University of Connecticut **K.R. Pattipati**
Dept. of Electrical & Computer Engineering **Fall 2012**

ECE 6095/4121: Digital Control of Mechatronic Systems
General Information

Instructor:

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Office Hours: Tuesday-Thursday: 11:00 AM – 12:00 Noon

Classes: Time: Tuesday, 6PM-9PM, Location: Classroom Building, CB302

Text: **(**Class Notes) Pattipati, K.R., and David L. Kleinman, **"Notes for a Comprehensive Course on Digital Control of Mechatronic Systems"**, 2011 (updated Digital Control course notes).
Franklin, G. F., J.D. Powell, and M.L. Workman, **Digital Control of Dynamic Systems**, Powell Publishing, 1998.
MATLAB Companion: Frederick, D., and J.H. Chow, N. W. Chbat, **Discrete-Time Control Problems using Matlab and the Control System Toolbox**,
Brooks Cole, Pacific Grove, CA, 2003
(Optional Reference Text): Clarence W. de Silva, "**Sensors and Actuators: Control Systems Instrumentation,"** Taylor & Francis/CRC Press, Boca Raton, FL, 2007.

Course Objective

This course is designed to provide students with a thorough understanding of the mathematical underpinnings of physical system modeling, sensors and actuators, data acquisition and signal conditioning, classical and modern digital control design methods and the associated computational algorithms for real-time closed-loop computer control of electromechanical systems. The course is addressed to students in engineering who had an undergraduate course in systems analysis and possibly the graduate course, "Introduction to Systems Theory".

Course Outline

Lecture 1: **Introduction and Mathematical Modeling of Systems**

- What is Mechatronics?
- Elements of Mechatronics
- Mechatronics Applications
- Example of Mechatronics Systems
- Mathematical Modeling of Systems and Linearization
  - Diesel Engine Driving a Pump
  - Armature-controlled DC Motor
  - Induction Motor Stray Painting in an Automotive Plant
- State space, transfer function, impulse response and descriptor systems

Lecture 2: Feedback Structures, Digital Control and Stability

- Feedback Control Structures for Continuous-time Systems
  - Output feedback (series compensation, Proportional-Integral-Derivative (PID), Feed forward-feedback, Internal Model Control)
  - State variable feedback
- Classification of Control Design Techniques
- Digital Control Loop Structure
  - Relationships among time signals
  - Typical algorithm implementation considerations
- Discrete-time System Stability
- Continuous-time-vs.-Discrete-time Relationships
  - $s \rightarrow z$ plane mapping

Lectures 3: Models of Sampled Data Systems

- Digital Interfacing
  - Signal Conditioning
  - A/D and D/A converters
- Signal Sampling and Data Reconstruction
  - Impulse sampling model
  - Nyquist theorem
  - Aliasing and interpretation
  - How to avoid aliasing?
  - Sampling period for control
- Discretization of Continuous-time Systems
  - Analysis of the basic digital control loop (Discrete-equivalent system)
  - Discrete Equivalents: State-Space Approach
  - Discrete Equivalents: Transfer Function Approach
  - Relation to original continuous system
  - Bode plot structure of a discrete transfer function
  - Model Modifications with delays in control signals

Lecture 4: Design Process, Performance Criteria, Sensor Rating and Actuator Issues

- Elements of feedback system design (feedback and feedforward, IMC, SVFB)
- Design approaches to be considered
- The Design process
- Performance criteria
  - Stability and phase margin
  - Steady-state accuracy
  - Max peak criteria
  - Speed of response/transient, sum of absolute error, sum of squared error
  - Sensitivity and return difference
  - Sensor rating parameters
  - Actuator nonlinearities
  - Bandwidth design
- Control system design evaluation and simulation
  - Simulation of closed-loop time response
  - Simulation structure and flow diagram
  - Control algorithm simulation
  - Simulation of time delays

Optional Lectures: Sensor and Actuator Models (Notes will be provided. No lectures on these)

- Analog and Digital Sensors
  - Position, Velocity and Acceleration
  - Temperature
  - Strain, Stress, Force and Torque
  - Pressure and Flow
- Continuous- and Incremental-Drive Actuators
  - Stepper Motors
  - DC Motors
  - Induction Motors
  - Synchronous Motors
  - Hydraulic Actuators

Lectures 5-6: Classical SISO (Continuous-time) Control Design Methods

- Loop shaping: Trade-offs and issues
- Design Methods
  - Lag compensator design
  - Lead compensator design
  - Lead-Lag Design
  - PID controller design
    - Different PID structures
    - Integral windup protection
    - PID parameter selection rules
  - IMC design (Shaping S, T or $Q = HS$)

Lectures 7-8: Compensator Design via Discrete-equivalent and Direct Methods

- H(z) Design via Discrete Equivalent to H(s)
  - Forms for discrete integration $1/s \rightarrow F(z)$
  - Different equivalents
  - Tustin equivalent
  - Tustin equivalent with pre-warping
- Example of Discrete Equivalent Design
  - H(s) design to meet specs
  - Discrete equivalent computations
  - Evaluation of CL discrete system
- Root Locus Design of H(z)
  - Example of design approach
  - Evaluation, redesign
- W-Plane Design of H(z)
  - $z \rightarrow w$ and $w \rightarrow z$ mappings
  - Example of design approach
  - Time and frequency domain evaluation
- Time Delay Systems
  - Smith predictor
  - Example
- Implementation of High-Order Compensators

Lecture 9: SVFB via Discrete-equivalent and Pole Placement

- Deadbeat controller
- Continuous-Discrete Gain Tranformation

- Time response equivalence
- Average gain method
- Example-double integrator

- Pole Placement via SVFB Design
  - Direct approach
  - Transformation approach
  - Ackermann formula/algorithm
  - Pole Placement for MIMO Systems
    - state feedback
    - output feedback
- Examples/Applications
  - Continuous-discrete transformation design
  - Direct digital design
- Implementation of High-Order Compensators
  - State prediction
  - Comparison with Smith compensator
  - Examples
- Command Inputs to SVFB Systems

Lecture 10-11: Linear Quadratic Regulator (LQR) Control

- Review of Lyapunov Stability Theory
  - Main theorem for linear systems
- Numerical Solution of Lyapunov Equation
- Constructive Application of Lyapunov Theorem
  - System stabilization
  - Lyapunov ("bang-bang") controller
  - Examples
- Least Squares Optimization
  - Problem definition
  - Optimization algorithm
  - Discrete Riccati equation
  - Properties of optimal control system (robustness, asymptotic properties)
  - sensitivity weighted LQR
  - Frequency-weighted LQR (Full state feedback)
- Examples/Applications
- Rate Weighting
  - Examples
- Minimax and H_∞ controller (full state feedback)
  - Mini-max differential game
  - Synthesizing Mini-max controllers

Lecture 12-13: H_2 and H_∞ optimal control

- Output feedback H_2 optimal controller
  - Synthesizing a H_2 optimal controller
  - LQG: a special H_2 optimal controller
  - Loop transfer recovery
- Output feedback H_∞ controller
  - Solution via bilinear transformation, continuous H_∞ controller and gain transformation
  - Two Riccati equation solution
- H_∞ loop shaping
- Example/Applications

Lecture 14: Numerical Optimization, Non-linear and Networked Control

- Numerical optimization-based approaches
  - l_1-optimal control

    - Design based on Linear Matrix Inequalities
    - Model Predictive Control
- Nonlinear Control
    - Linearization and Gain Scheduling
    - Model predictive Control
    - Sliding Mode Control
    - Neuro-Fuzzy Control
- Networked Control: Cyberphysical Systems
    - Convergence of Computers, Communication and Control
    - Network induced delays and packet drop outs
    - Compensation for Network Induced Delays and packet dropouts

Grading:

Homework/Project Assignments	50%
Sensors and Actuators Presentation	10%
Review Paper Presentation	5%
Term Project and Final Presentation	20%
Mid-term (Take Home)	15%
Total	100%

Additional Information:

- Starting with **Lecture 8**, lectures will be for 2.5 hours and the remaining 0.5-hour will be used for students to present reviews of recent journal publications.

- Paper reviews should be based on relevant and recent (2007 and up) journal articles from, e.g., IEEE Trans. On Automatic Control, IEEE Trans. On SMC, International Journal of Control, Automatica, Computers and Chemical Engineering, IEEE Trans. Control Systems Technology, Systems and Control Letters, etc.

- Term projects can be performed in teams of two students on relevant digital control design topics. Topics could be related to research, or based on at least two recent journal articles. **Numerical implementation** and **testing** are a must.

- Term project **proposals** are due **at the end of Lecture 8** and final presentations are scheduled for the week after last lecture.

- Programming can be done in any language.

References: Many references in "Mechatronics", "analysis of dynamic Systems", "linear control systems" and "numerical methods for linear systems" are available and may prove helpful to you. Some examples are:

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3. Astrom, K. J. and B. Wittenmark, Computer Controlled Systems –Theory and Design, Prentice-Hall Inc., 1984.
4. Astrom,K.J., and R.M.Murray, Feedback Systems: An Introduction for Scientists and Engineers, 2011. Available at http://www.cds.caltech.edu/~murray/amwiki/index.php/Version_2.10d
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7. Bolton, W., Mechatronics, 2nd edition, Essex, England, 1999.
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9. Chen, B.M., T.H Lee and V. Venkataramenan, Hard Disk Drive Servo Systems, Springer-Verlag, London, England, 2002.
10. Chen, T., and B. Francis, Optimal Sampled-data Control Systems, Springer 1995.
11. Chen, C-T., Linear System Theory and Design, Oxford Press, 1999.
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15. Dullerud, G.E., and F. Paganini, A Course in Robust Control Theory: A Convex Approach, Springer, 2000.
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18. Friedland, B., Control System Design: An Introduction to State-space Methods, McGraw-Hill, 1986.
19. Friedland, B., Advanced Control System Design, Prentice Hall, 1996.
20. Golub, G.H., and C.F. Van Loan, Matrix Computations, JHU Press, 1996.
21. Goodwin, G.C., S.F. Graebe and M.E. Salgado, Control System Design, Pearson Education, 2003.
22. Histand, M.B., and D.G. Alciatore, Introduction to Mechatronics and Measurement Systems, WCB McGraw-Hill, New York, NY, 1999.
23. Levine, W.S. (ed.)., The Control Handbook, CRC Press, 1996.
24. Moudgalya, K.M., Digital Control, Wiley, 2007.
25. Necsulescu, D., Mechatronics, Prentice-Hall, Upper Saddle River, NJ, 2002.
26. Patel, R.V., A.J. Laub and P.M. Van Dooren, Numerical Linear Algebra Techniques for Systems and Control, IEEE Press, 1994.
27. Sanchez-Pĕna, R.S., Robust Control Systems, Theory and Applications, Wiley, 1998.
28. Zak, S. h., Systems and Control, Oxford Press, 2003.
29. Zhou, K., J. Doyle and K. Glover, Robust and Optimal Control, Prentice Hall, 1996.