A Short Course on

Nonlinear Adaptive Robust Control

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Theory and Applications to the

Integrated Design of Intelligent and Precision Mechatronic Systems

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Objectives:

This short course is designed to introduce graduate students, faculty, and practicing engineers to the recently developed adaptive robust control (ARC) theory and its applications to the integrated design of intelligent and precision mechatronic systems.

Motivations:

The rapid advances in microelectronics and microprocessor technologies during the past decades have made the physical integration of mechanical systems, various sensors, and computer based control implementation platform (or a mecahtronic system) rather affordable and a standard choice for any modern precision machines. Such a hardware configuration enables the control (or the operation) of the overall system to be constructed in the same way as what a human brain normally does – seamless integration of the fast reaction (or instantaneous feedback reaction) to immediate feedback information and the slow learning utilizing large amount of stored past information that is available in the computer based control systems. The theoretically solid nonlinear adaptive robust control (ARC) theory that has been developed recently well reflects such an intuitive integrated design philosophy of human brains, and has been experimentally demonstrated achieving better control performance than existing nonlinear robust controls or nonlinear adaptive controls in a number of applications. It is thus beneficial for control engineers to get exposed to such an advanced nonlinear control design methodology and to master how the method can be used to build intelligent and precision mechatronic systems that are needed in industry.

Pre-requisites:

Graduate level introductory control courses in both linear systems and nonlinear systems.

Course Contents:

Traditional nonlinear adaptive and robust control design methodologies are reviewed, including both the nonlinear deterministic robust controls (either the sliding mode type control designs or the min-max Lyapunov type designs) and the backstepping nonlinear adaptive controls. Emphasis will be on the new perspectives on the underlining working mechanisms and performance limitations of these traditional approaches, from which the rational for the recently developed nonlinear adaptive robust control (ARC) becomes apparent. The control of first-order scalar uncertain nonlinear systems with uncertainties parameter is used to illustrate the fundamental design philosophy of the existing robust and adaptive controls and the presented adaptive robust control (ARC) approach – issues like the roles of nonlinear local high-gain feedback and the model based nonlinear compensation with on-line adaptation. Various specific ARC designs are then introduced, including the control performance oriented Direct Adaptive Robust Control (DARC) where the control goal is to reduce output tracking error only, the estimation based Indirect Adaptive Robust Control (IARC) that separates the parameter estimation from the control law design in order to obtain accurate parameter estimates for adding intelligent features such as machine health monitoring and prognostics, and the Integrated Direct/Indirect Adaptive Robust Control (DIARC) that achieves the dual objectives of having excellent control performance as well as accurate parameter estimates. Various extensions such as the ARC of MIMO nonlinear systems transformable to semi-strict feedback forms and output feedback ARC designs, the Adaptive Robust Repetitive Control (ARRC) for repetitive tasks, and the neural network ARC (NNARC) are briefly touched. The control of a high-speed/acceleration linear motor driven precision electro-mechanical system, the control of various electro-hydraulic systems, and the energy-saving control of electro-hydraulic systems using novel programmable valves are used as application examples to illustrate the effectiveness of the presented ARC approach in the integrated design of intelligent and precision mechatronic systems.

Course Outlines and Reference Readings:

A one and half days are devoted to Theoretic Topics:

Day 1: Morning Sessions (3 hours)

1) *Fundamental Design Philosophy of Adaptive Robust Control (ARC) illustrated through the control of first-order scalar nonlinear systems with uncertainties*

    a. *Role of Nonlinear Local High-Gain Feedback* and its connection to the traditional nonlinear robust control such as the sliding mode control.
    b. *Role of Model Based Compensation with slow learning* and its connection to the traditional nonlinear adaptive control design.
    c. *Direct Adaptive Robust Control* - integration of nonlinear local high-gain feedback and model based compensation with a controlled parameter adaptation (or learning) process for better control performance.

Afternoon Sessions (3 hours)

    d. *Desired Compensation Adaptive Robust Control Architecture* to attenuate the effect of measurement noises.
    e. *Indirect Adaptive Robust Control Architecture* – a total separation of control law design and parameter estimation design to obtain accurate parameter estimates for adding intelligent features such as machine health monitoring and prognostics.
    f. *Integrated Direct/Indirect Adaptive Robust Control Architecture* that achieves excellent control performance as well as accurate parameter estimates.

Day 2: Morning Sessions (3 hours)

Various specific designs and extensions are briefly touched including

2) *Adaptive Robust Control (ARC) of SISO nonlinear systems transformable to semi-strict feedback forms.*
    a. *Control Issues associated with Unmatched Model Uncertainties*
    b. *Direct Adaptive Robust Control Design with Backstepping*.
    c. *Indirect Adaptive Robust Control with Backstepping*.
    d. *Integrated Direct/Indirect Adaptive Robust Control with Backstepping*

3) *Adaptive Robust Control (ARC) of MIMO nonlinear systems transformable to semi-strict feedback forms.*

4) *Neural Network Adaptive Robust Control (ARC) for general learning*

5) *Adaptive Robust Repetitive Control (ARRC) for repetitive tasks*

6) *Output and Partial State Feedback Adaptive Robust Control Designs*

A one and half days are devoted to the applications of ARC theory to the integrated design of intelligent and precision mechatronic systems that emphasize

1) *Practical Ways to Achieve Fast Feedback*
    a. *Software*: nonlinear local high-gain-global-low-gain robust feedback instead of traditional linear high gain feedback.
    b. *Hardware*: innovative mechanical designs with product functionality in mind. For example, the use of linear motor drive systems instead of rotary motors for positioning systems, which provides the hardware possibility of having fast reaction due to rigid construction of linear motor based positioning systems.

2) *Practical Ways to Have Good Learning Capability for Better Intelligence*

    c. Separate estimation model from the controller design model
    d. Parameter estimation algorithms with better convergence properties
    e. Explicit on-line monitoring of persistence excitation level

3) *System Design Perspectives*

    f. Trade-off between software based complex control architectures and the use of innovative hardware redesign (i.e., novel hardware control elements such as programmable valves for energy-saving control of electro-hydraulic systems)

The above aspects will be illustrated through several application examples outlined below:

Application Example 1: *Precision Control of Linear Motor Driven High-speed/High-Acceleration Electro-Mechanical Systems*

Day 2: Afternoon Sessions (3 hours)

1) *Physical Systems and Dynamic Models*
2) *Problem Formulation and Major Control Issues to be Addressed*
3) *Direct Adaptive Robust Control Design*
4) *Output Feedback Direct Adaptive Robust Control Design*

Day 3: Morning Sessions (one and half hours)

5) *Indirect Adaptive Robust Control Design*
6) *Integrated Direct/Indirect Adaptive Robust Control Design*
7) *Comparative Experimental Studies*

Application Example 2: *Precision Control of Electro-Hydraulic Systems*

Day 3: Morning Sessions (one and half hours)

1) *Physical Systems and Dynamic Models*
2) *Problem Formulation and Major Control Issues to be Addressed*
3) *Direct Backstepping Adaptive Robust Control Design*

Day 3: Afternoon Sessions (one and half hours)

4) *Indirect Backstepping Adaptive Robust Control Design*
5) *Integrated Direct/Indirect Backstepping Adaptive Robust Control Design*
6) *Comparative Experimental Studies*

Application Example 3: *Energy-Saving Control of Electro-Hydraulic Systems using Novel Programmable Valves*

Day 3: Afternoon Sessions (one and half hours)

1) *Programmable Valve Hardware Configurations and Uniqueness*
2) *Energy-Saving Control of Electro-Hydraulic Systems*
3) *Experimental Studies*

References:

Theoretical Topics:

Direct Adaptive Robust Control

1) Bin Yao, "**High performance adaptive robust control of nonlinear systems: a general framework and new schemes**," *Proc. of IEEE Conf. on Decision and Control*, pp2489-2494, 1997. http://widget.ecn.purdue.edu/~byao/Papers/CDC97_ARC.pdf
2) Bin Yao, " **Desired compensation adaptive robust control**," *Proceedings of the ASME Dynamic Systems and Control Division, DSC-Vol.64, ASME International Mechanical Engineering Congress and Exposition (IMECE'98),* pp569-575, Anaheim, 1998. http://widget.ecn.purdue.edu/~byao/Papers/WAM98.pdf
3) Bin Yao and M. Tomizuka, "**Adaptive robust control of nonlinear systems: effective use of information**," *IFAC Symposium on System Identification*, pp913-918, 1997. http://widget.ecn.purdue.edu/~byao/Papers/yb016.pdf
4) Bin Yao and M. Tomizuka, "**Smooth robust adaptive sliding mode control with guaranteed transient performance**," *Trans. of ASME, J. of Dynamic Systems, Measurement and Control*, Vol.118, pp764-775, December issue, 1996. http://widget.ecn.purdue.edu/~byao/Papers/JDSMC96.pdf

5) Bin Yao and M. Tomizuka, "**Adaptive robust control of SISO nonlinear systems in a semi-strict feedback form**," *Automatica*, Vol.33, No.5, pp893-900, 1997. http://widget.ecn.purdue.edu/~byao/Papers/Automatica97.pdf
6) Bin Yao and M. Tomizuka, "**Adaptive robust control of MIMO nonlinear systems in semi-strict-feedback forms**," *Automatica*, Vol. 37, No. 9, pp1305-1321, 2001. http://widget.ecn.purdue.edu/~byao/Papers/Yb015j.pdf

Indirect and Integrated Adaptive Robust Control

7) Bin Yao and A. Palmer, "**Indirect adaptive robust control of SISO nonlinear systems in semi-strict feedback forms**", the 15th IFAC World Congress, Barcelona , Spain , July 21-26, 2002. http://widget.ecn.purdue.edu/~byao/Papers/IARC_IFAC02.pdf
8) Bin Yao and R. Dontha, "**Integrated Direct/Indirect adaptive robust precision control of linear motor drive systems with accurate parameter estimates**", the 2nd IFAC Conference on Mechatronic Systems, Berkeley , December, 2002. http://widget.ecn.purdue.edu/~byao/Papers/DIARC_Motor.pdf

Output and Partial State Feedback Adaptive Robust Control

9) Bin Yao and Li Xu, "**Observer based adaptive robust control of a class of nonlinear systems with dynamic uncertainties**," *International Journal of Robust and Nonlinear Control*, pp335-356, No.11, 2001. http://widget.ecn.purdue.edu/~byao/Papers/IJRNC99.pdf
10) L. Xu and B. Yao, " **Output feedback adaptive robust precision motion control of linear motors**," *Automatica*, Vol. 37, No.7, pp1029-1039, 2001. http://widget.ecn.purdue.edu/~byao/Papers/Automatica00_motor.pdf
11) Li Xu and Bin Yao, "**Output feedback adaptive robust control of uncertain linear systems with large disturbances**," *Proc. of American Control Conference*, pp556-560, San Diego, 1999. http://widget.ecn.purdue.edu/~byao/Papers/acc99_linear.pdf

Neural Network Adaptive Robust Control

12) J. Q. Gong and Bin Yao, "**Neural network adaptive robust control of nonlinear systems in semi-strict feedback form**'', *Automatica*, Vol. 37, No.8, pp1149-1160, 2001 http://widget.ecn.purdue.edu/~byao/Papers/Automatica01_NN.pdf
13) J. Q. Gong and Bin Yao, "**Neural network adaptive robust control of nonlinear systems in normal form**'', *Asian Journal of Control*, Vol. 3, No. 2, pp.96-110, June, 2001 (the Special Issue on Trend and Advancement in Neural Networks Based Control Designs). http://widget.ecn.purdue.edu/~byao/Papers/AJC00_neural.pdf
14) J. Q. Gong and Bin Yao, "**Neural network adaptive robust control with application to precision motion control of linear motors**'', *International Journal of Adaptive Control and Signal Processing*, Vol. 15, No. 8, 2001 (accepted for the Special Issue on Developments in Intelligent Control for Industrial Applications). http://widget.ecn.purdue.edu/~byao/Papers/ACSP00_neural.pdf

Adaptive Robust Repetitive Control

15) Bin Yao and L. Xu, "**On the design of adaptive robust repetitive controllers**", the *ASME International Mechanical Engineers Congress and Exposition (IMECE),* IMECE01/DSC-3B-4, pp1-9, 2001
http://widget.ecn.purdue.edu/~byao/Papers/IMECE01_motor.pdf
16) L. Xu and Bin Yao, "**Adaptive robust repetitive control of a class of nonlinear systems in normal form with applications to motion control of linear motors**", *the IEEE/ASME Conference on Advanced Intelligent Mechatronics (AIM)*, pp527-532, Como, Italy, 2001.
http://widget.ecn.purdue.edu/~byao/Papers/AIM01_motor.pdf

Application Topics:

Precision Control of Linear Motor Drive Systems

17) L. Xu and B. Yao, "**Adaptive robust precision motion control of linear motors with negligible electrical dynamics: theory and experiments**", the *IEEE/ASME Transactions on Mechantronics*, Vol. 6, No.4, pp444-452, 2001.
http://widget.ecn.purdue.edu/~byao/Papers/Trans_Mechatronics01_MT00-005.pdf
18) L. Xu and B. Yao, "**Adaptive robust precision motion control of linear motors with ripple force compensation: Theory and Experiments**", the I*EEE Transactions on Control System Technology* (conditionally accepted in 2001)
http://widget.ecn.purdue.edu/~byao/Papers/cca00e1.pdf
19) L. Xu and B. Yao, " **Output feedback adaptive robust control of linear motors with negligible electrical dynamics** ," *ASME International Mechanical Engineering Congress and Exposition (IMECE)*, DSC-Vol.69-1, pp247--254, Orlando, 2000 (**Finalist of the Best Student Paper Competition** of the **ASME** **Dynamic Systems and Control Division (DSCD)**).
http://widget.ecn.purdue.edu/~byao/Papers/IMECE00_motor.pdf
20) Bin Yao and L. Xu, "**Adaptive robust control of linear motors for precision manufacturing**," *International J. of Mechatronic*s, Vol.12, No.4, pp595-616, 2002.
http://widget.ecn.purdue.edu/~byao/Papers/Motor98.pdf

Precision Control of Electro-Hydraulic Systems

21) Bin Yao, F. Bu, J. T. Reedy, and G. C. T. Chiu, "**Adaptive Robust Control of Single-rod Hydraulic Actuators: Theory and Experiments**", *the IEEE/ASME Transactions on Mechatronics*. Vol.5, No.1, pp.79-91, 2000.
http://widget.ecn.purdue.edu/~byao/Papers/Mechatronics00.pdf
22) Fanping Bu and Bin Yao , "**Adaptive robust precision motion control of single-rod hydraulic actuators with time-varying unknown inertia**," *Automatica* (conditionally accepted in 2001).
http://widget.ecn.purdue.edu/~byao/Papers/Automatica01_EHswing.pdf
23) Bin Yao and C. Deboer, "**Energy-saving adaptive robust motion control of single-rod hydraulic cylinders with programmable valves**", the *American Control Conference*, pp4819-4824, Alaska , May, 2002.
http://widget.ecn.purdue.edu/~byao/Papers/Papers/ACC02_INV4802.pdf
24) F. Bu and Bin Yao, "**Nonlinear model based coordinated adaptive robust control of electro-hydraulic robotic manipulators: Practical Issues and Comparative**

Studies", the *ASME International Mechanical Engineers Congress and Exposition (IMECE)*, IMECE01/DSC-4A-3, pp.1-9, 2001
http://widget.ecn.purdue.edu/~byao/Papers/IMECE01_EH.pdf

25) F. Bu and Bin Yao, "**Desired compensation adaptive robust control of single-rod electro-hydraulic actuator**", *American Control Conference*, pp3926-3931, Arlington, 2001. http://widget.ecn.purdue.edu/~byao/Papers/acc2001_EH.pdf
26) F. Bu and Bin Yao, "**Performance improvement of proportional directional control valve: Methods and Comparative Experiments**", *ASME International Mechanical Engineering Congress and Exposition (IMECE)*, DSC-Vol.69-1, pp297-304, Orlando, 2000.
http://widget.ecn.purdue.edu/~byao/Papers/IMECE00_valve.pdf

Energy-Saving Control of Electro-Hydraulic Systems

27) Bin Yao and C. Deboer, "**Energy-saving adaptive robust motion control of single-rod hydraulic cylinders with programmable valves**", the *American Control Conference*, pp4819-4824, Alaska , May, 2002
http://widget.ecn.purdue.edu/~byao/Papers/ACC02_INV4802.pdf
28) Song Liu , Bin Yao , "**Energy-saving control of single-rod hydraulic cylinders with programmable valves and improved working mode selection**", the 2002 *International Fluid Power Exposition (IFPE): Powerful Forces for Motion Control*, joint IFPE/SAE technical sessions, NCFP I02-2.4/SAE OH 2002-01-1343, pp81-91, March 19-23, Las Vegas , 2002
http://widget.ecn.purdue.edu/~byao/Papers/IFPE02_Yao_EH.pdf