SIDRA Summer School, Bertinoro

Adaptive Control Systems: Methodologies for Analysis and Synthesis

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Aim: To give a fairly broad (albeit necessarily incomplete) treatment of classic and more recent methodologies for adaptive control of linear systems and fundamental issues in adaptive control design. The goal of the course is not that of giving a detailed description of several methodologies, rather to introducing a few selected techniques that serve the purpose of highlighting fundamental concepts in the analysis and design of adaptive control systems. Emphasis will be placed on understanding key issues in stability and robustness of adaptive control loops.

Synopsis:

1. **Overview of Adaptive Control Systems.** Direct and indirect adaptive control. The principle of certainty-equivalence. Motivating examples: Direct and indirect adaptive control of scalar linear systems. Introduction to stability analysis of adaptive control systems.

2. **Tools.** Stability concepts and Lyapunov theorems (recap). LaSalle/Yoshizawa theorem. Passivity theory. Zero-state detectability. Ultimate boundedness. Positive real and strictly positive real transfer functions. Kalman-Yakubovich-Popov lemmas.

3. **Stability of Adaptive Control Systems.** The standard form of passivity-based adaptive control systems. Uniform observability. The role of persistence of excitation. Exponential convergence vs. exponential stability and uniform asymptotic stability. Robustness issues.

4. **Model Reference Adaptive Control of SISO LTI Models.** Parameterization of certainty-equivalence controllers. State-feedback MRAC schemes. Output-feedback MRAC for systems with relative degree one. Uniform global asymptotic stability of MRACs. Extension to higher relative degrees.

5. **Adaptive Observers.** Systems in adaptive observer form. Filtered transformations.

6. **Robust Redesign of Adaptive Controllers**. Robustness of adaptive systems. Leakage, dead-zone and projection-based robustification techniques.

7. **Applications.** Sinusoidal disturbance rejection: Adaptive feedforward and adaptive internal model design.

References: Notes will be provided that cover most of the above topics. References include:

1. P. Ioannou and J. Sun. *Robust Adaptive Control.* Prentice Hall, Upper Saddle River, NJ, 1996. Available on line at `http://www-bcf.usc.edu/ioannou/Robust_Adaptive_Control.htm`
2. H. K. Khalil. *Nonlinear Systems, 3rd edition.* Prentice Hall, Upper Saddle River, NJ, 2001.
3. E. Panteley, A.Loria. and A.R. Teel. Relaxed persistency of excitation for uniform asymptotic stability. IEEE Transactions on Automatic Control, 46(12):1874-1886, 2001.
4. M. Krstic. Invariant manifolds and asymptotic properties of adaptive nonlinear stabilizers. IEEE Transactions on Automatic Control, 41(6):817 - 829, 1996.
5. Ioannou, P. A., and Kokotovic, P. V. Instability analysis and improvement of robustness of adaptive control. Automatica, 20(5), 583594,1984.
6. Riedle, B., Cyr, B., and Kokotovic, P. V. Disturbance instabilities in an adaptive system. IEEE Transactions on Automatic Control, 29(9), 822824, 1984.
7. Riedle, B., and Kokotovic, P. V. Stability of Slow Adaptation for Non-SPR Systems with Disturbances. IEEE Transactions on Automatic Control, 32(5), 451455, 1987.
8. Rohrs, C., Valavani, L., Athans, M., and Stein, G. Robustness of continuous-time adaptive control algorithms in the presence of unmodeled dynamics. IEEE Transactions on Automatic Control, 30(9), 881889, 1985.
9. Kokotovic, P., Riedle, B., and Praly, L. On a stability criterion for continuous slow adaptation. Systems and Control Letters, 6(1), 714, 1985.
10. H.K. Khalil. Adaptive output feedback control of nonlinear systems represented by input-output models. IEEE Transactions on Automatic Control, 41(2):177-188, 1996.
11. A. Isidori, L. Marconi, and A. Serrani, *Robust Autonomous Guidance. An Internal Model Approach.* Springer-Verlag, 2003. Chapter 1, available on line at `http://www.springer.com/engineering/book/978-1-85233-695-0`

Course prerequisites: A beginning graduate-level course in linear systems theory is required. Exposure to nonlinear control theory is desirable but not essential. Familiarity with the basic concepts of Lyapunov stability theory is highly desirable.

Examination and grading: Grading will be based on a take-home final exam or project.

Course Schedule

- **Monday, July 9 (Morning):** Overview of Adaptive Control Systems. Tools.
- **Monday, July 9 (Afternoon):** Stability of Adaptive Control Systems.
- **Tuesday, July 10 (Morning):** MRAC of SISO LTI Models.
- **Tuesday, July 10 (Afternoon):** MRAC of SISO LTI Models. Adaptive Observers.
- **Wednesday, July 11 (Morning):** Robust Redesign of Adaptive Controllers. Applications (time permitting).