control problems. In this project, we are interested in exploring the non-convex optimization landscape of some control problems, e.g., linear quadratic regular (LQR) [1] and linear quadratic Gaussian control (LQG) [2,3]; see [4] for a recent review. This will facilitate the understanding of model-free policy gradient algorithms for classical control problems.

In this project, the student will begin by reading some existing results on model-free optimization for LQR and LQG, e.g., [1]-[4], and the references therein. Then the student will need to explore different aspects of the non-convex landscape properties and develop new first-order optimization methods. Another major focus will be the implementation of the analysis and control methods in Matlab or Python.

This project will be in person.

**INTERNS NEEDED**
1 Student

PREREQUISITES
- A strong background in linear algebra, control engineering, and convex optimization and good programming skills (Python, Matlab, Julia, etc.) are required.

[1] Fazel, M., Ge, R., Kakade, S., & Mesbahi, M. (2018, July). Global convergence of policy gradient methods for the linear quadratic regulator. In International Conference on Machine Learning (pp. 1467-1476). PMLR.
[2] Zheng, Y., Tang, Y., & Li, N. (2021). Analysis of the Optimization Landscape of Linear Quadratic Gaussian (LQG) Control. arXiv preprint arXiv:2102.04393.
[3] Zheng, Y., Sun, Y., Fazel, M., & Li, N. (2022). Escaping High-order Saddles in Policy Optimization for Linear Quadratic Gaussian (LQG) Control. arXiv preprint arXiv:2204.00912.
[4] Hu, B., Zhang, K., Li, N., Mesbahi, M., Fazel, M., & Başar, T. (2022). Towards a Theoretical Foundation of Policy Optimization for Learning Control Policies. arXiv preprint arXiv:2210.04810.
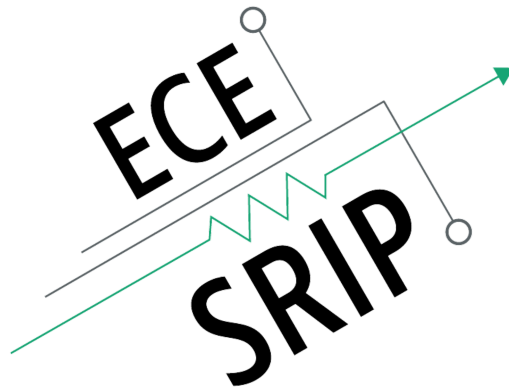
FACULTY MENTOR
Yang Zheng

PROJECT TITLE
Efficient Algorithm Design for Semidefinite Optimization

PROJECT DESCRIPTION
Convex optimization has profound impacts on many problems in control theory, discrete and nonlinear optimization, theoretical computer science, and machine learning. It is a fundamental tool to ensure efficient, resilient, and safe operations of many engineering systems, such as smart power grids, transportation, robotics, and many others. Optimization in these areas often takes the form of conic optimization, especially semidefinite programs. However, the existing interior-point methods for solving semidefinite programs are not very scalable for large-scale problems.

In this project, the student will explore different inner and outer approximation methods to improve the efficiency of solving large-scale semidefinite optimization. One particular focus will be on the balance of approximation quality and numerical efficiency. This project will also focus on efficient first-order algorithm design for the inner and outer approximations of semidefinite optimization. The student will begin with reading some existing methods, e.g., [1-3], and then explore new ideas and implement new algorithms.

This project will be in person.

INTERNS NEEDED
1 Student

PREREQUISITES
● A strong background in linear algebra and optimization and good programming skills (Python, Matlab, Julia, etc.) are required.

[1] Zheng, Y., Sootla, A., & Papachristodoulou, A. (2019). Block factor-width-two matrices and their applications to semidefinite and sum-of-squares optimization. arXiv preprint arXiv:1909.11076.
[2] Ahmadi, A. A., Dash, S., & Hall, G. (2017). Optimization over structured subsets of positive semidefinite matrices via column generation. Discrete Optimization, 24, 129-151.
[3] Zheng, Y., Fantuzzi, G., & Papachristodoulou, A. (2021). Chordal and factor-width decompositions for scalable semidefinite and polynomial optimization. Annual Reviews in Control.