Robust and Adaptive Control Theory Workshop

Presenters: Dr. Kevin A. Wise, Dr. Eugene Lavretsky
Boeing Phantom Works

This is a two-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, and model reference direct adaptive control. The workshop covers lessons learned in applying these methods to fighter aircraft and weapon system.

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. The first day of the workshop covers 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 in Day 2. The second day begins with section 5.0 which is an overview of the Lyapunov stability theory, followed by an introduction to the design and analysis of classical linear in parameters adaptive control systems. 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. The workshop ends with an overview of open problems and future research directions in adaptive control and its applications to flight control of unmanned 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 Lyapunov Stability Theory
- 5.1 Stability in the sense of Lyapunov. Local and global stability, uniform continuity.
- 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 Adaptive Control
- 6.1 Motivation
- 6.2 Control architectures: direct vs. indirect.
- 6.3 Model reference adaptive control (MRAC). Self-tuning controllers. Matching conditions.
- 6.4 MRAC design, analysis and simulation.
- 6.5 Adaptive Dynamic Inversion, (ADI).
- 6.6 Persistency of excitation.
- 6.7 Robustness in MRAC.
  - 6.7.1 Parameter drift
  - 6.7.2 Dead-Zone modification
  - 6.7.3 Parametric and non-parametric uncertainties

7.0 Artificial Neural Networks, (NN)
- 7.1 Historical notes, neural network architectures, learning processes
- 7.2 Single-hidden-layer feedforward neural networks
  - 7.2.1 Using sigmoids
  - 7.2.2 Using Radial Basis Functions, (RBF)
- 7.3 NN universal approximation theorems, rates of approximation, curse of dimensionality, practical considerations

8.0 Adaptive NeuroControl
- 8.1 N^{th} order MRAC design.
- 8.2 σ – modification, e – modification.
- 8.3 Projection operator for bounding NN weights.
- 8.4 Composite adaptation
- 8.5 Augmenting a baseline controller with direct MRAC.

9.0 Robust Adaptive Flight Control Design Examples
- 9.1 X-36 RESTORE
- 9.2 X-45A UCAV
- 9.3 MK-82 JDAM