ELECENG 4CL4
Control System Design

Course Outline
Please refer to course website for updated information.

CALENDAR/COURSE DESCRIPTION

McMaster UG Calendar: Design of linear control systems using classical and state-space techniques; performance limitation; sampled-data control; nonlinear systems; multi-input multi-output control systems

Instructor's Course Summary: This course delves into the analysis and design of modern control systems, particularly focusing on continuous-time linear dynamical systems within the state-space domain. The course covers fundamental concepts such as the state-space representation of dynamics, the solution of state-space dynamics, the linearization of nonlinear dynamics, the controllability and observability of state-space models, and the stability of linear dynamical systems. Additionally, the course introduces methodologies for the design of linear feedback control systems, utilizing state and output feedback for regulation and tracking applications. The analysis and design topics presented are drawn from modern control engineering applications.

PRE-REQUISITES AND ANTI-REQUISITES

Prerequisite(s): ELECENG 3CL4, ELECENG 3TP4;

SCHEDULE And MODE OF DELIVERY

The material for this course will be delivered through in-person lectures and tutorials. The students are expected to attend the in-person lectures and tutorials.

Lectures: Monday, Wednesday 8:30-9:20am, Friday 10:30am-11:20pm
Tutorial: Tuesday 11:30am-12:20pm
Labs: *Every other week*- L01 Mondays 2:30 p.m.- 5:20 p.m.; L02 Tuesdays 2:30 p.m.- 5:20 p.m.; L03 Thursdays 2:30 p.m.- 5:20 p.m.; L04 Fridays 2:30 p.m.- 5:20 p.m.

INSTRUCTOR OFFICE HOURS AND CONTACT INFORMATION

Dr. Shahin Sirouspour
ITB- A319
sirous@mcmaster.ca
ext. 26238

Office Hours: By appointment

TEACHING ASSISTANT OFFICE HOURS AND CONTACT INFORMATION

TA names, contact information and office hours are provided on the course website.

COURSE WEBSITE/ALTERNATE METHODS OF COMMUNICATION

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 dynamical system
- Linearize nonlinear continuous-time dynamics around operating points/trajectories to obtain approximate linear state-space models
- Find solutions to linear-time-invariant (LTI) state-space dynamics using time-domain and Laplace-domain techniques
- Comprehend and analyze fundamental properties of LTI state-space systems, i.e., stability, controllability, and observability
- 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 crucial. Additionally, a solid background in linear algebra is essential. Students are strongly encouraged to review the background linear algebra material in the third chapter of the recommended textbook and the slides on the same subject matter posted on Avenue to Learn.

COURSE MATERIALS

The primary course materials are lecture slides and pre-recorded videos that will be made available on the Avenue.

Primary Recommended Text (not required): C.-T Chen, *Linear System Theory and Design*, 4td edition, Oxford University Press, 2013.

Other Reading Materials:

- 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.

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

COURSE OVERVIEW

Week	Topic
1-2	**State-space Representation of Dynamical Systems**
1	Concept of State Space Dynamics
1	Examples of State-space Representations of Electrical and Mechanical Systems
1	Linear (Time-Invariant) State-space Representation
2	Linearization of Nonlinear Dynamical Systems
2	Composite Dynamic Systems
3-4	**Response of Linear Time-invariant Systems**
3	Solution of State-space Differential Equations: Homogenous and General cases
4	Impulse Response and Transfer Function
4	State Coordinate Transformation
5	Modal Canonical Representation of State-space Dynamics
5	**Stability of Linear Dynamical Systems**
5	Internal Stability
6	Input-Output Stability
6-8	**Controllability**
6	Concept and Fundamental Results
6	State Transformations and Controllability
7	Controllability Canonical Form
7-8	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
10-11	**Linear State Feedback Control**
10	State-feedback Control Law
11	Pole Placement
11	Stabilizability
12-13	**Linear Output Feedback Control**
12	Observers and Detectability
13	Observer-based Feedback Control and the Separation Principle
13	State and Output Feedback Control for MIMO Systems

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: MODELING, IDENTIFICATION AND CONTROL OF AN INVERTED PENDULUM MECHANISM

The course has a laboratory project to encourage problem-based learning and critical thinking. The project will expose the students to all aspects of modern control design process, from modeling and analysis, to design, implementation, and experimental verification of an advanced feedback control system. The project is organized into six phases with clear milestones that would 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.

Week	Topic
1	**Phase 0. Modeling and Simulation of State-space Control Systems in MATLAB/SIMULINK Environment:** Become familiar some of the tools available in MATLAB/Simulink environment for modelling and simulation of state-space dynamical systems.
2	**Phase 1. System Modeling and Simulation:** Develop a full nonlinear model of the 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. Estimation of Unknown Model Parameters:** 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. State-Feedback Control of Inverted Pendulum:** Examine stability and controllability of the open-loop linearized model. Synthesize a state-feedback controller to achieve the control objectives. Analyze and simulate the closed-loop system response in Matlab/Simulink environment to verify the design. Implement the state-feedback feedback controller on the inverted Pendulum using numerically computed joint velocities.
5	**Phase 4. Feedback Control Using Full-State Observer:** Develop and implement a full-state observer to estimate the Inverted Pendulum states from encoder measurements. Combine the estimator and state-feedback controller. Evaluate system response in simulations and in experiments with the actual inverted pendulum.
6	**Phase 5. Feedback Control with Reduced-order Observer:** Design and implement a reduced-order observer to estimate the two unmeasured states of the Inverted Pendulum, i.e., the joint velocities. Integrate this reduced-order observer with the state feedback controller from Phase 4 to control the Inverted Pendulum around its unstable upright equilibrium state.

Laboratory Operation

The lab project should be conducted in groups of two students. Students must form these groups at the beginning of the term and maintain them throughout the course. Each group will submit an electronic report for each phase of the project. Detailed lab instructions and report formats will be provided throughout the term.

Assessment

Component	Weight
Midterm	25%
Laboratory Project	40%
Final Exam	35%
Total	100%

Deferred Exams: FOR A DEFERRED MIDETERM EXAMINATION, THE WEIGHT WOULD BE GIVEN TO THE FINAL EXAM.

CEAB Graduate Attributes (GAs)

Note: The CEAB Graduate Attributes (GAs) 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 .

Attributes	Indicators		Measurement Method(s)
	Number	Description	
Knowledge Base for Engineering	1.1	Competence in Mathematics	Questions in Midterm & Final Examinations
Problem Analysis	2.2	Proposes problem solutions supported by substantiated reasoning, recognizing the limitations of the solutions	Questions in Midterm & Final Examinations
Investigation	3.2	Capable of selecting appropriate models and methods and identifying assumptions and constraints	Questions in Midterm & Final Examinations
Design	4.2	Explores a breadth of potential solutions, considering their benefits and trade-offs as they	Questions in the lab reports, Mid-term Exam or Final Exam

Attributes	Indicators		Measurement Method(s)
	Number	**Description**	
		relate to the project requirements.	
Use of Engineering Tools	5.2	Successfully uses engineering tools	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. It is your responsibility to understand what constitutes academic dishonesty. 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. For information on the various types of academic dishonesty please refer to the Academic Integrity Policy, located at https://secretariat.mcmaster.ca/university-policies-proceduresguidelines/
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.

AUTHENTICITY / PLAGIARISM DETECTION

Some courses may use a web-based service (Turnitin.com) to reveal authenticity and ownership of student submitted work. For courses using such software, students will be expected to submit their work electronically either directly to Turnitin.com or via an online learning platform (e.g. A2L, etc.) using plagiarism detection (a service supported by Turnitin.com) so it can be checked for academic dishonesty.
Students who do not wish their work to be submitted through the plagiarism detection software must inform the Instructor before the assignment is due. No penalty will be assigned to a student who does not submit work to the plagiarism detection software. All submitted work is subject to normal verification that standards of academic integrity have been upheld (e.g., on-line search, other software, etc.). For more details about McMaster’s use of Turnitin.com please go to www.mcmaster.ca/academicintegrity.

COURSES WITH AN ON-LINE ELEMENT

Some courses may use on-line elements (e.g. e-mail, Avenue to Learn (A2L), LearnLink, web pages, capa, Moodle, ThinkingCap, etc.). Students should be aware that, when they access the electronic components of a course using these elements, 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 a course that uses on-line elements will be deemed consent to this disclosure. If you have any questions or concerns about such disclosure please discuss this with the course instructor.

Some courses may use online proctoring software for tests and exams. This software may require students to turn on their video camera, present identification, monitor and record their computer activities, and/or lock/restrict their browser or other applications/software during tests or exams. This software may be required to be installed before the test/exam begins.

COPYRIGHT AND RECORDING

Students are advised that lectures, demonstrations, performances, and any other course material provided by an instructor include copyright protected works. The Copyright Act and copyright law protect every original literary, dramatic, musical and artistic work, including lectures by University instructors.
The recording of lectures, tutorials, or other methods of instruction may occur during a course. Recording may be done by either the instructor for the purpose of authorized distribution, or by a student for the purpose of personal study. Students should be aware that their voice and/or image may be recorded by others during the class. Please speak with the instructor if this is a concern for you.

CONDUCT EXPECTATIONS

As a McMaster student, you have the right to experience, and the responsibility to demonstrate, respectful and dignified interactions within all of our living, learning and working communities. These expectations are described in the Code of Student Rights & Responsibilities (the “Code”). All students share the responsibility of maintaining a positive environment for the academic and personal growth of all McMaster community members, whether in person or online. It is essential that students be mindful of their interactions online, as the Code remains in effect in virtual learning environments. The Code applies to any interactions that adversely affect, disrupt, or interfere with reasonable participation in University activities. Student disruptions or behaviours that interfere with university functions on online platforms (e.g. use of Avenue 2 Learn, WebEx or Zoom for delivery), will be taken very seriously and will be investigated. Outcomes may include restriction or removal of the involved students’ access to these platforms.

ACADEMIC ACCOMMODATIONS

Students with disabilities who require academic accommodation must contact Student Accessibility Services (SAS) at 905-525-9140 ext. 28652 or sas@mcmaster.ca to make arrangements with a Program Coordinator. 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 should submit their request to their Faculty 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.

REQUESTS FOR RELIEF FOR MISSED ACADEMIC WORK

McMaster Student Absence Form (MSAF): 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.

www.eng.mcmaster.ca/ece

Electrical and Computer Engineering Lab Safety

Information for Laboratory Safety and Important Contacts

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 and online https://hr.mcmaster.ca/app/uploads/2019/07/2019-McMaster-Lab-Manual.pdf

General Health and Safety Principles

Good laboratory practice requires that every laboratory worker and supervisor observe the following whether conducting lab work at school or at home:

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.
9. Personal ergonomics should be practiced when conducting lab work. https://bit.ly/3fOE71E
10. Current University health and safety issues, and protocol should be known.

https://hr.mcmaster.ca/resources/covid19/workplace-health-and-safety-guidance-during-covid-19/

Location of Safety Equipment

Fire Extinguisher
On walls in halls outside of labs

First Aid Kit
Main Lobby of ITB 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 laboratories, please contact 24103.

In Case of a Fire (On Campus 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 labs, 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

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	Shahram Shirani- ITB A111	shirani@mcmaster.ca
ECE Administrator	Shelby Gaudrault- ITB A111	gaudraus@mcmaster.ca
ECE Course Instructor	Please contact your specific course instructor directly	