ELEC ENG 4CL4
Control System Design

COURSE OUTLINE
Please refer to course website for updated information.

CALENDAR/COURSE DESCRIPTION

Calendar Description: Design of linear control systems using classical and state-space techniques; performance limitation; sampled-data control; nonlinear systems; multi-input multi-output control systems.
Course Summary: This is an advanced undergraduate course in analysis and design of modern control systems. The course focuses on continuous-time linear dynamical systems in the state-space domain. It exposes the students to fundamental concepts such as state-space representation of dynamics, solution of state-space dynamics, linearization of nonlinear dynamics, controllability and observability of state-space models, and stability of linear dynamical systems. The course also introduces methods for the design of linear feedback control systems via state and output feedback for regulation and tracking problems. The analysis and design topics cover examples from modern control engineering applications.

PRE-REQUISITES AND ANTI-REQUISITES

Prerequisite(s): ELECENG 3CL4, ELECENG 3TP4 or 3TP3
Antirequisite(s): IBEHS 4A03

SCHEDULE

Lectures: Monday, Thursday 9:30am-10:20am, Tuesday 10:30am-11:20am (HH-102)
Tutorial: Monday 12:30pm-1:20 pm (HH-102)
Labs: *Every Other Week*- L01 Mondays 2:30 p.m.- 5:20 p.m.; L02 Mondays 2:30 p.m.- 5:20 p.m.; L03 Tuesdays 2:30 p.m.- 5:20 p.m.; L04 Tuesdays 2:30 p.m.- 5:20 p.m.(ITB-155)

INSTRUCTOR

Dr. Shahin Sirouspour
Email: sirous@mcmaster.ca
Office: ITB-A319
Phone: 905-525-9140 ext. 26238
Office Hours: By appointment

TEACHING ASSISTANTS

Keyvan Mohammadi ; Sahand Ghaffari ; Ali Grivani

Contact information and office hours are provided on the course website.

COURSE WEBSITE

http://avenue.mcmaster.ca/

COURSE OBJECTIVES

By the end of this course, students should be able to:

- Develop state-space models from differential equations describing behaviour of a continuous-time system
- Linearize nonlinear continuous-time dynamics around operating points to obtain approximate linear state-space models
- Find solutions to linear-time-invariant (LTI) state-space dynamics using time-domain and Laplace-domain techniques
- Analyze fundamental properties of LTI state-space systems, i.e. stability, controllability, and observablity
- Derive various equivalent canonical form representations of LTI state-space dynamics using similarity transformations
- Convert state-space and transfer matrix representations of LTI systems to each other
- Design state-feedback controllers for LTI state-space systems
- Design output-feedback controllers with state-space observers for LTI state-space systems

ASSUMED KNOWLEDGE

Background knowledge from an introductory course in linear controls using Laplace-domain techniques (e.g. ELEC ENG 3CL4) is essential. The course also requires a solid background in linear algebra; students are also strongly encouraged to review the background linear algebra material in the third chapter of the textbook.

COURSE MATERIALS

Required Texts: C.-T Chen, *Linear System Theory and Design*, 4^{td} edition, Oxford University Press, 2012.

Calculator: Any type of calculator will be permitted in tests and examinations.

Other Materials:

- Instructor lecture slides available through the avenue system.
- R. L. Williams II and D.A. Lawrence, *Linear State-Space Control Systems*, John Wiley & Sons Inc., 2007.
- R.A. Horn and C.R. Johnson, *Matrix Analysis*, Cambridge University Press, 1985.

COURSE OVERVIEW

Week	Topic
1-3	**State-space Representation of Dynamical Systems**
1	Concept of State Space Dynamics
1	Examples of State-space Representations of Electrical and Mechanical Systems
2	Linear (Time-Invariant) State-space Representation
2	Linearization of Nonlinear Dynamical Systems
3	Composite Dynamic Systems
3-5	**Response of Linear Time-invariant Systems**
3	Solution of State-space Differential Equations: Homogenous and General cases
3	Impulse Response and Transfer Function
4-5	State Coordinate Transformation
5	Modal Canonical Representation of State-space Dynamics
6	**Stability of Linear Dynamical Systems**
6	Internal Stability
6	Input-Output Stability
7-8	**Controllability**
7	Concept and Fundamental Results
7	State Transformations and Controllability
8	Controllability Canonical Form
8	Controllability Tests
9	**Observability**
9	Concept and Fundamental Results
9	State Transformations and Observability
9	Observability Canonical Form
9	Observability Tests
9-10	**Minimal Realization of Linear Dynamical Systems**
9	Single-input/Single-output Systems
10	Multiple-input/Multiple-output Systems
10	Controllable & Observable Canonical Form Realizations
11-12	**Linear State Feedback Control**
11	State-feedback Control Law
12	Pole Placement
12	Stabilizability

13	**Linear Output Feedback Control**
13	Observers and Detectability
13	Observer-based Feedback Control and the Separation Principle

The instructor may modify elements of the course throughout the term and will notify students accordingly in class and/or on the course website of any potential changes.

LABORATORY OVERVIEW

The course has an open-ended laboratory project to encourage problem-based learning and critical thinking. The project will expose the students to all aspects of modern control engineering, from modeling and analysis, to design, implementation and experimental verification of an advanced feedback control system. There are no rigid step-by-step instructions to follow. Instead, a set of control system design requirements will be provided, which must be met by the end of the project. The project is organized into four phases with clear milestones that guide the students towards the development of the final control system.

The objective of the lab project is to develop, implement, and experimentally verify a control system for balancing and positioning of a non-conventional inverted pendulum mechanism. This is a variation of the challenging classic inverted pendulum control problem.

Date/Week	Topic
1-2	**Phase 1. Analytical Modeling and Simulation:** Develop a full nonlinear model of the custom inverted pendulum mechanism in the state-space domain. Linearize the model around desired equilibrium points. Implement the model in Matlab/Simulink environment and simulate the system response.
3	**Phase 2. System Identification and Verification:** Estimate the unknown model parameters by carrying out system identification experiments on the laboratory setup. Evaluate the quality of the parameter estimates.
4	**Phase 3. System Analysis & Control Synthesis:** Examine stability, controllability and observability of the open-loop linearized model. Synthesize feedback controllers to achieve the control objectives. Analyze and simulate the closed-loop system response in Matlab/Simulink environment in order to verify the design.
5	**Phase 4. Implementation & Demonstration:** Implement the controllers on the experimental setup and verify the results. Demonstrate the control system in action!

LABORATORY OPERATION

The lab project should be carried in groups of at most two students. The students must form these groups at the beginning of the term for the entire duration of the course. Each group will submit an electronic report for each of the phases as well as a final report through avenue system. Detailed lab instructions for each phase of the project and the format of the reports will be provided throughout the term.

ASSESSMENT

Component	Weight
Midterm	20%
Laboratory Project	40%
Final Exam	40%
Total	100%

Deferred Exams: FOR A DEFERRED MIDETERM EXAMINATION, THE WEIGHT WOULD BE GIVEN TO THE FINAL EXAM. THE INSTRUCTOR RESERVES THE RIGHT TO CHOOSE THE FORMAT OF ANY DEFERRED FINAL EXAM (I.E. FORMAT MAY BE WRITTEN OR ORAL)

ACCREDITATION LEARNING OUTCOMES

Note: The *Learning Outcomes* defined in this section are measured throughout the course and form part of the Department's continuous improvement process. They are a key component of the accreditation process for the program and will not be taken into consideration in determining a student's actual grade in the course. For more information on accreditation, please ask your instructor or visit: http://www.engineerscanada.ca .

Outcomes	Indicators	Measurement Methods(s)
Develop linear state-space models of physical systems and compute their response using time-domain and frequency (Laplace) domain techniques.	1.1 2.2	Questions in Midterm & Final Examinations
Understand and and analyze fundamental properties of state-space linear time-invariant systems such as stability, controllability, and observability using linear algebra tools.	2.2	Questions in Midterm & Final Examinations
Understand the design process, and can design state feedback controllers and state observers for linear state-space systems. Use tools in Matlab/Simulink environment to design controllers/observers and evaluate their performance using a model of the system.	5.1 5.2 5.3 4.1	Questions in Midterm & Final Examinations Performance in Laboratory Experiments & Lab Reports
Use Matlab/Simulink tools for real-time hardware-in-the-loop experiments.	5.1 5.2 5.3	Performance in Laboratory Experiments & Lab Reports

ACADEMIC INTEGRITY

You are expected to exhibit honesty and use ethical behaviour in all aspects of the learning process. Academic credentials you earn are rooted in principles of honesty and academic integrity.
Academic dishonesty is to knowingly act or fail to act in a way that results or could result in unearned academic credit or advantage. This behaviour can result in serious consequences, e.g. the grade of zero on an assignment, loss of credit with a notation on the transcript (notation reads: “Grade of F assigned for academic dishonesty”), and/or suspension or expulsion from the university.
It is your responsibility to understand what constitutes academic dishonesty. For information on the various types of academic dishonesty please refer to the Academic Integrity Policy, located at www.mcmaster.ca/academicintegrity .
The following illustrates only three forms of academic dishonesty:
• Plagiarism, e.g. the submission of work that is not one’s own or for which other credit has been obtained.
• Improper collaboration in group work.
• Copying or using unauthorized aids in tests and examinations.

ACADEMIC ACCOMMODATIONS

Students with disabilities who require academic accommodation must contact Student Accessibility Services (SAS) to make arrangements with a Program Coordinator. Student Accessibility Services can be contacted by phone 905-525-9140 ext. 28652 or e-mail sas@mcmaster.ca . For further information, consult McMaster University’s Academic Accommodation of Students with Disabilities policy.

Students requiring academic accommodation based on religious, indigenous or spiritual observances should follow the procedures set out in the RISO policy. Students requiring a RISO accommodation should submit their request to the Engineering Student Services office normally within 10 working days of the beginning of term in which they anticipate a need for accommodation or to the Registrar's Office prior to their examinations.

Students should also contact their instructors as soon as possible to make alternative arrangements for classes, assignments, and tests.

STUDENT ABSENCE AND SUBMISSION OF REQUEST FOR RELIEF FOR MISSED ACADEMIC WORK

In the event of an absence for medical or other reasons, students should review and follow the Academic Regulation in the Undergraduate Calendar “Requests for Relief for Missed Academic Term Work”.

EXTREME CIRCUMSTANCES

The University reserves the right to change the dates and deadlines for any or all courses in extreme circumstances (e.g., severe weather, labour disruptions, etc.). Changes will be communicated through regular McMaster communication channels, such as McMaster Daily News, A2L and/or McMaster email.

ONLINE ACCESS OR WORK

In this course we will be using Avenue To Learn. Students should be aware that, when they access the electronic components of this course, private information such as first and last names, user names for the McMaster e-mail accounts, and program affiliation may become apparent to all other students in the same course. The available information is dependent on the technology used. Continuation in this course will be deemed consent to this disclosure.
If you have any questions or concerns about such disclosure please discuss this with the course instructor.

The Department of Electrical & Computer Engineering website:
www.eng.mcmaster.ca/ece

Electrical and Computer Engineering Lab Safety

Information for Laboratory Safety and Important Contacts

This document is for users of ECE instructional laboratories in the Information Technology Building.

This document provides important information for the healthy and safe operation of ECE instructional laboratories. This document is required reading for all laboratory supervisors, instructors, researchers, staff, and students working in or managing instructional laboratories in ECE. It is expected that revisions and updates to this document will be done continually. A McMaster University lab manual is also available to read in every laboratory.

General Health and Safety Principles

Good laboratory practice requires that every laboratory worker and supervisor observe the following:

1. Food and beverages are not permitted in the instructional laboratories.
2. A Laboratory Information Sheet on each lab door identifying potential hazards and emergency contact names should be known.
3. Laboratory equipment should only be used for its designed purpose.
4. Proper and safe use of lab equipment should be known before using it.
5. The course TA leading the lab should be informed of any unsafe condition.
6. The location and correct use of all available safety equipment should be known.
7. Potential hazards and appropriate safety precautions should be determined, and sufficiency of existing safety equipment should be confirmed before beginning new operations.
8. Proper waste disposal procedures should be followed.

Location of Safety Equipment

Fire Extinguisher
On walls in halls outside of labs

First Aid Kit
ITB A111, or dial "88" after 4:30 p.m.

Telephone
On the wall of every lab near the door

Fire Alarm Pulls
Near all building exit doors on all floors

Who to Contact

Emergency Medical / Security: On McMaster University campus, call Security at extension **88** or **905-522-4135** from a cell phone.
Non-Emergency Accident or Incident: Immediately inform the TA on duty or Course Instructor.
University Security (Enquiries / Non-Emergency): Dial 24281 on a McMaster phone or dial 905-525-9140 ext. 24281 from a cell phone.
See TA or Instructor: For problems with heat, ventilation, fire extinguishers, or immediate repairs
Environmental & Occupational Health Support Services (EOHSS): For health and safety questions dial 24352 on a McMaster phone or dial 905-525-9140 ext. 24352 from a cell phone.
ECE Specific Instructional Laboratory Concerns: For non-emergency questions specific to the ECE

In Case of a Fire (Dial 88)

When calling to report a fire, give name, exact location, and building.

1. Immediately vacate the building via the nearest Exit Route. Do not use elevators!
2. Everyone is responsible for knowing the location of the nearest fire extinguisher, the fire alarm, and the nearest fire escape.
3. The safety of all people in the vicinity of a fire is of foremost importance. But do not endanger yourself!
4. In the event of a fire in your work area shout "*Fire!*" and pull the nearest fire alarm.
5. Do not attempt to extinguish a fire unless you are confident it can be done in a

prompt and safe manner utilizing a hand-held fire extinguisher. Use the appropriate fire extinguisher for the specific type of fire. Most labs are equipped with Class A, B, and C extinguishers. Do not attempt to extinguish Class D fires which involve combustible metals such as magnesium, titanium, sodium, potassium, zirconium, lithium, and any other finely divided metals which are oxidizable. Use a fire sand bucket for Class D fires.

6. Do not attempt to fight a major fire on your own.
7. If possible, make sure the room is evacuated; close but do not lock the door and safely exit the building.

Clothing on Fire

Do not use a fire extinguisher on people

1. Douse with water from safety shower immediately or
2. Roll on floor and scream for help or
3. Wrap with fire blanket to smother flame (a coat or other nonflammable fiber may be used if blanket is unavailable). Do not wrap a standing person; rather, lay the victim down to extinguish the fire. The blanket should be removed once the fire is out to disperse the heat.

Equipment Failure or Hazard

Failure of equipment may be indicative of a safety hazard - You must report all incidents.

Should you observe excessive heat, excessive noise, damage, and/or abnormal behaviour of the lab equipment:

1. Immediately discontinue use of the equipment.
2. In Power Lab, press wall-mounted emergency shut-off button.
3. Inform your TA of the problem.
4. Wait for further instructions from your TA.
5. TA must file an incident report.

Protocol for Safe Laboratory Practice

Leave equipment in a safe state for the next person - if you're not sure, ask!

In general, leave equipment in a safe state when you finish with it. When in doubt, consult the course TA.

Defined Roles

TA	The first point of contact for lab supervision	
ECE Lab Supervisor	Steve Spencer- ITB 147	steve@mail.ece.mcmaster.ca
ECE Chair	Tim Davidson- ITB A111	davidson@mcmaster.ca
ECE Administrator	Kerri Hastings- ITB A111	hastings@mcmaster.ca
ECE Course Instructor	Please contact your specific course instructor directly	