ME552 Electromechanical (Mechatronic) Systems Design
Fall 2007

Course Instructor

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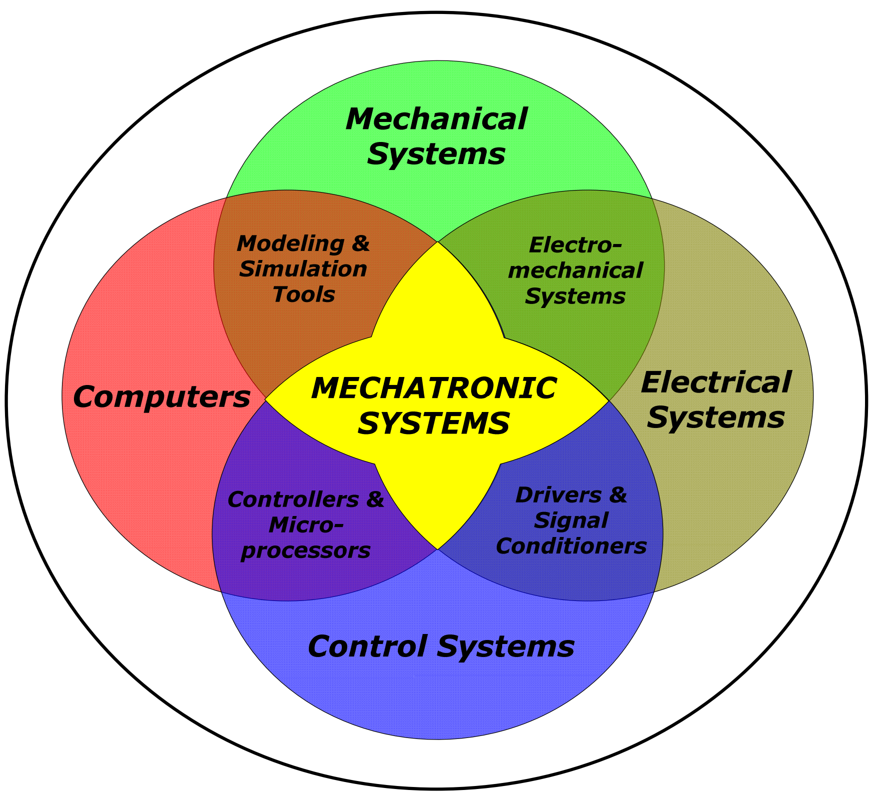
Course Description

'Mechatronic Systems Design' is the synergistic integration of mechanical disciplines, controls, electronics and computers in the design of high-performance machines, devices or processes. This course reviews principles of precision machine design, modeling of multi-domain dynamic systems, controls theory, electronic circuits, and real-time controls implementation. Hands-on lab exercises and design projects provide extensive coverage of mechanical components and assembly, sensors and actuators, electrical drives, signal conditioning circuits, modeling and simulation tools, DAQ hardware and software, and microprocessors.



Lectures

Mon & Wed 9:30-11:00am
(Please note that lectures will start at 9:30am and not 9:40am)
Windows Training Rooms 1 & 2, Third Floor of Duderstadt Center

Instructor Office Hours

Mon & Wed, 11:00am-noon

Course Pre-requisites

ME350 (or equivalent undergraduate mechanical design course)
ME360 (or equivalent undergraduate dynamic systems & controls course)
EECS314 (or equivalent undergraduate electronics course)

ME552 draws heavily from the above topics. Students who have not had one or more of these courses may not have adequate preparation to take ME552 at this point. If you lack the pre-requisites, please meet the instructor immediately to discuss your specific case. Pre-requisite waivers will be rare.

Course Learning Objectives

The overarching objective of this course is to learn a systematic and deterministic process for designing complex multi-disciplinary engineering systems by getting exposure to all aspects of system design: conception, modeling, analysis, performance prediction, component selection, detailed design, fabrication, assembly, system integration, and testing. By the end of this course, the student should develop a professional engineering sense and adequate maturity to design and implement real-life mechatronic systems. The key learning objectives for the student are to

- Understand and practice the 'mechatronic system design and investigation' process.
- Understand the importance of static and dynamic performance in mechatronic systems and identify fundamental design tradeoffs.
- Understand the importance of integrating modeling and controls in the design of mechatronic systems.
- Understand and apply principles of machine design and assembly using a standard Machinery Handbook.
- Be able to create solid models and engineering drawings, suitable for communication to a professional machine shop. Be able to understand and interpret engineering drawings.
- Understand the importance of physical and mathematical modeling (both from first principles and using system identification experimental techniques) in mechatronic

system design. Be able to model and analyze mechanical, electrical, magnetic, and multidisciplinary systems, and identify the analogies among the various physical systems.

- Become proficient in the use of LabVIEW and Matlab/Simulink to model and simulate linear and nonlinear mechatronic systems.
- Understand stability (absolute and relative) and performance (command following, bandwidth, steady-state error, disturbance rejection, robustness) as it applies to feedback control systems.
- Understand and be able to apply various control system design techniques (using of the LabVIEW and MatLab/Simulink): open-loop feedforward control, classical feedback control (root-locus and frequency response), and state-space control.
- Understand the key elements of a measurement system and the basic performance specifications. Be able to model of a variety of analog and digital mechatronic sensors, and read a sensor data sheet.
- Understand the characteristics and models of various electromechanical actuators (brushed dc motor, brushless dc motor, and stepper motor) and hydraulic and pneumatic actuators. Be able to read and understand an actuator data sheet.
- Understand electrical/electronics circuits and components as they apply to mechatronic systems. Be able to read and understand an electronic component data sheet.
- Understand the fundamentals of actuator drivers (power electronics) and sensor drivers / signal conditioning electronics as they apply to mechatronic systems. Be able to read and understand a driver data sheet.
- Understand the digital implementation of control algorithms. Be able to implement a real-time controller through the use of National Instruments control hardware and LabVIEW programming.

Given the nature of 'mechatronic system design' and the wide spectrum of topics covered, this course requires a considerable amount of self-learning on the part of students using study material carefully compiled and provided by the instructor. This study material is meant help students brush-up concepts they have learned in previous courses.

<u>Lab Sections</u>

The class will be divided in two equal-sized sections A and B. Each section will comprise of exactly 8 lab-teams of 2 or 3 students each. Sections A and B will meet for lab exercises on Monday and Wednesday, respectively, from 2:00-5:00pm in the X50 Mechatronics Teaching Lab (GGB 1089). Lab exercises will start in Week 2 (starting Sept 10) and will go on until Week 5 (starting Oct 1). In all, there will be four lab exercises in this course. Further details will be provided in the first lecture. Note that lab hours may be changed to suit the schedule of students taking the class.

Course Project

The course project will start in Week 6 (starting Oct 8) and will continue until Week 14 (nine weeks in all), culminating with the Design Expo on Dec 6, 2007. There will be no structured lab exercises during this period. New teams of approximately six members each will be formed and assigned some time during Weeks 4 and 5.

The course project will be the major thrust of the course. Students will apply the hardware design and analytical skills that they learn in the lectures and the lab-exercises in their projects. The course project involves designing, building and testing a complex mechatronic system of professional quality. Each team will work on the same project idea, which will be assigned by the instructor.

Project-team meetings will start on Oct 8 and will continue till the end of the semester. Each team will spend approximately one hour (per week) in a working meeting with the instructor on Mondays and Wednesdays between 2 and 5pm. Meeting schedule will be determined once the project-teams have been assigned. There will be two or three presentations during the nine weeks of the project, where each team will spend 15min reporting their progress to the entire class.

Project details will be provided in the first and subsequent lectures.

'X50 Mechatronics Lab (GGB 1089)' Access and Use Protocol

Often students may have to come back outside of the official lab hours to spend more time on the lab exercises and course project. For this purpose students will have access to the lab on a 24/7 basis.

As soon as lab-teams are assigned, one member from each 3-member team should provide his/her name to the instructor. Subsequently, this member should pick up a 'Key form' from Sally Smith (GGB 2218). This form has to be taken to the Key Office in the Central Campus, where a key to the 'X50 Mechatronics Lab' (GGB 1089) may be picked up. There will be a $10 dollar deposit which will be refunded at the end of the semester when the key is returned. Making unofficial duplicates of any University of Michigan lab or office key is strictly prohibited. Lending the key to students outside ME552 class is not allowed. During the project phase, every six-member project-team should end up having two or three keys to the lab.

During the extra hours, students will work independently without any instructor or GSI supervision. Professional conduct befitting graduate students in the lab is expected. Detailed lab rules and instructions (including safety instructions) will be provided in the first lecture and lab session. Failure to follow lab rules will result in temporary or permanent loss of lab privileges. Lab and machine shop etiquettes carry 10% of the overall course grade.

Machine Shop Skills and Use Protocols

Students will use one of two available facilities: GG Brown Machine Shop (run by Bob Coury) and the Auto Lab Machine Shop, aka Graduate Machine Shop (run by Steve 'Vice-grip' Emanuel).

Machine shop training is mandatory for every student before he/she is allowed to use any of the two facilities. Shop training has to be scheduled with Bob Coury (GGB 1103) within the first two weeks of the semester. Shop training scheduling instructions will be provided in the first lecture.

Machine shop rules and protocols have to be followed at all times while accessing and working in the machine shops. Detailed instructions will be provided in the first class and subsequently during the course. Failure to follow machine shop rules will result in temporary or permanent loss of shop privileges. Lab and machine-shop etiquettes carry 10% of the overall course grade.

This course requires a significant amount of hardware design and fabrication. It is assumed that students have basic machining and prototyping skills (band-saw cutting, drilling and tapping, machining on a lathe and mill, filing and deburring, etc.). These skills are critical to the successful completion of the course projects. The objective of the shop training is to help students brush-up their previously acquired skills, and NOT to teach them machining from scratch. If you have never used a machine shop in the past, please see the instructor to arrange for appropriate training.

Solid-Modeling and Engineering Drawings

This course will make extensive use of solid-modeling for design generation, presentation, and communication. After preliminary brain-storming using hand-sketches, all teams are expected to create detailed solid models of their designs. These solid models will also be used to generate engineering drawings that are necessary before starting any fabrication in the machine shops. The final report will also require solid models and engineering drawings.

It is assumed that the students will have some basic experience in solid-modeling. Other than online tutorials, no specific CAD training will be provided in this course. While students can use any CAD package of their choice, SolidWorks is the preferred program in this course and is installed on all computers in the 'X50 Mechatronics Lab' as well as on CAEN computers. Designs will often have to be reviewed and critiqued by the instructor, as frequently as the teams require such guidance. SolidWorks is the only allowable mode of design communication with the instructor if you send your files by email and want a quick answer/comment/feedback.

Analytical Tools

This course will utilize Matlab and Simulink to model and simulate physical systems and phenomena (including linear and non-linear behavior, parasitic effects, digitization, etc.), design and test controllers (classical, state-space, non-linear, and others), and verify system design performance before actual fabrication and testing. A good working knowledge of these analytical tools is a must. Optionally, students may also use LabView's Controls and Simulation modules for this purpose. Tutorials to brush-up these skills will be provided.

Experimental Tools

All controls implementation in this course will be carried out using National Instrument's hardware (PCI DAQ cards and cRIOs) and software (LabView, Simulation and Controls modules, FPGA). All computers in the X50 Mechatronics Lab are equipped with PCI -6230 DAQ cards that provide a variety of analog and digital inputs/outputs. Each experimental station is also equipped with a compact Reconfigurable Input-Output (cRIO) device. All computers in the Mechatronics Lab and the two CAEN labs in GG Brown have the latest versions of National Instruments software (LabView, Control Design Toolkit, Simulation Module, System Identification Toolkit, Digital Filter Design, Modulation Toolkit, SignalExpress, and Drivers). Detailed step-by-step tutorials will be provided for all aspects of LabView that are needed in this course.

Course Web-site

An 'ME552 Fall07 ctools' site has been set up for this course, and all students currently enrolled and on waiting list have been given access. If you drop this course and would like to be removed from this site, please send an email to the instructor or GSI. All course material (lectures, lab exercises, handouts, manuals, datasheets, tutorials, etc.) will be posted on this site.

In addition to the ctools site, a lot of useful mechatronics web-resources will be listed on http://www-personal.umich.edu/~awtar/me552

Students should follow both the ctools site and the above listed link throughout the semester.

Course Schedule and Road-Map

Week #	Week of	Date	Lec #	Lecture Topics	Lab#	Lab Topic
1	3-Sep	4-Sep		**Classes Start**		
		5-Sep	1	Course Introduction and Overview, MagLev System Case Study, Mechatronics Demos		
2	10-Sep	10-Sep	2	Electronics/Circuits Refresher: Passive (RLC) Circuits, Time Response / Frequency Response, OpAmp Circuits, Loading effects	1 Sec-A	Introduction to Electronics, Active and Passive Circuits, DAQ and LabView, loading effect
		12-Sep	3	Actuators/Sensors/Drivers: DC Motor, Tachometer, Optical Encoders	1 Sec-B	
3	17-Sep	17-Sep	4	Actuators/Sensors/Drivers: Servo Amplifers, H-Bridge and PWM control	2 Sec-A	Stepper Motor Control: Motor Driver, Open-loop control, optical encoder
		19-Sep	5	Actuators/Sensors/Drivers: Brushless/Stepper Motor, Motor Drivers (H-Bridge and PWM control)	2 Sec-B	
4	24-Sep	24-Sep	6	Dynamic System Modeling: Inverted Pendulum Case Study	3 Sec-A	DC Motor characterization and closed-loop Control
		26-Sep	7	Control System Design: Inverted Pendulum Case Study	3 Sec-B	
5	1-Oct	1-Oct	8	Parasitic Effects: Inverted Pendulum System Case Study (Friction, Backlash, Saturation, Sensor and Servo Amplifier Noise)	4 Sec-A	IP system (classical State-space and non-linear)
		3-Oct	9	Precision Machine Design: Inverted Pendulum System Case Study (mounting, alignment, fasteners, clamps, design detailing, assembly)	4 Sec-B	
6	8-Oct	8-Oct	10	Project Introduction and Overview, Administrative Issues, Team Assignment, Project timeline, Machine Shop Primer		**Projects Start: Design Phase Weekly project team meetings; Concept Generation and Selection, Solid Modeling**
		10-Oct	11	Dynamic System Modeling and Controls Design: Ball on Plate Balancing System Case Study		
7	15-Oct	15-Oct		**Study Break, No lecture, No lab**		Dynamic System Modeling, Control System Design, Design Detailing, Component Selection
		17-Oct	12	Precision Machine Design: Ball on Plate Balancing System Case Study (Component Selection, Fabrication and Assembly)		
8	22-Oct	22-Oct	13	Precision Machine Design: Linear and Rotary Bearings, Couplings, Gears, Ball/Lead Screws		Prepare to place any component orders by the end of this week. Final design is sealed. Start preparing engineering drawings and manufacturing/assembly plans
		24-Oct	14	Sensors (LVDT, Interferometry, Capacitance Probes, Linear Scales, Hall Effect) and Specifications (Range, Resolution, Noise, Bandwidth, Power Consumption)		

9	29-Oct	29-Oct	15	Actuators (Piezoelectric, SMA, Pneumatic, Hydraulic) and Specifications (Load Speed Curves, Power Density, Range, Resolution, Bandwidth)		**Fabrication and Procurement Phase; Class presentation (15min) to go over design details and manufacturing plan, Place all orders, Start Fabrication in the Machine Shop**
		31-Oct	16	Electrical / Electronic Parasitic Effects: noise, aliasing, discretization and digitization, transmission delays, loading effects, ground loops		
10	5-Nov	5-Nov	17	Mechanical Parasitic Effects: Backlash, Friction, Unmodeled resonances		Hardware Fabrication in the Machine Shops; Build/assemble/test any circuit components; Start using cRIO and FPGA
		7-Nov	18	Dynamic System Modeling: International Space Station Case Study		
11	12-Nov	12-Nov	19	Control System Design: International Space Station Case Study		All mechanical components fabricated and all ordered parts received by the end of this week
		14-Nov	20	Microprocessors: Real-time Controls Implementation		
12	19-Nov	19-Nov	21	Microprocessors: Real-time Controls Implementation		**Assembly, Integration and Testing Phase; Class presentation (15min) to report on progress; Start system assembly and integration**
		21-Nov	22	Microprocessors: Real-time Controls Implementation		
				Thanksgiving Break		
13	26-Nov	26-Nov		No Lecture		Controller Programming, testing and Debugging
		28-Nov		No Lecture		
14	3-Dec	3-Dec		No Lecture		Controller Programming, testing and Debugging, Final mechatronic system ready
		5-Dec		No Lecture		
		6-Dec		**DESIGN EXPO**		**SHOW TIME !!!**
15	10-Dec	10-Dec	23	**Last Day of classes: Course Wrap-up, Final Report Due**		
		13-Dec		**Final Exam**		

Grading Format and Policy

The grade break-down for the course is as follows:

Item #	Labs	Points	Credit
1	Lab1	10	100% individual
2	Lab2	10	100% individual
3	Lab3	10	100% individual
4	Lab4	10	100% individual
	Project		
5	System Modeling and Simulation in Design Phase	10	70% team 30% individual
6	Mechanical Design Detail and Manufacturing/Assembly Plan	10	70% team 30% individual
7	Sensor, Actuator, Drive Selection	10	70% team 30% individual
8	Final Prototype: Manufacturing/Assembly Plan execution, Professional Looks	10	70% team 30% individual
9	Final Prototype: Basic Functionality	10	70% team 30% individual
10	Final Report (one report per team)	10	70% team 30% individual
11	Lab and Machine Shop etiquettes	10	determined case by case
	Total Points (before bonus)	100	
12	Final Prototype: Advanced Functionality (bonus points)	10	70% team 30% individual
	Maximum Possible Points	110	

Grading Rules

1. Lowest grade from items 1 through 9 will be dropped for each student
2. Grades for items 10 and 11 will always be counted, and cannot be dropped
3. Item 12 provides 10 bonus points beyond the maximum of 100 points that can be earned from items 1 through 11
4. Peer evaluation will be an important aspect of determining individual contributions for items 5 through 10
5. Students are encouraged to discuss their grades with the instructor as frequently as needed. The student is always given the benefit of the doubt in all grade discussions and every effort will be made to find ways to help a student improve his/her grade throughout the semester.

General References *(NOT TO BE PURCHASED)*

A wealth of information is now available online, generally through google and specifically through Wikipedia, HowStuffWorks, eFunda, etc. Students are encouraged to seek web resources, especially on practical matters.

The following is a list of books that might be useful to refer to once in a while during the course. However, complete course material will be provided by the instructor in the form of slides, summaries, tutorials, hand-outs etc.

⇒ Machine Design

1. Machinery Handbook (available through the library)
2. ASM Handbook (http://products.asminternational.org/hbk/index.jsp, available through the library)
3. www.machinedesign.com
4. Precision Machine Design, A.H. Slocum, SME, 1992

⇒ Modeling, Analysis, and Control of Dynamic Systems

1. *Dynamics of Physical Systems,* R.H. Cannon, McGraw-Hill, 1967.
2. *System Dynamics*, E. O. Doebelin, Marcel Dekker, 1998.
3. *Modeling, Analysis, and Control of Dynamic Systems*, W.J. Palm, 2nd Edition, Wiley, 1999.
4. *System Dynamics*, 3rd Edition, K. Ogata, Prentice-Hall, 1998.
5. *Control System Principles and Design*, E.O. Doebelin, Wiley, 1985
6. *Feedback Control of Dynamic Systems*, Franklin, G., Powell, J., and Emami-Naeini, A., 4th Edition, Prentice Hall, 2002.
7. *Modern Control Engineering*, 4th Edition, K. Ogata, Prentice Hall, 2002.
8. *Advanced Control System Design*, B. Friedland, Prentice Hall, 1996.
9. *Digital Control of Dynamic Systems*, Franklin, G., Powell, J., and Workman, M., 3rd Edition, Addison-Wesley, 1998.
10. *Discrete-Time Control Systems*, 2nd Edition, K. Ogata, Prentice-Hall, 1995.
11. *Computer Control of Machines and Processes*, J. Bollinger & N. Duffie, Addison-Wesley, 1989.
12. *The Control Handbook*, W. Levine, Editor, CRC press, 1996.

⇒ Sensors and Actuators

1. *Measurement Systems*, E.O. Doebelin, 4th Edition, McGraw-Hill, 1990.
2. *Control Sensors and Actuators*, C.W. deSilva, Prentice-Hall, 1989.
3. *Electromechanical Motion Devices*, P. Krause and O. Wasynczuk, McGraw Hill, 1989.
4. *Electric Machinery Fundamentals*, 3rd Edition, S. Chapman, McGraw Hill, 1999.

5. *Stepping Motors: A Guide to Modern Theory and Practice*, 3rd Edition, P. Acarnley, IEE, 1992.
6. *Step Motor System Design Handbook*, 2nd Edition, A. Leenhouts, Litchfield Engineering Company, 1997.
7. *DC Motors, Speed Controls, Servo Systems*, The Electro-Craft Engineering Handbook, Reliance Motion Control, Inc.
8. *Electric Motors and Their Controls,* T. Kenjo, Oxford 1991.
9. www.machinedesign.com

⇒ Electronics and Microcontrollers

1. *Art of Electronics*, Horowitz, P. and Hill, W., 2nd Edition, Cambridge University Press, 1989.
2. *Principles and Applications of Electrical Engineering*, G. Rizzoni, 4th Edition, McGraw Hill, 2003.
3. *The Art of Designing Embedded Systems*, J. Ganssle, Newnes, 2000.

Recommendations for adding other good references to the above list are highly welcome. Please let the instructor know if you have found some reference material to be particularly useful and instructive.

Class Attendance and Participation:

Attendance in ALL lectures and lab sessions is mandatory and participation in class is strongly encouraged. There will be no make-up sessions if you miss a lecture or lab. In case of an emergency, please notify the instructor or GSI in advance. Student feedback is vital to the effectiveness of this class. Comments, suggestions and feedback from individual students or student groups are welcome throughout the course.

Academic integrity is a key component of the educational process. Students, GSI and the instructor are expected to conduct themselves in a professional manner at all times.