ECE1659H Robust and Optimal Control Project

Winter 2023
Instructor: J. W. Simpson-Porco

Department of Electrical and Computer Engineering
University of Toronto

Project Description

Each student must complete a class project related to robust and/or optimal control. As the project is intended to accommodate a wide variety of student interests and personal learning goals, there are no specific requirements on the style/nature of the investigation. Research students are strongly encouraged to apply course concepts (or related ideas in the literature) to their thesis research. Possible project styles include

(i) a review of a technical paper, including derivation/proof of key results and reproduction of simulations,

(ii) an application case study, applying course results or related results in the literature to a practical example, or

(iii) an attempt at a novel research project, applying course content in a new context or to your thesis research topic.

Unless your project attempts to develop *novel* theoretical results, it *must* contain a simulation component. Broadly, the goals of the project are for you to

(i) learn with breadth, by researching a topic outside the immediate scope of the lecture material,

(ii) learn with depth, by digging into the details for your topic of interest, and

(iii) develop your technical presentation skills, by conveying what you have learned to your colleagues in an oral presentation with a polished presentation deck.

Project Deliverables

There are two deliverables for the project; due dates will be posted on the course homepage.

(i) (15% of project grade) A proposal, maximum 3/4 of a page, giving a brief description of the topic you will investigate. Your proposal must

- state the nature of your particular project (e.g., a technical paper review, a case study, an attempt at original research, etc.)
- explain how the proposed project broadly relates to the material covered in the course, and
- clearly outline the what you will produce as project deliverables (e.g., review of problem formulation, review of key results, extension to some other scenario of interest, testing the method via simulations, etc.).

Your proposal mark will be based on the quality and clarity of your first submitted proposal.

You **must** receive explicit approval from the instructor before proceeding with your project, or you will receive a mark of zero. A revision to your proposal may be required before approval is granted. If you wish to change your project during the course of the work, you **must** prepare a new proposal and receive explicit approval from the instructor, or you will receive a mark of zero.

(ii) (85% of project grade) A 25 minute presentation, plus 5 minutes for questions from the audience. The primary purpose of the presentation is for you to demonstrate that you have developed an expert-level understanding of the material you have chosen for your project, and that you have carefully considered how to best communicate your understanding and educate your colleagues on this topic. This implies that

- you must do the individual work of developing your own understanding of the material, and
- you must externalize this knowledge in your presentation by deciding what are the key concepts, what is important to communicate in 25 minutes and what is not, how should you organize the presentation for maximal educational value to others, and so on.

The presentation will be evaluated based on (a) the slides themselves, and (b) your presentation of the slides. Evaluation criteria may include

- Clarity of problem motivation and description
- Placement of project within literature and connection to course material
- Clarity of main technical results / takeaways
- Evidence of independent work (e.g., demonstration of developed understanding and insight, construction of simulation models, plots showing testing of controllers, etc.)
- Quality, quantity, and appropriate use of visual aids for explaining results
- Appropriateness of quantity of material presented, timing of presentation, etc.
- Typesetting, formatting, organization, finishing on time without rushing, etc.
- Is the overall organization of the material effective and did the audience learn something?

Attendance and active participation for other student presentations is **required**.

Project Topics

A Universal Decomposition for Distributed Optimization Algorithms

As a rule of thumb, if your proposed project contains any of the major course key words (robust, optimal, performance, LMI, SDP) then it is eligible. I strongly encourage you to do a bit of digging and find something you are excited to learn about or work on. I reserve the right to reject any project proposal that I feel is too close in scope to the core course material or to another project.

Below, potential papers or topics (mostly recent) for review are listed, but you are **not** restricted to these topics or references.

1. Learning/perception and robust control [1, 2, 3, 4, 5]

2. Data-driven control [6, 7, 8, 9, 10, 11]
3. Numerical aspects of LMI computation for systems and control [12]
4. System Level Synthesis [13, 14, 15, 16]
5. Linear parameter-varying (LPV) systems and gain-scheduled control [17, 18]
6. Design of tracking and optimizing controllers [19, 20, 21, 22]
7. Large-scale systems analysis [23]
8. Theory of integral quadratic constraints [24, 25, 26, 27, 28, 29, 30]
9. SDP duality theory in control [31, 32, 33]
10. Unfalsifiable control [34]
11. Fragility of optimal controllers [35]
12. Optimization and game theory [36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49]
13. Neural network control: [50, 51]
14. Conic-sector and SPR control synthesis: [52, 53]

Other ideas: Autonomous vehicles, Soft robotics, System identification, $\mathcal{L}_1/\ell_1$ optimal control, estimator design, local stability analysis, robustness in biological systems (e.g., M. Khammash, J. Doyle, F. Doyle, R. Murray, . . .), Sum-of-squares SOS programming (e.g., Anderson, Papachristodoulou, Peet, Parillo, . . .), hybrid systems, . . .

Useful Documents and Templates

My suggestion is to use LaTeX for producing documents and presentations which include mathematics, but I leave the decision to you for what software to use. The following may be useful to you:

- IEEE-style conference templates for MS Word and LaTeX
- Template for Powerpoint presentations
- Tutorial on LaTeX
- Tutorial on Beamer for LaTeX presentations
- Advice on giving presentations
- Advice on reading technical research papers

References

[1] F. Berkenkamp and A. P. Schoellig, "Safe and robust learning control with gaussian processes," in *European Control Conference*, 2015, pp. 2496–2501.

[2] P. T. Claudio De Persis, "Low-complexity learning of linear quadratic regulators from noisy data," 2020, https://arxiv.org/abs/2005.01082.

[3] S. Dean, N. Matni, B. Recht, and V. Ye, "Robust guarantees for perception-based control," in *Proceedings of Machine Learning Research*, A. M. Bayen, A. Jadbabaie, G. Pappas, P. A. Parrilo, B. Recht, C. Tomlin, and M. Zeilinger, Eds., vol. 120, The Cloud, 10–11 Jun 2020, pp. 350–360.

[4] S. Dean, S. Tu, N. Matni, and B. Recht, "Safely learning to control the constrained linear quadratic regulator," in *American Control Conference*, 2019, pp. 5582–5588.

[5] J. Xu, B. Lee, N. Matni, and D. Jayaraman, "Are learned perception-based controllers bound by the limits of robust control?" 2021, https://jxu.ai/files/l4dc2020.pdf.

[6] J. Berberich, A. Koch, C. W. Scherer, and F. Allgöwer, "Robust data-driven state-feedback design," in *American Control Conference*, 2020, pp. 1532–1538.

[7] J. Berberich and F. Allgöwer, "A trajectory-based framework for data-driven system analysis and control," in *European Control Conference*, 2020, pp. 1365–1370.

[8] A. Koch, J. Berberich, J. Köhler, and F. Allgöwer, "Determining optimal input-output properties: A data-driven approach," 2020, https://arxiv.org/abs/2002.03882.

[9] ——, "Provably robust verification of dissipativity properties from data," 2020, https://arxiv.org/pdf/2006.05974.pdf.

[10] C. De Persis and P. Tesi, "Formulas for data-driven control: Stabilization, optimality, and robustness," *IEEE Transactions on Automatic Control*, vol. 65, no. 3, pp. 909–924, 2020.

[11] M. Rotulo, C. D. Persis, and P. Tesi, "Data-driven linear quadratic regulation via semidefinite programming," 2020, https://arxiv.org/abs/1911.07767.

[12] L. Vandenberghe, V. R. Balakrishnan, R. Wallin, A. Hansson, and T. Roh, "Interior-point algorithms for semidefinite programming problems derived from the kyp lemma," in *Positive Polynomials in Control*, D. H. D and A. Garulli, Eds. Springer-Verlag Berlin Heidelberg, 2005.

[13] J. C. Doyle, N. Matni, Y. Wang, J. Anderson, and S. Low, "System level synthesis: A tutorial," in *IEEE Conf. on Decision and Control*, 2017, pp. 2856–2867.

[14] J. Anderson, J. C. Doyle, S. H. Low, and N. Matni, "System level synthesis," *Annual Reviews in Control*, vol. 47, pp. 364 – 393, 2019.

[15] Y. Chen and J. Anderson, "System level synthesis with state and input constraints," in *IEEE Conf. on Decision and Control*, 2019, pp. 5258–5263.

[16] A. Xue and N. Matni, "Data-driven system level synthesis," https://arxiv.org/abs/2011.10674.

[17] C. W. Scherer, "Lpv control and full block multipliers," *Automatica*, vol. 37, no. 3, pp. 361 – 375, 2001.

[18] J. Veenman and C. W. Scherer, "A synthesis framework for robust gain-scheduling controllers," *Automatica*, vol. 50, no. 11, pp. 2799 – 2812, 2014.

[19] A. Pavlov, N. van de Wouw, and H. Nijmeijer, *Uniform Output Regulation of Nonlinear Systems: A Convergent Dynamics Approach.* Springer, 2005.

[20] M. Colombino, E. Dall'Anese, and A. Bernstein, "Online optimization as a feedback controller: Stability and tracking," *IEEE Transactions on Control of Network Systems*, vol. 7, no. 1, pp. 422–432, 2020.

[21] J. W. Simpson-Porco, "Analysis and synthesis of low-gain integral controllers for nonlinear systems," *IEEE Transactions on Automatic Control*, vol. 66, no. 9, pp. 4148–4159, Sep. 2021.

[22] M. Colombino, J. W. Simpson-Porco, and A. Bernstein, "Towards robustness guarantees for feedback-based optimization," in *IEEE Conf. on Decision and Control*, Nice, France, Dec. 2019, pp. 6207–6214.

[23] M. Arcak, C. Meissen, and A. Packard, *Networks of Dissipative Systems: Compositional Certification of Stability, Performance, and Safety.* Springer Briefs in Control, Automation and Robotics, 2016.

[24] M. Fetzer and C. W. Scherer, "Full-block multipliers for repeated, slope-restricted scalar nonlinearities," *International Journal on Robust and Nonlinear Control*, vol. 27, no. 17, pp. 3376–3411, 2017.

[25] J. Veenman and C. W. Scherer, "Stability analysis with integral quadratic constraints: A dissipativity based proof," in *IEEE Conf. on Decision and Control*, Florence, Italy, Dec. 2013, pp. 3770–3775.

[26] B. Hu and P. Seiler, "Exponential decay rate conditions for uncertain linear systems using integral quadratic constraints," *IEEE Transactions on Automatic Control*, vol. 61, no. 11, pp. 3631–3637, 2016.

[27] H. Pfifer and P. Seiler, "An overview of integral quadratic constraints for delayed nonlinear and parameter-varying systems," 2015, https://arxiv.org/abs/1504.02502.

[28] J. Carrasco and P. Seiler, "Integral quadratic constraint theorem: A topological separation approach," in *IEEE Conf. on Decision and Control*, Dec. 2015, pp. 5701–5706.

[29] R. Boczar, L. Lessard, and B. Recht, "Exponential convergence bounds using integral quadratic constraints," in *IEEE Conf. on Decision and Control*, Osaka, Japan, Dec. 2015, pp. 7516–7521.

[30] P. Seiler, "Stability analysis with dissipation inequalities and integral quadratic constraints," *IEEE Transactions on Automatic Control*, vol. 60, no. 6, pp. 1704–1709, 2015.

[31] V. Balakrishnan and L. Vandenberghe, "Semidefinite programming duality and linear time-invariant systems," *IEEE Transactions on Automatic Control*, vol. 48, no. 1, pp. 30–41, 2003.

[32] C. W. Scherer, "LMI relaxations in robust control," *European Journal of Control*, vol. 12, no. 1, pp. 3 – 29, 2006.

[33] B. Van Scoy and L. Lessard, “Integral quadratic constraints: Exact convergence rates and worst-case trajectories,” in *IEEE Conf. on Decision and Control*, 2019, pp. 7677–7682.

[34] M. G. Safonov, “Robust control: Fooled by assumptions,” *International Journal on Robust and Nonlinear Control*, vol. 28, no. 12, pp. 3667–3677, 2018. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/rnc.3562

[35] L. H. Keel and S. P. Bhattacharyya, “Robust, fragile, or optimal?” *IEEE Transactions on Automatic Control*, vol. 42, no. 8, pp. 1098–1105, 1997.

[36] L. Lessard, B. Recht, and A. Packard, “Analysis and design of optimization algorithms via integral quadratic constraints,” *SIAM Journal on Optimization*, vol. 26, no. 1, pp. 57–95, 2016.

[37] B. Hu and L. Lessard, “Control interpretations for first-order optimization methods,” in *American Control Conference*, Seattle, WA, USA, May 2017, pp. 3114–3119.

[38] ——, “Dissipativity theory for Nesterov’s accelerated method,” in *International Conference on Machine Learning*, vol. 70, Sydney, Australia, Aug. 2017, pp. 1549–1557.

[39] B. Van Scoy, R. A. Freeman, and K. M. Lynch, “The fastest known globally convergent first-order method for minimizing strongly convex functions,” *IEEE Control Systems Letters*, vol. 2, no. 1, pp. 49–54, 2018.

[40] S. Cyrus, B. Hu, B. Van Scoy, and L. Lessard, “A robust accelerated optimization algorithm for strongly convex functions,” in *American Control Conference*, 2018, pp. 1376–1381.

[41] N. K. Dhingra, S. Z. Khong, and M. R. Jovanović, “The proximal augmented lagrangian method for nonsmooth composite optimization,” *IEEE Transactions on Automatic Control*, vol. 64, no. 7, pp. 2861–2868, 2019.

[42] S. Michalowsky, C. Scherer, and C. Ebenbauer, “Robust and structure exploiting optimization algorithms,” 2019, https://arxiv.org/abs/1905.00279.

[43] G. Zhang, X. Bao, L. Lessard, and R. Grosse, “A unified analysis of first-order methods for smooth games via integral quadratic constraints,” 2020. [Online]. Available: https://arxiv.org/abs/2009.11359

[44] L. Lessard and P. Seiler, “Direct synthesis of iterative algorithms with bounds on achievable worst-case convergence rate,” in *American Control Conference*, 2020, pp. 119–125.

[45] H. Mohammadi, M. Razaviyayn, and M. R. Jovanovic, “Robustness of accelerated first-order algorithms for strongly convex optimization problems,” *IEEE Transactions on Automatic Control*, pp. 1–1, 2020.

[46] S. Samuelson, H. Mohammadi, and M. R. Jovanović, “Transient growth of accelerated first-order methods,” in *American Control Conference*, 2020, pp. 2858–2863.

[47] ——, “On the transient growth of nesterov’s accelerated method for strongly convex optimization problems,” in *IEEE Conf. on Decision and Control*, 2020, pp. 5911–5916.

[48] D. Gramlich, C. Ebenbauer, and C. W. Scherer, “Convex synthesis of accelerated gradient algorithms for optimization and saddle point problems using lyapunov functions,” 2020, https://arxiv.org/abs/2006.09946.

[49] ——, "Synthesis of accelerated gradient algorithms for optimization and saddle point problems using lyapunov functions and lmis," *Systems & Control Letters*, vol. 165, p. 105271, 2022.

[50] H. Yin, P. Seiler, and M. Arcak, "Stability analysis using quadratic constraints for systems with neural network controllers," 2021, https://arxiv.org/abs/2006.07579.

[51] F. Gu, H. Yin, L. E. Ghaoui, M. Arcak, P. Seiler, and M. Jin, "Recurrent neural network controllers synthesis with stability guarantees for partially observed systems," 2021, https://arxiv.org/abs/2109.03861.

[52] J. R. Forbes, "Dual approaches to strictly positive real controller synthesis with a performance using linear matrix inequalities," *International Journal on Robust and Nonlinear Control*, vol. 23, no. 8, pp. 903–918, 2013.

[53] L. J. Bridgeman and J. R. Forbes, "Conic-sector-based control to circumvent passivity violations," *International Journal of Control*, vol. 87, no. 8, pp. 1467–1477, 2014.