

CALIFORNIA INSTITUTE OF TECHNOLOGY  
Control and Dynamical Systems

CDS 270: Adaptive Control

Spring 2013

**Instructor**

Eugene Lavretsky, [eugene.lavretsky@boeing.com](mailto:eugene.lavretsky@boeing.com)  
Office Hours: Fridays, by appointment

**Grading**

Pass / Fail.

**Prerequisites**

Linear systems and control, basic understanding of nonlinear dynamics, Lyapunov stability theory, numerical methods, MATLAB.

**Course Outline**

The main goal of this course is to give a self-contained mathematical treatment of robust adaptive control theory and its current state of the art. Aerospace applications of adaptive flight control will be discussed. We will cover Part II, chapters 7 through 14 of the course textbook [1]. Homework will be assigned once a week. Mid-term and Final exams (in class) will be given.

**Course material**

The following is a tentative outline of the material to be covered.

## Part II Robust Adaptive Control

<b>7 Direct Model Reference Adaptive Control: Motivation and Introduction</b> . . . . .	211
7.1 Model Reference Control: Motivational Example . . . . .	211
7.2 Introduction to Direct Model Reference Adaptive Control . . . . .	215
7.3 Direct Model Reference Adaptive Control of Scalar Linear Systems with Parametric Uncertainties . . . . .	220
7.4 Historical Roots and Foundations of Model Reference Adaptive Control . . . . .	221
7.5 Exercises . . . . .	222
References . . . . .	223
<b>8 Lyapunov Stability of Motion</b> . . . . .	225
8.1 Dynamical Systems . . . . .	225
8.2 Existence and Uniqueness of Solutions . . . . .	227
8.3 System Equilibrium . . . . .	233
8.4 Lyapunov Stability Definitions . . . . .	235
8.5 Lyapunov Stability Theorems . . . . .	240
8.6 Uniform Ultimate Boundedness . . . . .	247
8.7 Barbalat's Lemma . . . . .	254
8.8 Summary and Historical Remarks . . . . .	259
8.9 Exercises . . . . .	259
References . . . . .	261
<b>9 State Feedback Direct Model Reference Adaptive Control</b> . . . . .	263
9.1 Introduction . . . . .	263
9.2 Command Tracking . . . . .	264
9.3 Direct MRAC Design for Scalar Systems . . . . .	265
9.4 Dynamic Inversion MRAC Design for Scalar Systems . . . . .	274
9.5 MRAC Design for Multi-Input Multi-Output Systems . . . . .	281
9.6 Summary . . . . .	291
9.7 Exercises . . . . .	291
References . . . . .	292

<b>10</b>	<b>Model Reference Adaptive Control with Integral Feedback</b>	
	<b>Connections</b> . . . . .	293
	10.1 Introduction . . . . .	293
	10.2 Control Design . . . . .	295
	10.3 MRAC Augmentation of an Optimal Baseline Controller . . . . .	303
	10.4 Summary . . . . .	314
	10.5 Exercises . . . . .	314
	References . . . . .	315
<b>11</b>	<b>Robust Adaptive Control</b> . . . . .	317
	11.1 MRAC Design in the Presence of Bounded Disturbances . . . . .	317
	11.2 MRAC Design Modifications for Robustness . . . . .	319
	11.2.1 The Dead-Zone Modification . . . . .	319
	11.2.2 The $\sigma$ -Modification . . . . .	323
	11.3 The $e$ -Modification . . . . .	327
	11.4 The Projection Operator . . . . .	329
	11.5 Projection-Based MRAC Design . . . . .	337
	11.6 Summary and Discussions . . . . .	350
	11.7 Exercises . . . . .	351
	References . . . . .	352
<b>12</b>	<b>Approximation-Based Adaptive Control</b> . . . . .	355
	12.1 Motivation . . . . .	355
	12.2 Basic Definitions . . . . .	356
	12.3 Approximation Properties of Feedforward Neural Networks . . . . .	360
	12.4 Adaptive Control with State Limiting Constraints . . . . .	362
	12.5 Summary . . . . .	383
	12.6 Exercises . . . . .	384
	References . . . . .	385
<b>13</b>	<b>Adaptive Control with Improved Transient Dynamics</b> . . . . .	387
	13.1 Motivation . . . . .	387
	13.2 Asymptotic Orders and Singular Perturbations . . . . .	394
	13.3 Asymptotic Properties of the Algebraic Riccati Equation . . . . .	399
	13.4 System Dynamics and Control Problem Formulation . . . . .	406
	13.5 Observer-Like Model Reference Adaptive Control . . . . .	408
	13.6 Transient Dynamics Analysis . . . . .	412
	13.7 Summary . . . . .	415
	13.8 Exercises . . . . .	416
	References . . . . .	416
<b>14</b>	<b>Robust and Adaptive Control with Output Feedback</b> . . . . .	417
	14.1 Introduction . . . . .	417
	14.2 Mathematical Preliminaries . . . . .	419
	14.3 System Dynamics and Control Problem Formulation . . . . .	421

**Course Textbook:**

1. E. Lavretsky, K.A. Wise, *Robust and Adaptive Control With Aerospace Applications*, Advanced Textbooks in Control and Signal Processing, Springer-Verlag, London, ISBN: 978-1-4471-4395-6 (Print), 978-1-4471-4396-3 (Online), 2013.

**Supplementary Textbooks**

1. P. Ioannou, B. Fidan, *Adaptive Control Tutorial*, SIAM, Advances in Design and control, SIAM, PA, 2006.
2. K. Narendra, A. Annaswamy, *Stable Adaptive Control*, Dover, N.Y., 2005.
3. H.K. Khalil, *Nonlinear Systems*, 3<sup>rd</sup> Edition, Prentice Hall, New Jersey, 2002.
4. J.J. Slotine, W. Li, *Applied Nonlinear Control*, Prentice Hall, 1995.
5. M. Krstic, I. Kanellakopoulos, P. Kokotovic, *Nonlinear and Adaptive Control Design*, John Wiley & Sons, New York, 1995.
6. R. Marino, P. Tomei, *Nonlinear Control Design: Geometric, Adaptive, Robust*, Prentice Hall, New Jersey, 1995.
7. S.S. Sastry, M. Bodson, *Adaptive Control: Stability, Convergence and Robustness*, Prentice Hall, 1989.