Robust and Adaptive Control Theory Workshop

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This is a one-day workshop. The workshop is designed for engineers/scientists that have had a minimum of an undergraduate level control systems course (root locus, Bode, Nyquist, etc.) and have an understanding of using state space methods for modeling control systems. The attendees will learn methods in robust linear control design (optimal control), robust stability analysis, Lyapunov stability theory, model reference direct adaptive control, and its recently developed modifications. The workshop presents lessons learned in applying these methods to fighter aircraft and advanced weapon systems.

The workshop covers in detail the adaptive control design and analysis methods used on X-36 RESTORE, X-45A Unmanned Combat Air Vehicle (UCAV), and on JDAM MK-82 guided weapon, JDAM MK-84, and the Laser-JDAM. The workshop begins with items 1.0 through 4.0 below, and is a summary of theory and lessons learned in developing robust linear control algorithms. These sections summarize the authors experience from 20 years of applying robust optimal control methods to aircraft and missiles within the Boeing Phantom Works. These methods are used to develop the baseline control algorithms that then are augmented with adaptive control, starting with Section 5.0 where an overview of the Lyapunov stability theory and an introduction to the design and analysis of classical linear in parameters adaptive control systems are given. Next, approximation properties of artificial neural networks and their application to the design of direct adaptive systems are presented. Key design points are discussed and illustrated through various simulation examples, followed by an overview of open problems and future research directions in adaptive control and its applications to flight control of aerial vehicles.

1.0 Review of Basics
   State space models, Linear vector spaces, Operators, Similarity transformations
   Norms, Eigenvalues, Eigenvectors, Matrix norms, Singular values, Singular vectors, State transition matrices, Controllability, Observability, Stability, Power signals, Norms for systems, Function spaces, Wellposedness and stability

2.0 Frequency Domain Analysis Methods
   Review of transfer functions and transfer function matrices, Classical frequency response methods, Nyquist theory, Multivariable Nyquist Theorem, Stability margins, Singular value stability margins, Performance specifications in the frequency domain, Robust stability analysis, Small Gain Theorem, Frequency dependent weights, Robust stability tests to specify hardware requirements, Analysis methods for real parameter uncertainties, Singular value robustness tests. These methods are applied to the X-45A UCAV and several missile and munition examples.

3.0 Control System Design Methods
   Robust servomechanism, Optimal control theory, Linear Quadratic Regulator (LQR), Projective control theory used to project state feedback controllers into output feedback

controllers (flown on X-45A, JDAM, HAVE SLICK, and other aircraft and missile within Boeing Phantom Works).

- 4.0 H_∞ Optimal Control (State Feedback)

  Motivation for H_∞ optimal control, H_∞ optimal state feedback control, H_∞ optimal control with μ–synthesis, Optimal disturbance rejection using projective controls, H_∞ optimal control with and without imaginary axis zeros. A summary comparison of classical, LQR, H_∞ (output and state feedback), and μ–synthesis controllers applied to a common design problem.
- 5.0 Review of Lyapunov Stability Theory
  - 5.1 Stability in the sense of Lyapunov
  - 5.2 System energy and positive definite functions
  - 5.3 Lyapunov's direct method, LaSalle's Extension
  - 5.4 Barbalat's Lemma, and Lyapunov-like Theorem
- 6.0 Model Reference Adaptive Control (MRAC)
  - 6.1 Introduction
  - 6.2 Motivating Example
  - 6.3 MRAC Design and Analysis
- 7.0 Robustness to Parametric / Non-Parametric Uncertainties
  - 7.1 Parameter drift
  - 7.2 Dead-Zone modification
  - 7.3 Parametric and non-parametric uncertainties
- 8.0 Artificial Neural Networks, (NN-s)
  - 8.1 Architectures
  - 8.2 Using Sigmoids
  - 8.3 Using Radial Basis Functions, (RBF-s)
- 9.0 Adaptive NeuroControl
  - 9.1 N^{th} order MRAC design using RBF NN
  - 9.2 σ – modification, e – modification
  - 9.3 Projection Operator
  - 9.4 Adaptive augmentation design
  - 9.5 MRAC design using sigmoidal NN
- 10.0 Adaptive Reconfigurable Flight Control using RBF NN-s
  - 10.1 X-45A UCAV design example
  - 10.2 F-16 adaptive pitch rate tracking design example
- 11.0 Adaptive Control Modifications
  - 11.1 Nonlinear-in-control design
  - 11.2 Dynamic Inversion MRAC for Flight Applications
  - 11.3 Composite / Combined MRAC
- 12.0 Flight Control Challenges, Tech Transition, Applications, and Flight Test Results