Appendix C
Course Samples

Some sample materials of the courses that I developed and taught can be found beginning on the next page. A list of the samples is found below.

- EE458 Automatic Controls and EE558 Advanced Automatic Controls:
  - EE458 course syllabus in Fall 2022.
  - EE558 course syllabus in Fall 2022.
  - A homework assignment (Homework 1) in Fall 2022.
  - Midterm Exam 2 in Fall 2022.
  - A hardware-based lab using the Temperature Control Lab (TCLab).
  - A computer-based lab using Matlab and Simulink.
- EE499 Introduction to Autonomous Driving:
  - Course syllabus in Spring 2020.
  - A lab for autonomous driving using a wall-following algorithm.
- EE222 Intermediate Programming: Course syllabus in Spring 2021.
- EE599/EE559 Modern Control Systems:
  - Course syllabus in Spring 2023.
  - A homework assignment.

NORTHERN ARIZONA UNIVERSITY

College of Engineering, Informatics & Applied Sciences
School of Informatics, Computing, and Cyber Systems

Term	Class No.	Section	Units	Days & Times	Room	Mode
Fall 2022	EE 458	001 A	3	MW 9:10-10:00 AM M 2:00 – 4:30 PM	Bldg. 90 – Rm. 102	In Person

Department/ Academic Unit:
School of Informatics, Computing, and Cyber Systems

Course prefix, Section number and Title:
EE 458, Section 001 (Lecture) and Section A (Lab), Automatic Controls

Term/ Year: Fall 2022

Total Units of Course Credit: 3

Course Pre-requisite(s), Co-requisite(s), Co-convened, and/or Cross-Listed Courses:
(EE 348 or ME 358) with grades of C or better. Familiarity with the following mathematical skills: complex arithmetic, vector and matrix arithmetic, integration, differentiation, differential equations and their solutions. Good Matlab programming skill.

Mode of Instruction: In Person

Course Website: http://bblearn.nau.edu

Instructor:

Name: Dr. Truong Nghiem
E-mail: truong.nghiem@nau.edu
Office Hours: Thursday 3:00 PM - 4:00 PM.
Only via BBLearn: use "Virtual Classroom" link on BBLearn shell.
In-person meetings available by appointment only.
Other times available by appointment.
Office: Room 303, SICCS Building #90, 1295 S. Knoles Drive.
In-person meetings available by appointment only.

Teaching Assistant:

Name: Yujian Huang
E-mail: yh298@nau.edu
Office Hours: Tuesday 3:00 PM - 4:00 PM. In person; Place: SICCS Building, Room 318.

Grader: N/A.

Course Purpose: This course develops an understanding of the theory of automatic control and its applications. The focus is on the modeling, analysis, design, and simulation of linear feedback control systems in the frequency domain.

Course Student Learning Outcomes: Upon completion of this course, students will:

LO1) Understand the principles, advantages and limitations of feedback control.
LO2) Be familiar with the widespread application areas of automatic control, especially in electrical and mechanical systems.
LO3) Understand and have practiced developing linear models of physical systems, linearization, Laplace transforms, transfer functions, and manipulating block diagrams.
LO4) Understand the concept of and learn methods for stability and performance analysis of feedback control systems, steady-state error analysis, Routh-Hurwitz stability analysis.
LO5) Learn and practice the root locus method for analyzing and designing feedback control systems, PID controller and PID tuning, and lead-lag compensators.
LO6) Learn and practice frequency response method for analyzing and designing feedback control systems, Bode plots, and the Nyquist criterion.
LO7) Learn to use Matlab, Simulink, and the Matlab's Control System Toolbox for modeling, analysis, and design of feedback control systems.
LO8) Apply learned knowledge and develop practical skills in modeling, analyzing, and designing automatic control systems through several real-world design projects.

Assignments/Assessment of Course Student Learning Outcomes:
The following methods of assessment are designed to evaluate a student's mastery of the materials in this course for the learning outcomes LO1-LO8.

- **Quizzes (assessing learning outcomes LO1, LO2, LO3, LO4, LO5, LO6)**: There will be a quiz after each week's lectures to assess the student's basic understanding of the topics discussed in the lectures. The questions are usually at the low and medium levels of difficulty. The lowest quiz grade will be dropped in the calculation of the final grade.
- **Homework (assessing learning outcomes LO3, LO4, LO5, LO6)**: Homework assignments will be assigned on a regular basis and will typically be due one week after being assigned (unless specified otherwise by the instructor). Some assignments may involve working in Matlab and reporting code, computation results, and plots. The questions in homework assignments are usually at the medium to high levels of difficulty, to prepare students for the exams.
- **Exams (assessing learning outcomes LO1, LO2, LO3, LO4, LO5, LO6)**: There will be two midterm exams and a final exam, equally spaced throughout the semester. The final exam is comprehensive, on all topic covered in the semester.
- **Labs (assessing learning outcomes LO3, LO4, LO5, LO6, LO7, LO8)**: There will be computer-based and hardware-based lab assignments. For each lab assignment, each student must submit Matlab code / Simulink model and a lab report, which will be graded. Detailed instructions will be provided for each lab assignment.
- **Assessment test (not included in final course grade)**: In the first week, a mathematical assessment test will be given. The assessment results will not be included in the final course grade; however, students with low scores are recommended to improve their respective mathematical skills to succeed in this course.

Grading System: Final letter grades will be assigned as follows:
A: ≥ 90%;

B: ≥ 80% and < 90%
C: ≥ 70% and < 80%
D: ≥ 60% and < 70%
F: < 60%

Course grades will be calculated as follows:

Quizzes:	10%
Homework:	10%
Mid-term Exams:	30% (15% each)
Final Exam:	30%
Labs:	20%

This course does not grade students relative to each other. There is no grading curve. Please address concerns regarding the grading of your assignments during office hours, or by appointment. Do not ask about your grade before, during, or after class.

Reading and Materials:

Textbook: R.C. Dorf and R.H. Bishop, *Modern Control Systems*, Prentice Hall, 13th Edition, 2016

Suggested References:

- K. Astrom and R. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*, First Edition, Princeton University Press, 2008. This text is publicly available for download from http://www.cds.caltech.edu/~murray/amwiki
- N.S. Nise, *Control Systems Engineering*, 7th Edition, Wiley, 2015
- K. Ogata, *Modern Control Engineering*, 5th Edition, Prentice Hall, 2010

Lectures will occasionally include material not found in the textbook. You are responsible for all material discussed in class or assigned in the text.

Required software: Each student must have access to a computer with a recent version of Matlab and Simulink, available for free as part of NAU's standard software distribution and in most computer labs.

Emergency Textbook Loan Program: Eligible students can apply for assistance with acquisition of textbooks for the semester. More information can be found at: https://in.nau.edu/dean-of-students/course-materials-assistance-program/

Important NAU Resources:

- The NAU Resilience Project is an online toolkit that helps you build healthy coping skills and learn about wellness resources to help you "bounce back" in the face of adversity (https://bounceback.healthpromotion.nau.edu/).
- The Academic Success Center helps student with many challenging topics (including CS) across campus. Check out their website for FREE tutoring and other resources (https://in.nau.edu/academic-success-centers/).
- The Office of the Dean of Students understands that Life happens to everybody! If you find yourself in need of help during your attendance of classes here at NAU, the Office of the Dean of Students can help you navigate those major life events (https://in.nau.edu/dean-of-students/).

Class Outline:

Although the lectures will generally follow the material in the text, we will occasionally skip certain material and may include supplementary topics.

- Introduction to control systems: Definitions, Control system design cycle
- Mathematical Models of Systems
  - Differential equations, Classification of systems, Linearization, Laplace transform
  - Transfer functions, block diagrams
- Properties of feedback control systems
  - Error signal analysis, sensitivity of control systems to parameter variations, disturbance rejection, noise attenuation
  - LTI systems response to test input signals, performance of feedback control systems
  - Transient response analysis
  - Steady-state error
- The stability of linear feedback systems
  - The concept of stability
  - Routh-Hurwitz stability criterion
- Root locus method
  - Root locus concept and procedure
  - Parameter design by the root locus method
- PID Control:
  - Properties, realization, design methods
- Design of Feedback Control Systems
  - Cascade compensation networks
  - Lead compensator design via root locus
  - Lag compensator design via root locus

Tentative Schedule:

Important:

- The schedule is tentative and is subject to changes, including due dates for assignments. Updates will be posted on BBLearn. Please check BBLearn frequently for updates.
- The sections listed in the "Reading" column below are required reading (in the textbook, unless otherwise noted). Lectures do not necessarily cover everything in the listed sections but only the most important topics and are also reserved for discussions and questions. All contents in the listed sections may be tested in the quizzes, assignments, and exams. Students are therefore required to read and learn all the listed sections, regardless of the contents covered in the lectures. Section numbers in red color are unlikely to be covered in class but still required (most are examples or software instructions).

Week	Lecture / Lab Topics	Reading	Assignments & Notes
Week 1	Introduction to course, Fundamental concepts	1.1, 1.3, 1.5, 1.8, 1.9 2.2, 2.3, 2.4	Assessment Test. Review in textbook: Matlab basics (Appendix A), Complex numbers (Appendix G).
Weeks 2-4	System modeling	2.4, 2.5, 2.6, 2.7, 2.8, 2.9	Homework 1 Project starts
Weeks 5	Control system characteristics	4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9	
Week 6	Control system performance **Review & Midterm Exam 1**	5.2, 5.3, 5.4, 5.5, 5.6, 5.9, 5.10	

Week 7-9	Control system performance Stability of linear feedback systems	5.2, 5.3, 5.4, 5.5, 5.6, 5.9, 5.10 6.1, 6.2, 6.3, 6.5, 6.6	Homework 2 Project Stage 1 due
Week 10-11	Root Locus Method **Review & Midterm Exam 2**	7.1, 7.2, 7.3, 7.4, 7.5, 7.7, 7.8, 7.9	Homework 3
Week 12	Root Locus Method	7.1, 7.2, 7.3, 7.4, 7.5, 7.7, 7.8, 7.9	Project Stage 2 due
Weeks 13-14	Design of Feedback Control Systems: Root Locus, PID control	7.6, 10.2, 10.3, 10.5, 10.6, 10.7, 10.13	Homework 4
Week 15	Review Week	All chapters	Project Stage 3 due
Week 16	**Finals Week**	All chapters	**Final Exam**

Class Policies:

Syllabus Adjustments: Everything in this syllabus is subject to change. If it becomes necessary or prudent for me to change something, I will try to do so fairly and transparently.

Copyright Notice: The instructor holds the copyright for all slides, instructor lecture notes, assignments, and exams for this class. You may not redistribute these materials to anyone, including others in the class, without **written permission** from the instructor. Students enrolled in the class are encouraged to obtain their own copies of available materials from the course website. Violation of this policy constitutes academic misconduct and may further result in criminal or civil penalties for copyright violation.

Attendance:

- The Class Attendance policy in the NAU Academic Policies requires students to assume the responsibility for regular class attendance. When absence is unavoidable, students should report the reason to the instructor and assume the responsibility for any work they miss. Instructors are under no obligation to make special arrangements for students who have been absent.
- Students should make every effort to be in their seats (if in-person) or logged in online (if remote) and ready when class begins. In the rare cases where being tardy is unavoidable, a student should enter the class or the virtual classroom as quietly as possible so that other students are not disturbed. Students with tardiness or attendance problems may have points deducted from their grade and might not be allowed to join a class in progress.
- You are responsible for all materials covered by the assigned reading and during the classes, whether you attend or not. I am happy to answer any questions you have about a missed lecture, but I will not repeat it for you.
- Students who are experiencing illness (including COVID-19) are asked to follow isolation and/or quarantine protocols as described on the NAU Jacks Are Back website (https://nau.edu/legacy/jacks-are-back/health-and-mitigation/). Other accommodation for life events and illness may be available after contacting the Office of the Dean of Students (https://in.nau.edu/dean-of-students/).

Academic Integrity:

- Every student should fully understand and comply with the *NAU Academic Integrity Policy*: https://policy.nau.edu/policy/policy.aspx?num=100601 and https://in.nau.edu/academic-affairs/academic-integrity/
- Academic dishonesty, including cheating and plagiarism, will not be tolerated. All academic integrity violations are treated seriously. All work you submit for grading must be your own. You are encouraged to discuss the intellectual aspects of assignments with other class participants. However, each student is responsible for formulating responses and solutions on their own and in their own works. Academic integrity violations will result in penalties including, but not limited to, a zero on the assignment / project / exam, a failing grade in the class, or expulsion from NAU.
- Not knowing that certain activities qualify as academic dishonesty is not a defense to a charge of academic dishonesty.
- If you are charged with academic dishonesty, you are subject to the procedures established in the *NAU Academic Integrity Policy*. See the policy document for more information.

Homework assignments:

- Homework assignments, whether typed or handwritten, must be neat and legible. Students are encouraged to type the assignments.
- Assignments must be completed outside of class and submitted through BBLearn. Assignments submitted by email or in person will not be accepted. Illegible submissions (for example, low scan quality) will not be graded.
- On all assignments, any sources of information that are not the original creation of the author nor taught in class nor in the textbook must be cited in sufficient detail that the instructor can locate and verify the sources. If you are repeating this class, you may not use previous work that you completed for a previous class.

Quizzes:

- Quizzes are given to increase student participation in classes and enhance student learning. There will be no make-up quizzes.
- Quizzes are in both the form of multiple choices and the form of written answers to be submitted online through BBLearn.
- The following policy is designed to account for unexpected, emergency life events that may happen to some students, while maintaining fairness for all students: The lowest quiz grade will be dropped in the calculation of the final grade.

Exams:

- If conducted in-person: exams are closed book and closed notes. You may use dedicated calculators, unless mentioned otherwise, but you are not allowed to use laptops and cell phones. Calculator software is not allowed.
- If conducted online: exams are open book, open notes, and conducted through an online service (such as BBLearn). Measures will be taken to prevent cheating, including but not limited to: randomized questions, combination of multiple-choice questions and long-answer questions, timed exam, displaying questions one-by-one without the ability to re-visit a previous question.
- Exams are individualized, meaning that questions are different between students.
- No makeup exams will be given except by prior arrangement in exceptional or emergency situations at the discretion of the instructor and will require a documented emergency supported by a class missed memo from Student Life (https://nau.edu/student-life/classes-missed-memos/)

and with approval from the instructor. Make-up exams may be considerably different than the original exam.

Labs:

- Labs are conducted during the scheduled lab time. Labs are divided into several lab assignments, for each of which Matlab code / Simulink models and a lab report must be submitted and will be due approximately two weeks after the assignment.
- For every lab, each student must do all the activities in the lab by himself/herself and submit his/her own work in his/her own words individually. Group submissions of labs are not allowed.

Late submissions:

- The following late submission policy is designed to account for unexpected, emergency life events that may happen to some students, while maintaining fairness for all students.
- For all exams (midterms and final) and quizzes, late submissions will not be accepted and will result in zeros for the grades.
- For all assignments, students are highly encouraged to submit their works before the deadlines.
- The penalty for a late submission of a homework or project assignment, unless permitted otherwise in advance by the instructor, is determined as follows:
    - Late by 0-1 day (0-24 hours): deduct 25 percentage points absolute (not relative) from the earned grade; for example: if your earned grade is 85% but it was submitted 10 hours late, then your grade is 85% - 25% = 60%.
    - Late by more than 1 day (24 hours): grade is zero (0).

Grading:

- Grades will be entered in BBLearn but your final grade will be calculated in Excel using the grading system described above and then entered in LOUIE. Your final course grade will not necessarily appear in BBLearn. Please check LOUIE for your final grade.
- Grades will be calculated based not only on technical content but also on the presentation of your work. The presentation should be neat, legible, clear, using standard technical terms and symbols.
- Most problems in homework and exams will be graded using the following scale: a first quarter of available points for formulating a solution (identifying the technique/equations necessary for the solution); a second quarter of available points for carrying out the solution but a major error is found in the work; a third quarter of available points for a correct solution; and a fourth quarter of available points for a good presentation. Full or half points can be subtracted for small errors. Illegible answers will have no points.
- No other grading accommodations will be made, with the exception of extreme cases where the university administration becomes involved, such as extended hospitalization.
- University policy for grade appeals (applied only to the final course grade) can be found at https://www5.nau.edu/policies/Client/Details/437.

Extenuating Circumstances:

- Exceptions to the late assignment, attendance, class activity, and examination policies may be made only under certain extenuating circumstances such as a serious illness or an institutional excuse, and will require valid written verification.
- A valid medical excuse must state that you are unable to attend classes due to the severity of the illness or the risk of spreading it and should clearly state the dates that you should be absent from

the university. A written medical note that simply states that you visited a clinic or were seen by a doctor or nurse is not valid and will not be accepted.

- Students should inform the instructor of an institutional excuse or any significant scheduled events – such as religious ceremonies, away games for NAU athletes, weddings, conference travel, etc. – in writing at least 5 working days prior to the absence. Given these conditions, make-up work may be assigned and due before the student leaves for the event.
- Be aware that neither medical nor institutional excuses absolve you of making up any required work or exams. Remember also that you can always turn in an assignment early.
- Details of the student institutional excuses policy can be found in https://nau.edu/university-policy-library/wp-content/uploads/sites/26/Student-Institutional-Excuses.pdf

Communication: Email to the instructor and teaching assistants must be respectful and professional. Specifically, all emails should:

- Have the subject prefixed with "EE458" so that the message can be easily identified or placed in an auto-folder. The subject should also use lower case and upper case correctly.
- Contain a formal salutation: "Dear Dr. Nghiem"
- Contain a closing, (for example, "Best, Jane Doe")
- The body should contain complete sentences and correct grammar including correct usage of lowercase and uppercase letters. Composing emails on a mobile device is **not** an excuse for poor writing.
- The body of your message should also be respectful and explain the full context of the query.
- Although email will typically be answered quickly, you should allow up to three (3) business days for a response.
- If you have a question that would require a long response or you have a lot of questions, please come to office hours or schedule an appointment with the instructor.

Other means of electronic communication are also used in this course, which will be described by the instructor.

Learning:

- You are expected to read the textbook, and watch the posted lecture / supplementary videos, to learn the material and achieve the objectives in the course. This includes reading and working the example problems in detail. Not all topics are covered in depth in lectures, nor can examples be done for each type of problems you may encounter in the homework. To be able to do the homework assignments, exams, and project, it is not sufficient to rely only on the in-class lectures; you should invest your study time in reading the textbook on the topics covered in this course.
- Students are strongly encouraged to complete all assignments to prepare for the examinations.
- Students are strongly encouraged to seek assistance for their learning either from the instructor and/or the TA(s) and other campus' resources. The Academic Success Centers offer free tutoring and academic support to improve students' study skills and review course material in a number of engineering and math courses. Students can schedule an appointment by visiting http://nau.edu/asc, calling the Academic Success Center at 928-523-7391 or visiting Dubois Center - Room 140.

Cell Phone, Laptop, and Other Electronic Device Policies:

- In class: Electronic device usage must support learning in the class. Laptop computers and tablets may only be used for class activities during class time. All cell phones, PDAs, music players and other entertainment devices must be turned off (or in silent mode) during lecture, and may not be used at any time. Texting and phone calls are not allowed during class. If you do receive an emergency call, ask to be excused so that you can take it outside the classroom.

- During an exam: Cell phones, pagers and other electronic devices MUST be turned off. Their use is prohibited during an exam. You may use a dedicated calculator, not calculator software on a device such as smartphone or tablet.

APPENDIX A. UNIVERSITY POLICY STATEMENTS

COVID-19 REQUIREMENTS AND INFORMATION

Additional information about the University's response to COVID-19 is available from the **Jacks are Back!** web page located at https://nau.edu/jacks-are-back.

Syllabus Policy Statements

ACADEMIC INTEGRITY

NAU expects every student to firmly adhere to a strong ethical code of academic integrity in all their scholarly pursuits. The primary attributes of academic integrity are honesty, trustworthiness, fairness, and responsibility. As a student, you are expected to submit original work while giving proper credit to other people's ideas or contributions. Acting with academic integrity means completing your assignments independently while truthfully acknowledging all sources of information, or collaboration with others when appropriate. When you submit your work, you are implicitly declaring that the work is your own. Academic integrity is expected not only during formal coursework, but in all your relationships or interactions that are connected to the educational enterprise. All forms of academic deceit such as plagiarism, cheating, collusion, falsification or fabrication of results or records, permitting your work to be submitted by another, or inappropriately recycling your own work from one class to another, constitute academic misconduct that may result in serious disciplinary consequences. All students and faculty members are responsible for reporting suspected instances of academic misconduct. All students are encouraged to complete NAU's online academic integrity workshop available in the E-Learning Center and should review the full *Academic Integrity* policy available at https://policy.nau.edu/policy/policy.aspx?num=100601.

COURSE TIME COMMITMENT

Pursuant to Arizona Board of Regents guidance (ABOR Policy 2-224, *Academic Credit*), each unit of credit requires a minimum of 45 hours of work by students, including but not limited to, class time, preparation, homework, and studying. For example, for a 3-credit course a student should expect to work at least 8.5 hours each week in a 16-week session and a minimum of 33 hours per week for a 3-credit course in a 4-week session.

DISRUPTIVE BEHAVIOR

Membership in NAU's academic community entails a special obligation to maintain class environments that are conductive to learning, whether instruction is taking place in the classroom, a laboratory or clinical setting, during course-related fieldwork, or online. Students have the obligation to engage in the educational process in a manner that does not interfere with normal class activities or violate the rights of others. Instructors have the authority and responsibility to address disruptive behavior that interferes with student learning, which can include the involuntary withdrawal of a student from a course with a grade of "W". For additional information, see NAU's *Disruptive Behavior in an Instructional Setting* policy at https://nau.edu/university-policy-library/disruptive-behavior.

NONDISCRIMINATION AND ANTI-HARASSMENT

NAU prohibits discrimination and harassment based on sex, gender, gender identity, race, color, age, national origin, religion, sexual orientation, disability, or veteran status. Due to potentially unethical consequences, certain consensual amorous or sexual relationships between faculty and students are also prohibited as set forth in the *Consensual Romantic and Sexual Relationships* policy. The Equity and Access Office (EAO) responds to complaints regarding discrimination and harassment that fall under NAU's *Nondiscrimination and Anti-Harassment* policy. EAO also assists with religious accommodations. For additional information about nondiscrimination or anti-harassment or to file a complaint, contact EAO located in Old Main (building 10), Room 113, PO Box 4083, Flagstaff, AZ 86011, or by phone at 928-523-3312 (TTY: 928-523-1006), fax at 928-523-9977, email at equityandaccess@nau.edu, or visit the EAO website at https://nau.edu/equity-and-access.

TITLE IX
Title IX is the primary federal law that prohibits discrimination on the basis of sex or gender in educational programs or activities. Sex discrimination for this purpose includes sexual harassment, sexual assault or relationship violence, and stalking (including cyber-stalking). Title IX requires that universities appoint a "Title IX Coordinator" to monitor the institution's compliance with this important civil rights law. NAU's Title IX Coordinator is Elyce C. Morris. The Title IX Coordinator is available to meet with any student to discuss any Title IX issue or concern. You may contact the Title IX Coordinator by phone at 928-523-3515, by fax at 928-523-0640, or by email at elyce.morris@nau.edu. In furtherance of its Title IX obligations, NAU will promptly investigate and equitably resolve all reports of sex or gender-based discrimination, harassment, or sexual misconduct and will eliminate any hostile environment as defined by law. Additional important information about Title IX and related student resources, including how to request immediate help or confidential support following an act of sexual violence, is available at https://in.nau.edu/title-ix.

ACCESSIBILITY
Professional disability specialists are available at Disability Resources to facilitate a range of academic support services and accommodations for students with disabilities. If you have a documented disability, you can request assistance by contacting Disability Resources at 928-523-8773 (voice), 928-523-6906 (TTY), 928-523-8747 (fax), or dr@nau.edu (e-mail). Once eligibility has been determined, students register with Disability Resources every semester to activate their approved accommodations. Although a student may request an accommodation at any time, it is best to initiate the application process at least four weeks before a student wishes to receive an accommodation. Students may begin the accommodation process by submitting a self-identification form online at https://nau.edu/disability-resources/student-eligibility-process or by contacting Disability Resources. The Director of Disability Resources, Jamie Axelrod, serves as NAU's Americans with Disabilities Act Coordinator and Section 504 Compliance Officer. He can be reached at jamie.axelrod@nau.edu.

RESPONSIBLE CONDUCT OF RESEARCH
Students who engage in research at NAU must receive appropriate Responsible Conduct of Research (RCR) training. This instruction is designed to help ensure proper awareness and application of well-established professional norms and ethical principles related to the performance of all scientific research activities. More information regarding RCR training is available at https://nau.edu/research/compliance/research-integrity.

MISCONDUCT IN RESEARCH
As noted, NAU expects every student to firmly adhere to a strong code of academic integrity in all their scholarly pursuits. This includes avoiding fabrication, falsification, or plagiarism when conducting research or reporting research results. Engaging in research misconduct may result in serious disciplinary consequences. Students must also report any suspected or actual instances of research misconduct of which they become aware. Allegations of research misconduct should be reported to your instructor or the University's Research Integrity Officer, Dr. David Faguy, who can be reached at david.faguy@nau.edu or 928-523-6117. More information about misconduct in research is available at https://nau.edu/university-policy-library/misconduct-in-research.

SENSITIVE COURSE MATERIALS
University education aims to expand student understanding and awareness. Thus, it necessarily involves engagement with a wide range of information, ideas, and creative representations. In their college studies, students can expect to encounter and to critically appraise materials that may differ from and perhaps challenge familiar understandings, ideas, and beliefs. Students are encouraged to discuss these matters with faculty.

College of Engineering, Informatics & Applied Sciences
School of Informatics, Computing, and Cyber Systems

Term	Class No.	Section	Units	Days & Times	Room	Mode
Fall 2022	EE 558	001 A	3	MW 9:10-10:00 AM M 2:00 – 4:30 PM	Bldg. 90 – Rm. 102	In Person

Department/ Academic Unit:
School of Informatics, Computing, and Cyber Systems

Course prefix, Section number and Title:
EE 558, Section 001 (Lecture) and Section A (Lab), Automatic Controls

Term/ Year: Fall 2022

Total Units of Course Credit: 3

Course Pre-requisite(s), Co-requisite(s), Co-convened, and/or Cross-Listed Courses:
Admission to Electrical Engineering MS, Mechanical Engineering MS, or Mechanical Engineering MEng. Good understanding of differential equations, systems of linear differential equations, and their solutions (equivalent to EE 325). Good mathematical skills in complex arithmetic, vector and matrix arithmetic, integration and differentiation (equivalent to EE 325). Good Matlab programming skill (equivalent to CS 122).
This course is co-convened with EE 458 – Automatic Controls.

Mode of Instruction: In Person

Course Website: http://bblearn.nau.edu

Instructor:

Name: Dr. Truong Nghiem
E-mail: truong.nghiem@nau.edu
Office Hours: Thursday 3:00 PM - 4:00 PM.
Only via BBLearn: use "Virtual Classroom" link on BBLearn shell.
In-person meetings available by appointment only.
Other times available by appointment.
Office: Room 303, SICCS Building #90, 1295 S. Knoles Drive.
In-person meetings available by appointment only.

Teaching Assistant:

Name: Yujian Huang
E-mail: yh298@nau.edu
Office Hours: Tuesday 3:00 PM - 4:00 PM. In person; Place: SICCS Building, Room 318.

Grader: N/A.

Course Purpose: This course develops an advanced understanding of the theory and practice of automatic control systems and its applications. The focus is on the modeling, analysis, design, and simulation of linear feedback control systems in the frequency domain.

Course Student Learning Outcomes: Compared to the co-convened course EE 458, students in this course will develop more advanced understanding and skills of modeling, analysis, design, and simulation of linear feedback control systems. Upon completion of this course, students will:

LO1) Have advanced understanding of the principles, advantages, limitations, and applications of automatic controls.
LO2) Develop knowledge and advanced skills in deriving mathematical models of complex electrical and mechanical physical systems.
LO3) Understand and practice block diagrams, linearization, and Laplace transforms to obtain transfer functions of systems.
LO4) Understand the concept of and learn methods for stability and performance analysis of feedback control systems, steady-state error analysis, Routh-Hurwitz stability analysis.
LO5) Learn and practice the root locus method for analyzing and designing feedback control systems, PID controller and PID tuning, and lead-lag compensators.
LO6) Learn and practice frequency response method for analyzing and designing feedback control systems, Bode plots, and the Nyquist criterion.
LO7) Develop advanced skills in Matlab, Simulink, and Control System Toolbox for modeling, analysis, and design of feedback control systems.
LO8) Apply learned knowledge and develop practical skills in modeling, analyzing, and designing automatic control systems through a real-world hardware-based project.

Assignments/Assessment of Course Student Learning Outcomes:
The following methods of assessment are designed to evaluate a student's mastery of the materials in this course for the learning outcomes LO1-LO8.

- **Quizzes (assessing learning outcomes LO1, LO2, LO3, LO4, LO5, LO6)**: There will be a quiz after each week’s lectures to assess the student’s basic understanding of the topics discussed in the lectures. The questions are usually at the low and medium levels of difficulty. The lowest quiz grade will be dropped in the calculation of the final grade.
- **Homework (assessing learning outcomes LO2, LO3, LO4, LO5, LO6)**: Homework assignments will be assigned on a regular basis and will typically be due one week after being assigned (unless specified otherwise by the instructor). Some assignments may involve working in Matlab and reporting code, computation results, and plots. The questions in homework assignments are usually at the medium to high levels of difficulty, to prepare students for the exams.
- **Exams (assessing learning outcomes LO1, LO2, LO3, LO4, LO5, LO6)**: There will be two midterm exams and a final exam, equally spaced throughout the semester. The final exam is comprehensive, on all topic covered in the semester.
- **Labs (assessing learning outcomes LO2, LO3, LO4, LO5, LO6, LO7, LO8)**: There will be computer-based and hardware-based lab assignments. For each lab assignment, each student must submit Matlab code / Simulink model and a lab report, which will be graded. Detailed instructions will be provided for each lab assignment.

- **Assessment test (not included in final course grade)**: In the first week, a mathematical assessment test will be given. The assessment results will not be included in the final course grade; however, students with low scores are recommended to improve their respective mathematical skills to succeed in this course.

Graduate students in this course will have different and/or additional questions on assignments and exams than undergraduate students in the co-convened course will have. These questions will test more advanced knowledge and skills, as well as topics not required for undergraduate students.
For all course-related work, graduate students will be held to a higher standard of professionalism and quality of work than one would expect to find in the equivalent undergraduate course, as befits a graduate level experience.

Grading System: Final letter grades will be assigned as follows:

A: ≥ 90%;
B: ≥ 80% and < 90%
C: ≥ 70% and < 80%
D: ≥ 60% and < 70%
F: < 60%

Course grades will be calculated as follows:

Quizzes:	10%
Homework:	10%
Mid-term Exams:	30% (15% each)
Final Exam:	30%
Labs:	20%

This course does not grade students relative to each other. There is no grading curve. Please address concerns regarding the grading of your assignments during office hours, or by appointment. Do not ask about your grade before, during, or after class.

Reading and Materials:

Textbook: R.C. Dorf and R.H. Bishop, *Modern Control Systems*, Prentice Hall, 13th Edition, 2016
Suggested References:

- K. Astrom and R. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*, First Edition, Princeton University Press, 2008. This text is publicly available for download from http://www.cds.caltech.edu/~murray/amwiki
- N.S. Nise, *Control Systems Engineering*, 7th Edition, Wiley, 2015
- K. Ogata, *Modern Control Engineering*, 5th Edition, Prentice Hall, 2010

Lectures will occasionally include material not found in the textbook. You are responsible for all material discussed in class or assigned in the text.

Required software: Each student must have access to a computer with a recent version of Matlab and Simulink, available for free as part of NAU's standard software distribution and in most computer labs.

Emergency Textbook Loan Program: Eligible students can apply for assistance with acquisition of textbooks for the semester. More information can be found at: https://in.nau.edu/dean-of-students/course-materials-assistance-program/

Important NAU Resources:

- The NAU Resilience Project is an online toolkit that helps you build healthy coping skills and learn about wellness resources to help you "bounce back" in the face of adversity (https://bounceback.healthpromotion.nau.edu/).
- The Academic Success Center helps student with many challenging topics (including CS) across campus. Check out their website for FREE tutoring and other resources (https://in.nau.edu/academic-success-centers/).
- The Office of the Dean of Students understands that Life happens to everybody! If you find yourself in need of help during your attendance of classes here at NAU, the Office of the Dean of Students can help you navigate those major life events (https://in.nau.edu/dean-of-students/).

Class Outline:

Although the lectures will generally follow the material in the text, we will occasionally skip certain material and may include supplementary topics.

- Introduction to control systems: Definitions, Control system design cycle
- Mathematical Models of Systems
    - Differential equations, Classification of systems, Linearization, Laplace transform
    - Transfer functions, block diagrams
- Properties of feedback control systems
    - Error signal analysis, sensitivity of control systems to parameter variations, disturbance rejection, noise attenuation
    - LTI systems response to test input signals, performance of feedback control systems
    - Transient response analysis
    - Steady-state error
- The stability of linear feedback systems
    - The concept of stability
    - Routh-Hurwitz stability criterion
- Root locus method
    - Root locus concept and procedure
    - Parameter design by the root locus method
- PID Control:
    - Properties, realization, design methods
- Design of Feedback Control Systems
    - Cascade compensation networks
    - Lead compensator design via root locus
    - Lag compensator design via root locus

Tentative Schedule:

Important:

- The schedule is tentative and is subject to changes, including due dates for assignments. Updates will be posted on BBLearn. Please check BBLearn frequently for updates.
- The sections listed in the "Reading" column below are required reading (in the textbook, unless otherwise noted). Lectures do not necessarily cover everything in the listed sections but only the most important topics and are also reserved for discussions and questions. All contents in the listed sections may be tested in the quizzes, assignments, and exams. Students are therefore required to

read and learn all the listed sections, regardless of the contents covered in the lectures. Section numbers in red color are unlikely to be covered in class but still required (most are examples or software instructions).

Week	Lecture / Lab Topics	Reading	Assignments & Notes
Week 1	Introduction to course, Fundamental concepts	1.1, 1.3, 1.5, 1.8, 1.9 2.2, 2.3, 2.4	Assessment Test. Review in textbook: Matlab basics (Appendix A), Complex numbers (Appendix G).
Weeks 2-4	System modeling	2.4, 2.5, 2.6, 2.7, 2.8, 2.9	Homework 1 Project starts
Weeks 5	Control system characteristics	4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9	
Week 6	Control system performance **Review & Midterm Exam 1**	5.2, 5.3, 5.4, 5.5, 5.6, 5.9, 5.10	
Week 7-9	Control system performance Stability of linear feedback systems	5.2, 5.3, 5.4, 5.5, 5.6, 5.9, 5.10 6.1, 6.2, 6.3, 6.5, 6.6	Homework 2 Project Stage 1 due
Week 10-11	Root Locus Method **Review & Midterm Exam 2**	7.1, 7.2, 7.3, 7.4, 7.5, 7.7, 7.8, 7.9	Homework 3
Week 12	Root Locus Method	7.1, 7.2, 7.3, 7.4, 7.5, 7.7, 7.8, 7.9	Project Stage 2 due
Weeks 13-14	Design of Feedback Control Systems: Root Locus, PID control	7.6, 10.2, 10.3, 10.5, 10.6, 10.7, 10.13	Homework 4
Week 15	Review Week	All chapters	Project Stage 3 due
Week 16	**Finals Week**	All chapters	**Final Exam**

Class Policies:

Syllabus Adjustments: Everything in this syllabus is subject to change. If it becomes necessary or prudent for me to change something, I will try to do so fairly and transparently.

Copyright Notice: The instructor holds the copyright for all slides, instructor lecture notes, assignments, and exams for this class. You may not redistribute these materials to anyone, including others in the class, without **written permission** from the instructor. Students enrolled in the class are encouraged to obtain their own copies of available materials from the course website. Violation of this policy constitutes academic misconduct and may further result in criminal or civil penalties for copyright violation.

Attendance:

- The Class Attendance policy in the NAU Academic Policies requires students to assume the responsibility for regular class attendance. When absence is unavoidable, students should report the reason to the instructor and assume the responsibility for any work they miss. Instructors are under no obligation to make special arrangements for students who have been absent.
- Students should make every effort to be in their seats (if in-person) or logged in online (if remote) and ready when class begins. In the rare cases where being tardy is unavoidable, a student should enter the class or the virtual classroom as quietly as possible so that other students are not disturbed.

Students with tardiness or attendance problems may have points deducted from their grade and might not be allowed to join a class in progress.

- You are responsible for all materials covered by the assigned reading and during the classes, whether you attend or not. I am happy to answer any questions you have about a missed lecture, but I will not repeat it for you.
- Students who are experiencing illness (including COVID-19) are asked to follow isolation and/or quarantine protocols as described on the NAU Jacks Are Back website (https://nau.edu/legacy/jacks-are-back/health-and-mitigation/). Other accommodation for life events and illness may be available after contacting the Office of the Dean of Students (https://in.nau.edu/dean-of-students/).

Academic Integrity:

- Every student should fully understand and comply with the *NAU Academic Integrity Policy*: https://policy.nau.edu/policy/policy.aspx?num=100601 and https://in.nau.edu/academic-affairs/academic-integrity/
- Academic dishonesty, including cheating and plagiarism, will not be tolerated. All academic integrity violations are treated seriously. All work you submit for grading must be your own. You are encouraged to discuss the intellectual aspects of assignments with other class participants. However, each student is responsible for formulating responses and solutions on their own and in their own works. Academic integrity violations will result in penalties including, but not limited to, a zero on the assignment / project / exam, a failing grade in the class, or expulsion from NAU.
- Not knowing that certain activities qualify as academic dishonesty is not a defense to a charge of academic dishonesty.
- If you are charged with academic dishonesty, you are subject to the procedures established in the *NAU Academic Integrity Policy*. See the policy document for more information.

Graduate-level work: Graduate students must make sure that they do the course-related work intended for graduate students in the course, including questions on assignments and exams, and projects, which will be clearly indicated. No excuse for doing the wrong work or missing graduate-level work will be accepted.

Homework assignments:

- Homework assignments, whether typed or handwritten, must be neat and legible. Students are encouraged to type the assignments.
- Assignments must be completed outside of class and submitted through BBLearn. Assignments submitted by email or in person will not be accepted. Illegible submissions (for example, low scan quality) will not be graded.
- On all assignments, any sources of information that are not the original creation of the author nor taught in class nor in the textbook must be cited in sufficient detail that the instructor can locate and verify the sources. If you are repeating this class, you may not use previous work that you completed for a previous class.

Quizzes:

- Quizzes are given to increase student participation in classes and enhance student learning. There will be no make-up quizzes.
- Quizzes are in both the form of multiple choices and the form of written answers to be submitted online through BBLearn.

- The following policy is designed to account for unexpected, emergency life events that may happen to some students, while maintaining fairness for all students: The lowest quiz grade will be dropped in the calculation of the final grade.

Exams:

- If conducted in-person: exams are closed book and closed notes. You may use dedicated calculators, unless mentioned otherwise, but you are not allowed to use laptops and cell phones. Calculator software is not allowed.
- If conducted online: exams are open book, open notes, and conducted through an online service (such as BBLearn). Measures will be taken to prevent cheating, including but not limited to: randomized questions, combination of multiple-choice questions and long-answer questions, timed exam, displaying questions one-by-one without the ability to re-visit a previous question.
- Exams are individualized, meaning that questions are different between students.
- <u>No makeup exams will be given</u> except by prior arrangement in exceptional or emergency situations at the discretion of the instructor and will require a documented emergency supported by a class missed memo from Student Life (https://nau.edu/student-life/classes-missed-memos/) and with approval from the instructor. Make-up exams may be considerably different than the original exam.

Labs:

- Labs are conducted during the scheduled lab time. Labs are divided into several lab assignments, for each of which Matlab code / Simulink models and a lab report must be submitted and will be due approximately two weeks after the assignment.
- For every lab, each student must do all the activities in the lab by himself/herself and submit his/her own work in his/her own words individually. Group submissions of labs are not allowed.

Late submissions:

- The following late submission policy is designed to account for unexpected, emergency life events that may happen to some students, while maintaining fairness for all students.
- For all exams (midterms and final) and quizzes, late submissions will not be accepted and will result in zeros for the grades.
- For all assignments, students are highly encouraged to submit their works before the deadlines.
- The penalty for a late submission of a homework or project assignment, unless permitted otherwise in advance by the instructor, is determined as follows:
    - Late by 0-1 day (0-24 hours): deduct 25 percentage points absolute (not relative) from the earned grade; for example: if your earned grade is 85% but it was submitted 10 hours late, then your grade is 85% - 25% = 60%.
    - Late by more than 1 day (24 hours): grade is zero (0).

Grading:

- Grades will be entered in BBLearn but your final grade will be calculated in Excel using the grading system described above and then entered in LOUIE. Your final course grade will not necessarily appear in BBLearn. Please check LOUIE for your final grade.
- Grades will be calculated based not only on technical content but also on the presentation of your work. The presentation should be neat, legible, clear, using standard technical terms and symbols.
- Most problems in homework and exams will be graded using the following scale: a first quarter of available points for formulating a solution (identifying the technique/equations necessary for the

solution); a second quarter of available points for carrying out the solution but a major error is found in the work; a third quarter of available points for a correct solution; and a fourth quarter of available points for a good presentation. Full or half points can be subtracted for small errors. Illegible answers will have no points.
- No other grading accommodations will be made, with the exception of extreme cases where the university administration becomes involved, such as extended hospitalization.
- University policy for grade appeals (applied only to the final course grade) can be found at https://www5.nau.edu/policies/Client/Details/437.

Extenuating Circumstances:
- Exceptions to the late assignment, attendance, class activity, and examination policies may be made only under certain extenuating circumstances such as a serious illness or an institutional excuse, and will require valid written verification.
- A valid medical excuse must state that you are unable to attend classes due to the severity of the illness or the risk of spreading it and should clearly state the dates that you should be absent from the university. A written medical note that simply states that you visited a clinic or were seen by a doctor or nurse is not valid and will not be accepted.
- Students should inform the instructor of an institutional excuse or any significant scheduled events – such as religious ceremonies, away games for NAU athletes, weddings, conference travel, etc. – in writing at least 5 working days prior to the absence. Given these conditions, make-up work may be assigned and due before the student leaves for the event.
- Be aware that neither medical nor institutional excuses absolve you of making up any required work or exams. Remember also that you can always turn in an assignment early.
- Details of the student institutional excuses policy can be found in https://nau.edu/university-policy-library/wp-content/uploads/sites/26/Student-Institutional-Excuses.pdf

Communication: Email to the instructor and teaching assistants must be respectful and professional. Specifically, all emails should:
- Have the subject prefixed with "EE558" so that the message can be easily identified or placed in an auto-folder. The subject should also use lower case and upper case correctly.
- Contain a formal salutation: "Dear Dr. Nghiem"
- Contain a closing, (for example, "Best, Jane Doe")
- The body should contain complete sentences and correct grammar including correct usage of lowercase and uppercase letters. Composing emails on a mobile device is **not** an excuse for poor writing.
- The body of your message should also be respectful and explain the full context of the query.
- Although email will typically be answered quickly, you should allow up to three (3) business days for a response.
- If you have a question that would require a long response or you have a lot of questions, please come to office hours or schedule an appointment with the instructor.

Other means of electronic communication are also used in this course, which will be described by the instructor.

Learning:
- You are expected to read the textbook, and watch the posted lecture / supplementary videos, to learn the material and achieve the objectives in the course. This includes reading and working the

example problems in detail. Not all topics are covered in depth in lectures, nor can examples be done for each type of problems you may encounter in the homework. To be able to do the homework assignments, exams, and project, it is not sufficient to rely only on the in-class lectures; you should invest your study time in reading the textbook on the topics covered in this course.
- Students are strongly encouraged to complete all assignments to prepare for the examinations.
- Students are strongly encouraged to seek assistance for their learning either from the instructor and/or the TA(s) and other campus' resources. The Academic Success Centers offer free tutoring and academic support to improve students' study skills and review course material in a number of engineering and math courses. Students can schedule an appointment by visiting http://nau.edu/asc, calling the Academic Success Center at 928-523-7391 or visiting Dubois Center - Room 140.

Cell Phone, Laptop, and Other Electronic Device Policies:
- In class: Electronic device usage must support learning in the class. Laptop computers and tablets may only be used for class activities during class time. All cell phones, PDAs, music players and other entertainment devices must be turned off (or in silent mode) during lecture, and may not be used at any time. Texting and phone calls are not allowed during class. If you do receive an emergency call, ask to be excused so that you can take it outside the classroom.
- During an exam: Cell phones, pagers and other electronic devices MUST be turned off. Their use is prohibited during an exam. You may use a dedicated calculator, not calculator software on a device such as smartphone or tablet.

APPENDIX A. UNIVERSITY POLICY STATEMENTS

COVID-19 REQUIREMENTS AND INFORMATION

Additional information about the University's response to COVID-19 is available from the **Jacks are Back!** web page located at https://nau.edu/jacks-are-back.

Syllabus Policy Statements

ACADEMIC INTEGRITY

NAU expects every student to firmly adhere to a strong ethical code of academic integrity in all their scholarly pursuits. The primary attributes of academic integrity are honesty, trustworthiness, fairness, and responsibility. As a student, you are expected to submit original work while giving proper credit to other people's ideas or contributions. Acting with academic integrity means completing your assignments independently while truthfully acknowledging all sources of information, or collaboration with others when appropriate. When you submit your work, you are implicitly declaring that the work is your own. Academic integrity is expected not only during formal coursework, but in all your relationships or interactions that are connected to the educational enterprise. All forms of academic deceit such as plagiarism, cheating, collusion, falsification or fabrication of results or records, permitting your work to be submitted by another, or inappropriately recycling your own work from one class to another, constitute academic misconduct that may result in serious disciplinary consequences. All students and faculty members are responsible for reporting suspected instances of academic misconduct. All students are encouraged to complete NAU's online academic integrity workshop available in the E-Learning Center and should review the full *Academic Integrity* policy available at https://policy.nau.edu/policy/policy.aspx?num=100601.

COURSE TIME COMMITMENT

Pursuant to Arizona Board of Regents guidance (ABOR Policy 2-224, *Academic Credit*), each unit of credit requires a minimum of 45 hours of work by students, including but not limited to, class time, preparation, homework, and studying. For example, for a 3-credit course a student should expect to work at least 8.5 hours each week in a 16-week session and a minimum of 33 hours per week for a 3-credit course in a 4-week session.

DISRUPTIVE BEHAVIOR

Membership in NAU's academic community entails a special obligation to maintain class environments that are conductive to learning, whether instruction is taking place in the classroom, a laboratory or clinical setting, during course-related fieldwork, or online. Students have the obligation to engage in the educational process in a manner that does not interfere with normal class activities or violate the rights of others. Instructors have the authority and responsibility to address disruptive behavior that interferes with student learning, which can include the involuntary withdrawal of a student from a course with a grade of "W". For additional information, see NAU's *Disruptive Behavior in an Instructional Setting* policy at https://nau.edu/university-policy-library/disruptive-behavior.

NONDISCRIMINATION AND ANTI-HARASSMENT

NAU prohibits discrimination and harassment based on sex, gender, gender identity, race, color, age, national origin, religion, sexual orientation, disability, or veteran status. Due to potentially unethical consequences, certain consensual amorous or sexual relationships between faculty and students are also prohibited as set forth in the *Consensual Romantic and Sexual Relationships* policy. The Equity and Access Office (EAO) responds to complaints regarding discrimination and harassment that fall under NAU's *Nondiscrimination and Anti-Harassment* policy. EAO also assists with religious accommodations. For additional information about nondiscrimination or anti-harassment or to file a complaint, contact EAO located in Old Main (building 10), Room 113, PO Box 4083, Flagstaff, AZ 86011, or by phone at 928-523-3312 (TTY: 928-523-1006), fax at 928-523-9977, email at equityandaccess@nau.edu, or visit the EAO website at https://nau.edu/equity-and-access.

TITLE IX
Title IX is the primary federal law that prohibits discrimination on the basis of sex or gender in educational programs or activities. Sex discrimination for this purpose includes sexual harassment, sexual assault or relationship violence, and stalking (including cyber-stalking). Title IX requires that universities appoint a "Title IX Coordinator" to monitor the institution's compliance with this important civil rights law. NAU's Title IX Coordinator is Elyce C. Morris. The Title IX Coordinator is available to meet with any student to discuss any Title IX issue or concern. You may contact the Title IX Coordinator by phone at 928-523-3515, by fax at 928-523-0640, or by email at elyce.morris@nau.edu. In furtherance of its Title IX obligations, NAU will promptly investigate and equitably resolve all reports of sex or gender-based discrimination, harassment, or sexual misconduct and will eliminate any hostile environment as defined by law. Additional important information about Title IX and related student resources, including how to request immediate help or confidential support following an act of sexual violence, is available at https://in.nau.edu/title-ix.

ACCESSIBILITY
Professional disability specialists are available at Disability Resources to facilitate a range of academic support services and accommodations for students with disabilities. If you have a documented disability, you can request assistance by contacting Disability Resources at 928-523-8773 (voice), 928-523-6906 (TTY), 928-523-8747 (fax), or dr@nau.edu (e-mail). Once eligibility has been determined, students register with Disability Resources every semester to activate their approved accommodations. Although a student may request an accommodation at any time, it is best to initiate the application process at least four weeks before a student wishes to receive an accommodation. Students may begin the accommodation process by submitting a self-identification form online at https://nau.edu/disability-resources/student-eligibility-process or by contacting Disability Resources. The Director of Disability Resources, Jamie Axelrod, serves as NAU's Americans with Disabilities Act Coordinator and Section 504 Compliance Officer. He can be reached at jamie.axelrod@nau.edu.

RESPONSIBLE CONDUCT OF RESEARCH
Students who engage in research at NAU must receive appropriate Responsible Conduct of Research (RCR) training. This instruction is designed to help ensure proper awareness and application of well-established professional norms and ethical principles related to the performance of all scientific research activities. More information regarding RCR training is available at https://nau.edu/research/compliance/research-integrity.

MISCONDUCT IN RESEARCH
As noted, NAU expects every student to firmly adhere to a strong code of academic integrity in all their scholarly pursuits. This includes avoiding fabrication, falsification, or plagiarism when conducting research or reporting research results. Engaging in research misconduct may result in serious disciplinary consequences. Students must also report any suspected or actual instances of research misconduct of which they become aware. Allegations of research misconduct should be reported to your instructor or the University's Research Integrity Officer, Dr. David Faguy, who can be reached at david.faguy@nau.edu or 928-523-6117. More information about misconduct in research is available at https://nau.edu/university-policy-library/misconduct-in-research.

SENSITIVE COURSE MATERIALS
University education aims to expand student understanding and awareness. Thus, it necessarily involves engagement with a wide range of information, ideas, and creative representations. In their college studies, students can expect to encounter and to critically appraise materials that may differ from and perhaps challenge familiar understandings, ideas, and beliefs. Students are encouraged to discuss these matters with faculty.

EE 458/558 – Fall 2022
Homework 1
Due: 11:59 PM Thursday, September 22, 2022

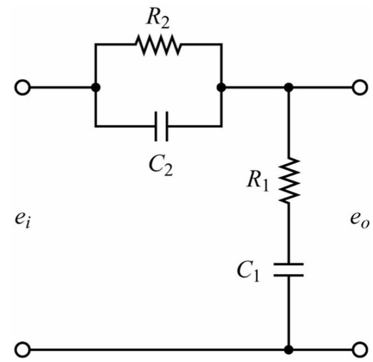
Instructions:

- Total score: 40 points.
- Each answer must be worked out in detailed steps. Writing only the final answer is incomplete.
- Write your answers neatly and legibly.

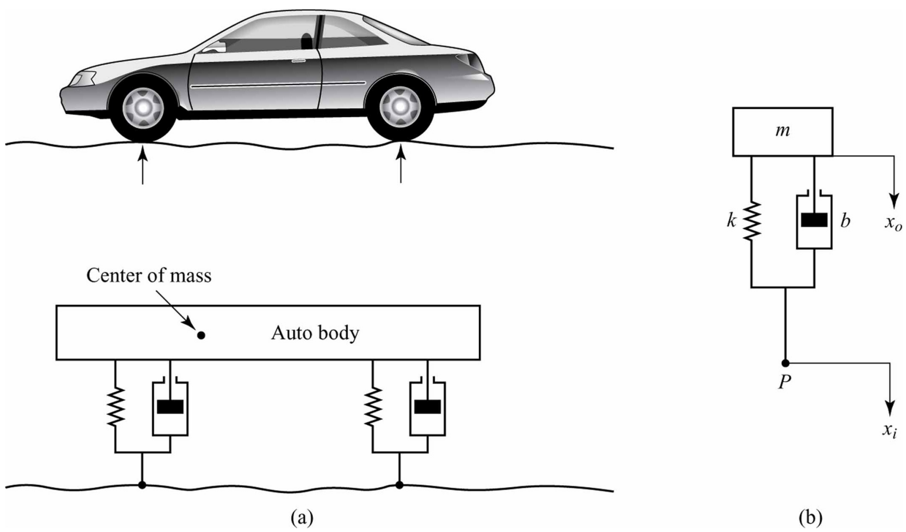
Have you read and fully understood the **"Instructions for All Assignments"** on the "Homework" page or the "Syllabus and Schedule" page on BBLearn? Failure to follow the instructions, including how to submit the homework and the quality requirements of the electronic submission, may result in a grade reduction or a zero for this homework. Acknowledge below that you have read and fully understood the instructions?

☐ **I acknowledge that I have read and fully understood the instructions.**

Prob 1 | (8 points) Consider a circuit in the following schematic. The system's input is the input voltage $e_i(t)$ and the system's output is the output voltage $e_o(t)$. Write the differential equation of the system relating the input $e_i(t)$ and the output $e_o(t)$ (4 points). Then obtain the transfer function $E_o(s)/E_i(s)$ (4 points).

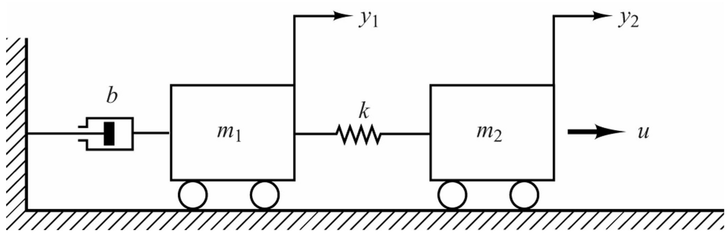


Prob 2 | (8 points) **[Answer this question <u>ONLY IF you are a student in EE-458 (Undergraduate)</u>]** The figure below shows the suspension system of a car. The diagram on the left (a) is the schematic of the system, which consists of two spring-damper pairs attached to the car's body and to the road (through the tires). The diagram on the right (b) is a very simplified schematic of the system, consisting of only one spring-damper pair. The system's input is the vertical displacement $x_i(t)$ of the tires at point P. The system's output is the vertical motion $x_o(t)$ of the car's body. Here, we only consider the body's motion in the vertical direction (not considering its horizontal movement). The parameters are: m is the body's mass, k is the spring constant, and b is the damper constant. Write the differential equation of the system relating the input $x_i(t)$ and the output $x_o(t)$ (4 points). Then obtain the transfer function $X_o(s)/X_i(s)$ (4 points).



3

Prob 3 | (8 points) **[Answer this question <u>ONLY IF you are a student in EE-558 (Graduate)</u>]** The figure below shows a mass-spring-damper system in series. The system's input is the force $u(t)$ applied on the second mass m_2. The system has two outputs: the translational position $y_1(t)$ of the first mass m_1 and the translational position $y_2(t)$ of the second mass m_2. Write a system of two differential equations relating the input $u(t)$ and the outputs $y_1(t)$ and $y_2(t)$ (4 points). Then obtain the transfer function $Y_1(s)/U(s)$ from the input to the **first output** $Y_1(s)$ (4 points).



Prob 4 | Find the Laplace transforms of the following signals, for $t \geq 0$

a) (2 points) $f(t) = 1 + 5t$

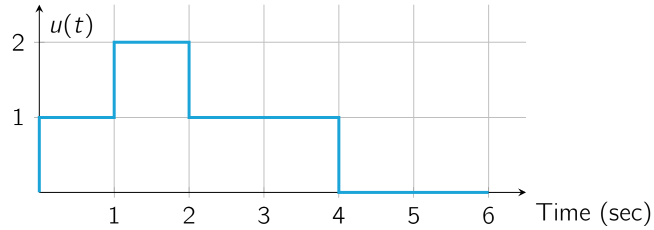
b) (2 points) $f(t) = (t + 2)^2$

c) (2 points) $f(t) = 4 \cos 6t$

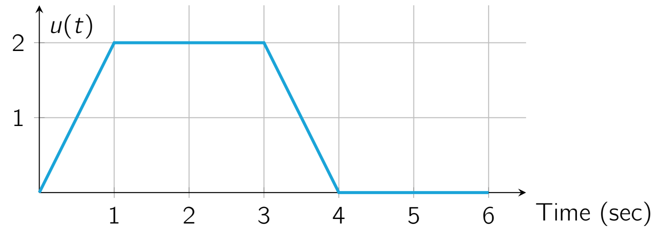
d) (2 points) $f(t) = t^2 + e^{-3t} \cos 2t$

Prob 5 | Laplace transform of signals.

a) (4 points) Consider the signal $v(t)$ shown in the figure below, where $v(t) = 0$ for all $t \geq 4$. Write the Laplace transform of the signal $v(t)$.



b) (4 points) Consider the signal $u(t)$ shown in the figure below, where $u(t) = 0$ for all $t \geq 4$. Write the Laplace transform of the signal $u(t)$.



Prob 6 | Find the inverse Laplace transforms of the following functions in the Laplace / frequency domain.

a) (4 points) $F(s) = \dfrac{5}{s(s+1)(s+5)}$

b) (4 points) **[Answer this question <u>ONLY IF you are a student in EE-458 (Undergraduate)</u>]**

$$F(s) = \frac{3}{s^2 + 4s + 13}$$

c) (4 points) **[Answer this question <u>ONLY IF you are a student in EE-558 (Graduate)</u>]**

$$F(s) = \frac{5}{s(s+1)(s+5)(s^2 + 2s + 3)}$$

EE 458 - Midterm 2 Exam

Student Name: [redacted]
Student I.D.: [redacted]

Answer the questions in the spaces provided. **If you run out of room for an answer, continue on the back of the page**.

The number of points for each problem is shown in parentheses.

Read and follow the instructions of each problem carefully.

Write your answers neatly and legibly.

Question:	1	2	3	4	5	6	7	8	9	Total
Points:	1	1	1	1	1	1	2	4	8	20
Score:										

Total: / 20

1. (1 point) *Mark **ONE** correct answer.*
   A primary advantage of an **open-loop control system** is the ability to reduce the system's sensitivity. Is this statement true or false?
   - ◯ True
   - ◯ False

2. (1 point) *Mark **ONE** correct answer.*
   Which of the following systems has oscillation (possibly decaying) in its step response?
   - A. A first-order system
   - B. A critically damped second-order system
   - C. An under-damped second-order system
   - D. An over-damped second-order system
   - E. None of the other choices

3. (1 point) *Mark **ALL** correct answers.*
   Which statements are true? Feedback control systems...
   - A. ...can feed sensor noise into the system.
   - B. ...do not need sensors.
   - C. ...can be made robust to model errors.
   - D. ...always have system sensitivity of exactly 1.

4. (1 point) *Mark **ONE** correct answer.*
   A negative feedback control system has the open loop transfer function $L(s) = \dfrac{s+2}{s^2(s+1)(s+4)}$. What is the **type number** of the control system?
   - A. Type 0
   - B. Type 1
   - C. Type 2
   - D. Type 3

5. (1 point) *Mark **ALL** correct answers.*
   Which statements are true? Feedforward control systems...
   - A. ...rely on precise knowledge of the plant.
   - B. ...is widely used because it has many advantages over feedback control systems.
   - C. ...reject external disturbances.
   - D. ...always have system sensitivity of exactly 1.

6. (1 point) *Mark **ONE** correct answer.*
   When identifying a **first-order system** using a step response experiment, what are the key parameters that we need to determine?
   - A. Percentage overshoot and peak time
   - B. Percentage overshoot and settling time
   - C. Time constant and steady-state gain
   - D. Natural frequency and damping ratio

7. (2 points) Consider a unity negative feedback control system with the open-loop transfer function

$$L(s) = G_c(s)G(s) = \frac{4}{s(s+2)}$$

What is the estimated percent overshoot (P.O.) of the output of the closed-loop system to a unit step input? Write your answer in the box below.

8. (4 points) Consider a unity negative feedback control system with the open loop transfer function $L(s) = G_c(s)G(s) = \frac{4}{s(s+5)}$. What is the steady-state error of the closed-loop system to the ramp input signal $u(t) = 2t$? Write your answer in the box below.

9. (8 points) A unity negative feedback control system has the plant's transfer function $G(s) = \frac{2}{s(s+a)}$ and the controller's transfer function $G_c(s) = K$, where a and K are parameters. Its unit step response has the following properties:

- The percent overshoot (P.O.) is 10%,
- The 5% settling time is 3 seconds.

Estimate the values of the parameters a and K of the system. Write your answer in the space below. Use $\ln 0.1 = -2.3026$. *Hint: estimate the damping ratio and natural frequency of the system, then use them to calculate the parameters.*

Lab 4: System Identification and PID Control of Temperature Control Lab

EE 458 – Fall YYYY

Due: Time, Date – Total score: 100 points and 20 bonus points.

Contents

1 General Instructions

- Always do the Prelab Preparation tasks in each Experiment before doing the Lab Tasks.
- Each student must **submit a lab report, and other files as instructed in the lab** (such as Matlab scripts and Simulink models), by the due date.
- **Each student must do all parts of the lab and must submit his/her own work, in his/her own words, for the lab individually.** Group submission is not allowed.
- **The final submission for the lab of each student will be graded as it is the student's own work, independently of other students' works, regardless of how the students collaborated in the lab.**
- For each lab task, it will be clearly indicated whether it involves the lab report **(Report)**, or code submission **(Code)**, or both **(Code & Report)**, followed by the number of points. A bonus task will be indicated by **(Bonus)** followed by the number of bonus points.
- The lab report **must be typed and exported to the PDF format**. Handwritten reports will not be accepted and will receive a zero. The report must include the following contents:
  - The lab number and title, the course number and semester (EE 458 - Fall 2019).
  - The date of the report.
  - The lab team number (see BBLearn) and the name and NAU ID of the student whom this report belongs to.
  - One section for each experiment, one subsection for each lab task in each experiment.
  - For each lab task (subsection), include the answers for the task and any other details as instructed in the task. **If the task is performed in Matlab, always include the Matlab commands used to do the task and their results. Furthermore, if the task involves equations, always write the answers in mathematical form in addition to the Matlab results. In other words, you must show both how you did the task and the final formal answers. Points will be substracted if any of these two parts is missing.**
  - A task may ask you to include other details, such as a plot, a screenshot, a Matlab script, or a Simulink model file. Remember to include those details in your submission, either in the lab report or in separate files as instructed.

1.1 Lab Submission

For this lab, the following files must be submitted by each student by the due date: 1) the lab report (a PDF file) named `lab4_report.pdf`; 2) a ZIP archive file named `lab4_code.zip` of the submitted files as instructed in the lab, organized into directories as instructed in the lab.

For the code submission, you will be asked to write several code files or create several Simulink model files. After you have finished the lab tasks, compress the entire resulting code directory (including all the files you have completed and created) to a ZIP file and submit it with your lab report. Refer to the lab assignment instructions on how to name the lab report file and the code file in your submission.

2 Experiment 1: System Identification of TCL System

2.1 Introduction and Objectives

In this experiment, you will implement a step test and perform the system identification of the Temperature Control Lab. You will test the accuracy of the identified model versus the new and the previous step test data. As a bonus task, you will identify a model not by a graphical method but by using optimization, then compare the accuracies of the different models.

Objectives:

- Learn about system identification.
- Learn how to conduct a proper step test for system identification.
- Learn how to fit models to experiment data using different methods.

2.2 Prelab Preparation

- Review Lab 3 about FOPDT models and the graphical method to identify an FOPDT model from a step test.
- Read the Matlab's documentation of the function `lsim` for simulating a dynamical system, for example by running `doc lsim` in Matlab.

2.3 Lab Task: Revised Step Test

In this task, you will revise the step test from Lab 3 and perform it again to obtain data for identifying an FOPDT model of the TCL system. The key requirement is to keep the step input signal long enough for the temperature output to reach its steady state (i.e., the output stops changing).

Do the following tasks:

1. **(Code)** (10 points) Put all the code files from this task in the directory named `1_step_test`. Write a script named `step_test.m` that does the following:
    - Runs a step test with the TCL for a duration long enough for the output to reach a steady state. Select a suitable step test duration. Typically 10 minutes is long enough. However, if the temperature output has not reached a steady state after that duration, you will need to increase the test duration, wait for the heaters to cool down completely, then re-run the test.
    - Initially both heaters are turned off.
    - At 5 seconds: turn on heater 1 at 50% power, do not change heater 2.
    - During the experiment, after every second, save heater 1's power to a vector `h1s`, heater 2's power to a vector `h2s` (it should be all zeros), temperature 1's values to a vector `t1s`, and temperature 2's values to a vector `t2s`.
    - After the test duration, turn off both heaters. Then save `h1s`, `h2s`, `t1s`, and `t2s` to a MAT file named `step_test_single.mat`.

If you have recently run the TCL, *wait until the temperature readings are at the steady state, which is the same as the ambient air temperature*. Run the script `step_test.m` to perform the new step test. Then submit the script `step_test.m` and the resulting data file `step_test_single.mat`, both in the directory `1_step_test`, as instructed in Section 1.1.

2. **(Report)** (5 points) Plot all the results (`h1s`,`h2s`, `t1s`, and `t2s`) obtained in the previous task in one plot using different line colors or line styles to distinguish them. Include a legend box for the different lines. Include the final plot in your report.

2.4 Lab Task: FOPDT Model Identification

In this task, you will re-identify an FOPDT model of the TCL system from the new step test data.

Do the following tasks:

1. **(Report)** (20 points) Use the graphical / visual method on the plot of the step test obtained in Section 2.3 to calculate the parameters of an FOPDT model that fits the data. Graphically identify all the parameters (like the time constant, the dead time, etc.) on the plot of the step test that you already produced in the previous section. Include the step response plot superimposed with the FOPDT graphical identification. Report the calculated values of all model parameters and the final transfer function.
   Hint: In a Matlab figure (of a plot), you can use the interactive editing and annotation tools to add lines, arrows, and text to an existing plot.
2. **(Code)** (5 points) In the directory named `1_fopdt`, write a Matlab script named `fopdt_test.m` that uses the function `lsim` to simulate the FOPDT model obtained in the previous task for the same input as in the step test (in the variable `h1s`). Then plot the output temperature of the FOPDT model and the actual temperature from the experiment data on the same plot to compare them. Submit the script file as instructed in Section 1.1.
3. **(Report)** (5 points) Include the resulting plot of the previous task in your lab report. Comment on the accuracy of the FOPDT model.
4. **(Code & Report) (Bonus)** (Bonus 5 points) Copy the script `fopdt_test.m` to a new file named `fopdt_test_bonus.m`. Modify the new file to simulate the FOPDT model for the input signal `h1s` used in the experiment in Lab 3 (the previous lab, not this lab), loaded from the MAT file `step_test.mat`. Then plot the output temperature of the FOPDT model and the actual temperature from the experiment data on the same plot to compare them. Submit the script file as instructed in Section 1.1. Include the plot in your lab report and comment on the accuracy of the FOPDT model for this experiment.

2.5 Bonus Lab Task: FOPDT Model Identification using Optimization

This is a bonus lab task for bonus points. Skip this section if you do not want bonus points.

Another method to estimate the parameters of a model from experiment data is to use optimization. The basic idea is as follows:

- Given a set of the model parameter values, a function can simulate the model for the same input signal as in the experiment, obtain the output signal, and calculate an error score between the simulated output and the actual output. Typically, the squared error (SE) is used:

  $$\text{SE} = \sum_{t=1}^{N} (y_t - \tilde{y}_t)^2$$

  where N is the number of time steps (also the number of output values) in the experiment, y_t is the actual output at time t, and $\tilde{y}_t$ is the simulated output at time t.
- A black-box optimization method is used to find an optimal set of model parameters to minimize the SE (that is to maximize the fitness of the simulated outputs).

In this bonus task, you will perform this optimization-based method to identify the parameters of an FOPDT model for the TCL system.

Do the following tasks:

1. **(Code)** (Bonus 5 points) Complete the code in the template files `fopdt_sim.m` and `fopdt_optim.m`, in the directory `1_fopdt`, to implement the method. Follow the instructions embedded as comments in these files. Submit the completed files `fopdt_sim.m` and `fopdt_optim.m`.
2. **(Report)** (Bonus 5 points) Run the script `fopdt_optim.m` that you have completed to find the parameters of the FOPDT model. Report the found parameters and the final transfer function of the FOPDT model.
3. **(Code and Report)** (Bonus 5 points) Copy the script `fopdt_test.m` that you wrote in section 2.4 to a new file named `fopdt_test_optim.m`. Modify the TCL model in the new file to the parameters found by the optimization method in the previous task. Submit the script file as instructed in Section 1.1. Run the script. Include the resulting plot in your lab report. Comment on the accuracy of the new FOPDT model and compare its accuracy to that of the FOPDT model identified by the graphical method in section 2.4.

3 Experiment 2: PID Control of TCL System

3.1 Introduction and Objectives

Objectives: Implement different PID controllers in Matlab for the TCL system, and compare their performance.

3.2 Prelab Preparation

Review PID control and PID controller implementation in the lectures. A PID controller implemented in a computer program will be executed with discrete sampling periods (in the case of the TCL system, the sampling period is 1 second). Therefore, a discrete form of the PID equation is needed to approximate the integral of the error and the derivative. This modification replaces the continuous form of the integral with a summation of the error and uses Δt as the time between sampling instances. It also replaces the derivative with either a filtered version of the derivative or another method to approximate the instantaneous slope of the measured plant's output.

$$u(t) = K_c\, e(t) + \frac{K_c}{\tau_I}\sum_{i=0}^{t} e(i)\Delta t - K_c\tau_D \frac{y(t) - y(t-1)}{\Delta t} \tag{1}$$

where $e(t) = r(t) - y(t)$ is the tracking error, $r(t)$ is the reference value (or set-point), and $y(t)$ is the measured output. Note here that, to avoid the "derivative kick" issue, the derivative component is calculated with the plant's output rather than the tracking error.

In an iterative implementation, assume that $u_I(t)$ is the accumulated integral value until time t: $u_I(t) = \sum_{i=0}^{t} e(i) = u_I(t-1) + e(t)$, with $u_I(-1) = 0$. Then the above equation can be calculated as

$$u_I(t) = u_I(t-1) + e(t) \tag{2}$$

$$u(t) = K_c\, e(t) + \frac{K_c}{\tau_I} u_I(t) - K_c\tau_D \frac{y(t) - y(t-1)}{\Delta t} \tag{3}$$

An important feature of a controller with an integral term is to consider the case where the controller output $u(t)$ saturates at an upper or lower bound for an extended period of time. This causes the integral term to accumulate to a large summation that causes the controller to stay at the saturation limit until the integral summation is reduced. **Anti-reset windup** is that the integral term does not accumulate if the controller output is saturated at an upper or lower limit. In this lab, we will use the anti-reset windup method presented in the lecture, where the integral component is switched off (i.e., it does not accumulate) when the controller output is saturated.

For tuning the PID parameters for an FOPDT model with transfer function $\dfrac{K_p}{\tau_p s + 1} e^{-\theta_p s}$, we will use the following methods:

- PI control:

– **PI-IMC** method: $\tau_c = \max\left(0.1\tau_p, 0.8\theta_p\right)$ $\quad K_c = \dfrac{1}{K_p}\dfrac{\tau_p}{\left(\theta_p + \tau_c\right)}$ $\quad \tau_I = \tau_p$

– **PI-ITAE** method: $K_c = \dfrac{0.586}{K_p}\left(\dfrac{\theta_p}{\tau_p}\right)^{-0.916}$ $\quad \tau_I = \dfrac{\tau_p}{1.03 - 0.165\left(\theta_p/\tau_p\right)}$

- PID control: **PID-IMC** method:

$$\tau_c = \max\left(0.1\tau_p, 0.8\theta_p\right) \qquad K_c = \frac{1}{K_p}\frac{\tau_p + 0.5\theta_p}{\left(\tau_c + 0.5\theta_p\right)} \qquad \tau_I = \tau_p + 0.5\theta_p \qquad \tau_D = \frac{\tau_p\theta_p}{2\tau_p + \theta_p}$$

3.3 Lab Task: PID Control of TCL System

Do the following tasks:

1. **(Code)** (20 points) In the directory `2_pid`, complete the Matlab function template `pid_calc.m` to implement a discrete PID controller with anti-reset windup where the PID parameters can be specified in the input arguments. Follow the instructions in the comments. Submit the completed file `pid_calc.m`.
2. **(Code and Report)** (30 points) For each of the above PID tuning methods (10 points / method), do the following tasks:
   a) Calculate the parameters of the PID controller for your identified FOPDT model. If you did the bonus lab task in Section 2.5, you can use the model identified by the optimization method; otherwise, use the model identified by the graphical method in Section 2.4. Report which FOPDT model used and the calculated PID parameters.
   b) Then implement the PID control experiment of the TCL by completing the script `pid_control.m`. The experiment sets the reference value to 60 °C, then changes it to 50 °C, then finally changes it to 70 °C.
   c) Run the script to perform the PID control experiment with the specified PID controller and obtain a plot of the output. **Remember to let the heaters cool down** to the ambient air temperature before running an experiment.
   d) Include the plot in your report.
3. **(Report)** (5 points) Comment on the control performance of the above PID tuning methods.

Lab 2: Modeling of Ball and Beam System

EE 458 – Fall YYYY

Due: Time and Date – Total score: 60 points.

Contents

1 General Instructions

- Always do the Prelab Preparation tasks in each Experiment before doing the Lab Tasks.
- Each student must **submit a lab report, and other files as instructed in the lab** (such as Matlab scripts and Simulink models), by the due date.
- **Each student must do all parts of the lab and must submit his/her own work, in his/her own words, for the lab individually.** Group submission is not allowed.
- **The final submission for the lab of each student will be graded as it is the student's own work, independently of other students' works, regardless of how the students collaborated in the lab.**
- For each lab task, it will be clearly indicated whether it involves the lab report **(Report)**, or code submission **(Code)**, or both **(Code & Report)**, followed by the number of points. A bonus task will be indicated by **(Bonus)** followed by the number of bonus points.
- The lab report **must be typed and exported to the PDF format**. Handwritten reports will not be accepted and will receive a zero. The report must include the following contents:
  - The lab number and title, the course number and semester (EE 458 - Fall YYYY).
  - The date of the report.
  - The name and NAU ID of the student whom this report belongs to.
  - One section for each experiment, one subsection for each lab task in each experiment.
  - For each lab task (subsection), include the answers for the task and any other details as instructed in the task. **If the task is performed in Matlab, always include the Matlab commands used to do the task and their results. Furthermore, if the task involves equations, always write the answers in mathematical form in addition to the Matlab results. In other words, you must show both how you did the task and the final formal answers. Points will be substracted if any of these two parts is missing.**
  - A task may ask you to include other details, such as a plot, a screenshot, a Matlab script, or a Simulink model file. Remember to include those details in your submission, either in the lab report or in separate files as instructed.

2 Lab Submission

For this lab, the following files must be submitted by each student by the due date: 1) the lab report (a PDF file) named lab2_report_<your last name>.pdf; 2) a ZIP archive file named lab2_code_<your last name>.zip of the submitted files as instructed in the lab, which contains two files: a Matlab script model_ballbeam.m and a Simulink model model_ballbeam.slx.

For the code submission, you will be asked to write several code files or create several Simulink model files. After you have finished the lab tasks, compress the entire resulting code directory (including all the files you have completed and created) to a ZIP file and submit it with your lab report. Refer to the lab assignment instructions on how to name the lab report file and the code file in your submission.

3 Modeling of Ball and Beam Control System

3.1 Objectives

Learn about cascaded control (or multi-loop control). Develop nonlinear model and linearized model of a ball-and-beam system. Implement models in Matlab and Simulink.

3.2 Lab Preparation

- Read Section 1.1 in the textbook, especially Figure 1.5, and read the accompanying slides titled "Control Schemes" until slide number 7 to understand about *cascaded control* (or *multi-loop control*).
- Re-read Section 2.2 in the textbook on modeling of physical systems, especially mechanical systems.
- Re-read Section 2.3 in the textbook on linearization of nonlinear models.
- Re-read Example 2.5 (page 72) in the textbook on DC motor modeling.

3.3 Ball and Beam physical system

In this system, a ball is placed on a beam as shown in Figure 1. The ball is only allowed to roll along the length of the beam. A lever arm is attached to the beam at one end and a servo gear at the other. When the servo gear turns by an angle θ, the lever tilts the beam by an angle α, which causes the ball to roll along the beam. The servo gear is driven by an armature-controlled DC motor. A control system will be designed to manipulate the ball's position on the beam, i.e., to roll the ball to a desired position and keep it there.

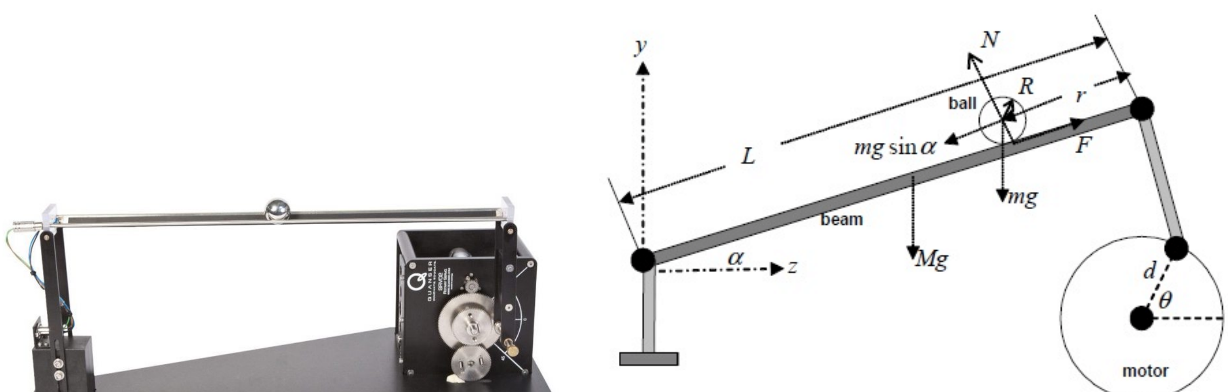


Figure 1: Real ball-beam system on the left and its model on the right.

The ball-and-beam control system is a cascaded control system with two feedback control sub-systems:

- A feedback system to control the position of the DC motor that drives the servo gear, and

- A feedback system to control the position of the ball by providing the desired / reference gear position to the above motor control loop.

3.3.1 DC motor control system

We will use an *armature-controlled* DC motor to drive the servo gear. The modeling, analysis, and control design of this system are discussed in details in the textbook (Example 2.5, page 72). Students should refer to the textbook during this lab. The DC motor is illustrated in Figure 2, reproduced from the textbook.

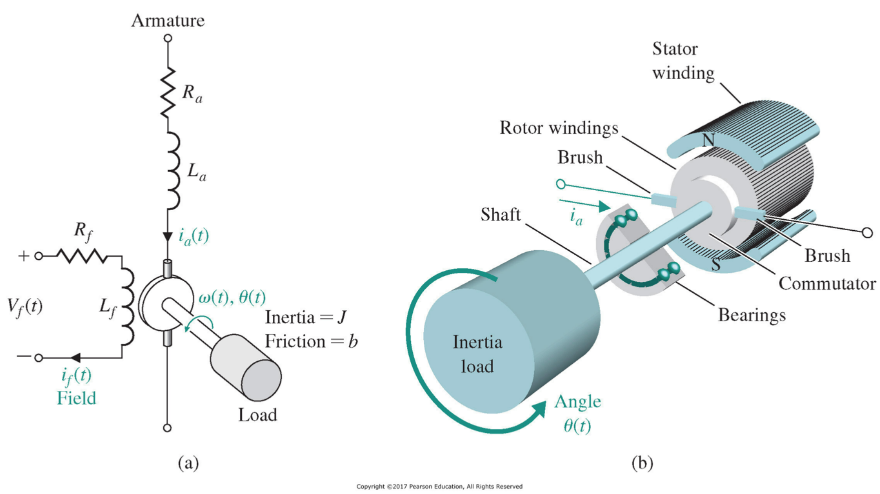


Figure 2: Electrical diagram and sketch of a DC motor (source: textbook).

The system parameters of the motor are summarized in Table 1. We will use similar notations as in the textbook.

Table 1: System parameters of the armature-controlled DC motor.

Variable	Description	Unit
J_m	moment of inertia of the rotor	$\mathrm{kg\,m^2}$
b	motor viscous friction constant	N m s
K_b	back electromotive-force constant	V/rad/sec
K_m	motor torque constant	N m/Amp
R_a	electric resistance	Ohm
L_a	electric inductance	H
v_a	armature voltage	V
θ	motor position	rad

3.3.2 Ball and beam control system

This is the mechanical system as described in Figure 1. Its system parameters are summarized in Table 2.

3.4 Lab Task: Control System Configuration

To aid the design process of the system, a block diagram of the control system, including both the motor control loop and the ball-beam control loop, should be developed. You also need to identify the various variables in the control system.

Table 2: Parameters of the ball and beam system.

Variable	Description	Unit
m	mass of the ball	kg
R	radius of the ball	m
d	lever arm offset	m
g	gravitational acceleration	$\mathrm{m/s^2}$
L	length of the beam	m
J_b	ball's moment of inertia	$\mathrm{kg\,m^2}$
r	ball position coordinate	m
α	beam angle coordinate	rad
θ	servo gear angle	rad

Your task:

1. **(Report)** (10 points) Draw a block diagram of the overall control system, including both the motor control loop and the ball-beam control loop. Identify the two processes (or plants) in this system as well as their input and output variables. *Hint: You should read Section 3.3 thoroughly to understand clearly the relationship between the two feedback control loops and the signals / variables between them. You should follow a top-down design approach (design the overall structure of the system, then work out the details of each subsystem / block).*
2. **(Report)** (5 points) Write a brief description of the entire control system and the relationship between the two control loops.

3.5 Lab Task: System modeling

A critical task in a control design project is to obtain the models of the various components to be used for control analysis and design. The second derivative of the input angle α actually affects the second derivative of r. However, we will ignore this contribution. The Lagrangian equation of motion for the ball is then given by the following:

$$0 = \left(\frac{J_b}{R^2} + m\right)\ddot{r} + mg\sin\alpha - mr\dot{\alpha}^2 \tag{1}$$

The equation which relates the beam angle to the angle of the gear can be approximated as linear by the equation $\alpha = \frac{d}{L}\theta$.

Do the following tasks:

1. **(Report)** (10 points) Is the differential equation of the motion of the ball linear or nonlinear? Why? If the equation is nonlinear, linearize it about $\alpha = 0$ and $\dot{\alpha} = 0$. Write the linearized equations. Then write the transfer function $G_b(s)$ of the (linearized) ball-beam process from its input as identified above to the position of the ball (its output). How many integrators (i.e., s terms in the denominator of the transfer function) are there in the transfer function $G_b(s)$?
2. **(Report)** (5 points) Write the full-order transfer function $G_m(s)$ of the armature-controlled DC motor, from the armature voltage to the motor position. *Hint: you can refer to the textbook, in particular Eq. (2.69) or row 6 in Table 2.4, but note a slight difference in the notations.*
3. **(Code)** (10 points) In the code directory, complete the script `model_ballbeam.m` to implement the transfer functions $G_b(s)$ (variable `P_ball`) and $G_m(s)$ (variable `P_motor`). Read and follow the instructions in the script template. The parameters of the motor are provided in the script, while the parameters of the ball and beam system are provided in the text file `parameters_<your last name>_<your email ID>.txt` accompanying this lab. Note that each student will have a different set of parameter values; a student must use his/her assigned parameters. Include the completed script `model_ballbeam.m` in

your code submission as instructed in Section 2.

4. **(Code & Report)** (20 points) Create a Simulink model file named `model_ballbeam.slx`. In this Simulink model, implement the **original differential equation** (not the linearized equation, if any) of the ball-beam dynamics as in Equation (1), using the unique parameters assigned to you (see the previous task). In the same Simulink model, implement also the linearized transfer function $G_b(s)$ (remember to add the position $r^\star$ of the ball around which the nonlinear equation is linearized). Simulate the ball-beam system in Simulink for 10 seconds with $\theta(t) = 0.15\sin(\pi + 2\pi t)$ (a sinusoidal signal with magnitude 0.15 rad, frequency 1 Hz, and phase π rad) and with the initial conditions $r(0) = 0.5L$ and $\dot{r}(0) = 0$. Plot both the exact position of the ball and the approximated position of the ball by the linearized model in the same plot, and include the plot in the lab report. Comment on the position of the ball over time and the accuracy of the linearized model. Include the completed model `model_ballbeam.slx` in your code submission as instructed in Section 2.

College of Engineering, Informatics & Applied Sciences
School of Informatics, Computing, and Cyber Systems

Term	Class No.	Section	Units	Days & Times	Room	Mode
Spring 2020	EE 499	TBD	3	TBD	TBD	Face-to-face

Department / Academic Unit:
School of Informatics, Computing, and Cyber Systems

Course prefix, Section number and Title:
EE 499, Section TBD (Lecture) and Section TBD (Lab), Introduction to Autonomous Driving

Term/ Year:
Spring 2020

Total Units of Course Credit:
3

Course Pre-requisite(s), Co-requisite(s), Co-convened, and/or Cross-Listed Courses:
CS 126 with a grade of C or better, CS 205 with a grade of C or better, MAT 136 with a grade of C or better, MAT 316 with a grade of C or better. Instructor permission is required to enroll.
Familiarity with the following mathematical skills: basic algebra and calculus, basic linear algebra (vectors, matrices, linear transformation), basic statistics and probability. Familiarity with the following computer science skills and tools: object-oriented programming, Python and/or C++ programming, algorithms, Linux shell, version control systems (git). Good programming skills.

Mode of Instruction:
Face-to-Face.

Course Website:
http://bblearn.nau.edu

Instructor: Dr. Truong Nghiem
Office: Room 303, SICCS Building #90, 1295 S. Knoles Drive
E-mail: truong.nghiem@nau.edu
Office Hours: TBD, and by appointment (please write "EE499" in the subject line).

Teaching Assistant: TBD.

Course Purpose: This course develops an understanding and practical skills of the theory, technologies, and tools for autonomous driving (self-driving cars). The focus is on algorithms and software tools for autonomous driving, based on the Robot Operating System (ROS) and the F1/10 autonomous race car platform.

Course Student Learning Outcomes (Course Objectives): Upon completion of this course, students will:

- Be familiar with the applications of autonomous robots and self-driving vehicles.
- Learn and practice the following software platform, tools, libraries, and languages for robotics: Robot Operating System (ROS), Linux, Python, C++, NumPy.
- Learn and understand common hardware and software components of autonomous cars (autonomous robots in general).
- Understand and practice the concepts, algorithms, and tools for the perception pipeline for robotics, including: LiDAR, Camera, IMU, Odometry.
- Understand the basic concepts and apply tools for mapping and SLAM.
- Understand the basic concepts and apply tools for localization and planning.
- Understand and practice the PID control algorithm.
- Learn and implement basic algorithms for obstacle detection and avoidance, and autonomous racing strategies.
- Learn and practice visualization, simulation, and debugging tools for robotics in ROS.
- Apply learned knowledge and skills to programming a small-scale autonomous race car platform and participate in a racing competition.

Assignments/Assessment of Course Student Learning Outcomes:

- **Exams**: This course does not have a midterm exam or a final exam.
- **The final grade** is determined on the basis of labs, competition, and participation.
- **Teams:** Students will be divided into teams. Members of each team will work together on all labs and competitions. Students are graded both individually and in teams.
- **Labs**: There will be regularly assigned labs for students to learn and practice hands-on skills. For each lab, each student team must <u>submit code</u> online to a pre-assigned repository. The submitted code will be tested and reviewed. Students may be required to present their code (code walk-through or code tracing). Code quality (e.g., comments, code structure, modularity, etc.) counts towards the grade.
- **Final race and final report:** Student teams will compete against each other in a final race at the end of the semester. The race performance will be evaluated on two criteria: safety and completion time. A final report that summarizes the racing strategies / algorithms and evaluation of each team will be required.

Grading System: Final letter grades will be assigned as follows:

A: ≥ 90%;
B: ≥ 80% and < 90%
C: ≥ 70% and < 80%
D: ≥ 60% and < 70%
F: < 60%

Course grades will be calculated as follows:

Labs:	50%
Final race performance:	30%
Final report:	10%

Participation and TA evaluation: 10%

Reading and Materials:

- There is no textbook for this course. All the learning materials will be provided online through BBLearn and other channels.
- Each student team will be provided with an F1/10 autonomous car for use in their labs.
- Each student must have his/her own laptop computer with enough computing power, which can run Linux and ROS either natively, in a Virtual Machine, or on Docker.

Class Outline:

- Course Introduction
- Robot Operating System (ROS):
  - Introduction and Setup
  - Basic concepts: workspace, packages, build, nodes, topics, publish, subscribe, services, ROS bags.
  - Programming ROS: rospy (Python), roscpp (C++)
  - Visualization: rviz, gazebo
- Introduction to F1/10 autonomous race car platform: hardware, software, ROS architecture, simulator
- Keyboard control / Teleop
- LiDAR data, scan message, perception basics
- PID control
- Wall Following
- Gap Following
- Basics of navigation, localization and odometry basics, scan matching
- Simultaneous Localization and Mapping (SLAM), Hector SLAM, particle filter localization
- Path planning, pure pursuit

Class Policies:

Teams:

- Students will be divided into teams. The members of each team will work together on all labs and competitions.
- The members of each team are responsible for their own collaboration (team work).
- Students are graded both individually and in teams.

Labs:

- Labs are conducted during the scheduled lab time. Labs are divided into several lab assignments.
- Each lab will be typically due approximately one week after the assignment, unless specified otherwise.
- For each lab, each student team must submit code online to a pre-assigned repository by the deadline. The submitted code will be tested and reviewed. Students may be required to present their code (code walk-through or code tracing).
- Code quality (e.g., comments, code structure, modularity, etc.) counts towards the grade.

Final race:

- Student teams will compete against each other in a final race at the end of the semester.
- The race performance will be evaluated on two criteria: safety and completion time.
- A final report of no more than 10 pages that summarizes the racing strategies / algorithms and evaluation of each team will be required and graded.

Safety:

- Students must strictly follow all the safety rules and operation instructions provided at the beginning of the course to ensure the safety of all persons involved in the course and of the lab equipment.
- If damages are caused to the lab equipment by a student or a student team due to negligence of the safety rules and/or operation instructions, the student or student team may be held responsible for the cost of the damages at the discretion of the instructor.

Grading:

- Grades will be entered in BBLearn but your final grade will be calculated externally and then entered in LOUIE. Your final course grade will not necessarily appear in BBLearn. Please check LOUIE for your final grade.
- No other grading accommodations will be made, with the exception of extreme cases where the university administration becomes involved, such as extended hospitalization.
- University policy for grade appeals (applied only to the final course grade) can be found at https://www5.nau.edu/policies/Client/Details/437.

Attendance and in-class participation:

- As stated in the Class Attendance policy in the NAU Academic Policies, students are expected to assume the responsibility for regular class attendance. When absence is unavoidable, students should report the reason to the instructor and assume the responsibility for any work they miss. Instructors are under no obligation to make special arrangements for students who have been absent.
- Class attendance will be recorded. Students should make every effort to be in their seats and ready when class begins. In the rare cases where being tardy is unavoidable, a student should enter the class as quietly as possible so that other students are not disturbed. Students with tardiness or attendance problems may have points deducted from their grade and might not be allowed to join a class in progress.
- You are encouraged to ask relevant questions and actively participate in the class.
- Attendance / Participation grade is part of the final grade of a student and includes: class attendance, participation in in-class activities and online discussions (details will be announced in class), participation and performance in other learning activities.

Extenuating Circumstances:

- Exceptions to the late submission, attendance, class activity, and examination policies may be made only under certain extenuating circumstances such as a serious illness or an institutional excuse, and will require valid written verification.
- A valid medical excuse must state that you are unable to attend classes due to the severity of the illness or the risk of spreading it and should clearly state the dates that you should be absent from the university. A written medical note that simply states that you visited a clinic or were seen by a doctor or nurse is not valid and will not be accepted.

- Students should inform the instructor of an institutional excuse or any significant scheduled events – such as religious ceremonies, away games for NAU athletes, weddings, conference travel, etc. – in writing at least 5 working days prior to the absence. Given these conditions, make-up work may be assigned and due before the student leaves for the event.
- Be aware that neither medical nor institutional excuses absolve you of making up any required work or exams. Remember also that you can always turn in an assignment early.
- Details of the student institutional excuses policy can be found in https://nau.edu/university-policy-library/wp-content/uploads/sites/26/Student-Institutional-Excuses.pdf

Communication: Email to the instructor and teaching assistants must be respectful and professional. Specifically, all emails should:

- Contain a formal salutation, (for example, "Dear Dr. Nghiem")
- Contain a closing, (for example, "Best, Jane Doe")
- The body should contain complete sentences and correct grammar including correct usage of lowercase and uppercase letters. Composing emails on a mobile device is **not** an excuse for poor writing.
- The body of your message should also be respectful and explain the full context of the query.
- The subject should be prefixed with "EE485" so that the message can be easily identified or placed in an auto-folder. The subject should also use lower case and upper case correctly.
- Although email will typically be answered quickly, you should allow up to three (3) business days for a response.
- If you have a question that would require a long response or you have a lot of questions, please come to office hours or schedule an appointment with the instructor.

Other means of electronic communication are also used in this course, which will be described by the instructor.

Academic Integrity:

- See the *NAU Academic Integrity Policy* for more information: https://policy.nau.edu/policy/policy.aspx?num=100601 and https://in.nau.edu/academic-affairs/academic-integrity/
- Keep in mind that exceptionally high standards of honor and integrity are fundamental and essential to the study and practice of science and engineering.
- Every student should fully understand and comply with the *NAU Academic Integrity Policy*.

Academic Dishonesty:

- Academic dishonesty, including cheating and plagiarism, will not be tolerated in this class and could result in failing the course or even expulsion from the college and university. If you are charged with academic dishonesty, you are subject to the procedures established in the *NAU Academic Integrity Policy*. See the policy document for more information.
- The immediate consequence of academic dishonesty on an assignment, project, or examination will be a zero grade, and possibly a failing grade in the course.
- Not knowing that certain activities qualify as academic dishonesty is not a defense to a charge of academic dishonesty.

Learning:

- You are expected to learn all the assigned materials and achieve the objectives in the course. Not all topics are covered in depth in lectures. To be able to do the labs, it is not sufficient to rely only on the in-class lectures; you should invest your study time in studying the assigned materials and practicing the learned knowledge and skills.

- Students are strongly encouraged to seek assistance for their learning either from the instructor and/or the TA(s) and other campus' resources. The Academic Success Centers offer free tutoring and academic support to improve students' study skills and review course material in a number of engineering and math courses. Students can schedule an appointment by visiting http://nau.edu/asc, calling the Academic Success Center at 928-523-7391 or visiting Dubois Center - Room 140.

Cell Phone, Laptop, and Other Electronic Device Policies:

- In class and in lab: Electronic device usage must support learning in the class. Laptop computers and tablets may only be used for class activities during class time. All cell phones, PDAs, music players and other entertainment devices must be turned off (or in silent mode) during lecture, and may not be used at any time. Texting and phone calls are not allowed during class. If you do receive an emergency call, ask to be excused so that you can take it outside the classroom / lab.

Appendix A. UNIVERSITY POLICY STATEMENTS

ACADEMIC INTEGRITY

NAU expects every student to firmly adhere to a strong ethical code of academic integrity in all their scholarly pursuits. The primary attributes of academic integrity are honesty, trustworthiness, fairness, and responsibility. As a student, you are expected to submit original work while giving proper credit to other people's ideas or contributions. Acting with academic integrity means completing your assignments independently while truthfully acknowledging all sources of information, or collaboration with others when appropriate. When you submit your work, you are implicitly declaring that the work is your own. Academic integrity is expected not only during formal coursework, but in all your relationships or interactions that are connected to the educational enterprise. All forms of academic deceit such as plagiarism, cheating, collusion, falsification or fabrication of results or records, permitting your work to be submitted by another, or inappropriately recycling your own work from one class to another, constitute academic misconduct that may result in serious disciplinary consequences. All students and faculty members are responsible for reporting suspected instances of academic misconduct. All students are encouraged to complete NAU's online academic integrity workshop available in the E-Learning Center and should review the full academic integrity policy available at https://policy.nau.edu/policy/policy.aspx?num=100601.

COURSE TIME COMMITMENT

Pursuant to Arizona Board of Regents guidance (Academic Credit Policy 2-224), for every unit of credit, a student should expect, on average, to do a minimum of three hours of work per week, including but not limited to class time, preparation, homework, and studying.

DISRUPTIVE BEHAVIOR

Membership in NAU's academic community entails a special obligation to maintain class environments that are conductive to learning, whether instruction is taking place in the classroom, a laboratory or clinical setting, during course-related fieldwork, or online. Students have the obligation to engage in the educational process in a manner that does not interfere with normal class activities or violate the rights of others. Instructors have the authority and responsibility to address disruptive behavior that interferes with student learning, which can include the involuntary withdrawal of a student from a course with a grade of "W". For additional information, see NAU's disruptive behavior policy at https://nau.edu/university-policy-library/disruptive-behavior.

NONDISCRIMINATION AND ANTI-HARASSMENT

NAU prohibits discrimination and harassment based on sex, gender, gender identity, race, color, age, national origin, religion, sexual orientation, disability, or veteran status. Due to potentially unethical consequences, certain consensual amorous or sexual relationships between faculty and students are also prohibited. The Equity and Access Office (EAO) responds to complaints regarding discrimination and harassment that fall under NAU's Safe Working and Learning Environment (SWALE) policy. EAO also assists with religious accommodations. For additional information about SWALE or to file a complaint, contact EAO located in Old Main (building 10), Room 113, PO Box 4083, Flagstaff, AZ 86011, or by phone at 928-523-3312 (TTY: 928-523-1006), fax at 928-523-9977, email at equityandaccess@nau.edu, or via the EAO website at https://nau.edu/equity-and-access.

TITLE IX

Title IX is the primary federal law that prohibits discrimination on the basis of sex or gender in educational programs or activities. Sex discrimination for this purpose includes sexual harassment, sexual assault or relationship violence, and stalking (including cyber-stalking). Title IX requires that universities appoint a "Title IX Coordinator" to monitor the institution's compliance with this important civil rights law. NAU's Title IX Coordinator is Pamela Heinonen, Director of the Equity and Access Office located in Old Main (building 10), Room 113, PO Box 4083, Flagstaff, AZ 86011. The Title IX Coordinator is available to meet with any student to discuss any Title IX issue or concern. You may contact the Title IX Coordinator by phone at 928-523-3312 (TTY: 928-523-1006), by fax at 928-523-9977, or by email at pamela.heinonen@nau.edu. In furtherance of its Title IX obligations, NAU will promptly investigate and equitably resolve all reports of sex or gender-based discrimination, harassment, or sexual misconduct and will eliminate any hostile environment as defined by law. Additional important information about Title IX and related student resources, including how to request immediate help or confidential support following an act of sexual violence, is available at http://nau.edu/equity-and-access/title-ix.

ACCESSIBILITY

Professional disability specialists are available at Disability Resources to facilitate a range of academic support services and accommodations for students with disabilities. If you have a documented disability, you can request assistance by contacting Disability Resources at 928-523-8773 (voice), 928-523-6906 (TTY), 928-523-8747 (fax), or dr@nau.edu (e-mail). Once eligibility has been determined, students register with Disability Resources every semester to activate their approved accommodations. Although a student may request an accommodation at any time, it is best to initiate the application process at least four weeks before a student wishes to receive an accommodation. Students may begin the accommodation process by submitting a self-identification form online at https://nau.edu/disability-resources/student-eligibility-process or by contacting Disability Resources. The Director of Disability Resources, Jamie Axelrod, serves as NAU's Americans with Disabilities Act Coordinator and Section 504 Compliance Officer. He can be reached at jamie.axelrod@nau.edu.

RESPONSIBLE CONDUCT OF RESEARCH

Students who engage in research at NAU must receive appropriate Responsible Conduct of Research (RCR) training. This instruction is designed to help ensure proper awareness and application of well-established professional norms and ethical principles related to the performance of all scientific research activities. More information regarding RCR training is available at https://nau.edu/research/compliance/research-integrity.

MISCONDUCT IN RESEARCH

As noted, NAU expects every student to firmly adhere to a strong code of academic integrity in all their scholarly pursuits. This includes avoiding fabrication, falsification, or plagiarism when conducting research or reporting research results. Engaging in research misconduct may result in serious disciplinary consequences. Students must also report any suspected or actual instances of research misconduct of which they become aware. Allegations of research misconduct should be reported to your instructor or the University's Research Integrity Officer, Dr. David Faguy, who can be reached at david.faguy@nau.edu or 928-523-6117. More information about Misconduct in Research is available at https://nau.edu/university-policy-library/misconduct-in-research.

SENSITIVE COURSE MATERIALS

University education aims to expand student understanding and awareness. Thus, it necessarily involves engagement with a wide range of information, ideas, and creative representations. In their college studies, students can expect to encounter and to critically appraise materials that may differ from and perhaps challenge familiar understandings, ideas, and beliefs. Students are encouraged to discuss these matters with faculty.

PID and Wall Following Lab

Truong X. Nghiem and Trong-Doan Nguyen

Based on a similar lab in UPenn's course "F1/10 Autonomous Racing"

GitHub repo for lab code: https://github.com/FF1RR-NAU-Spring-2020/course-labs

The following instructions assume that

- You created a Catkin workspace `catkin_ws` folder on your ROS machine, using the instructions discussed during the previous lab sessions.
- You created a github folder in your home directory and cloned the `course-labs` repository.
- You have sucessfully completed the previous labs.

Pull the latest code from the GitHub repo of the lab (that you already cloned in the previous lab).

```
$ cd ~/github/course-labs
$ git pull
```

Then copy the new files from the directory `wall_follow` of the GitHub repo to your Catkin workspace, taking care not to overwrite the existing files:

```
$ cp -an ~/github/course-labs/wall_follow ~/catkin_ws/src/
```

You have just copied the template code files for the lab, but you have not created the package yet. Use the command `catkin_create_pkg` to create the package `wall_follow` that depends on the following packages: `roscpp`, `rospy`, `std_msgs`, and `sensor_msgs`. If you don't remember how to create a ROS package, refer to ROS Lab 1.

Make the Python files executable and remake the workspace by running the commands:

```
cd ~/catkin_ws
find . -name "*.py" -exec chmod +x {} \;
catkin_make
```

NOTE: If you follow the instructions in this lab and get an error that something does not exist or is not found, run `catkin_make` again in your Catkin workspace. This will ensure that all the changes you made to the structure of the package / workspace are registered. Sometimes you may need to delete the directories `build` and `devel` from the workspace directory before running `catkin_make` to refresh it fully. Finally, make sure that you source the file `devel/setup.bash` of your workspace.

1 Lab objective

In this lab, you will learn to implement a practical PID controller (more complex and more practical than the P controller in the previous lab), learn how to use scan data from a LiDAR sensor to calculate distances to objects, and learn how to control your car to drive autonomously using feedbacks from the sensors.

2 Wall-Following: An Application of PID

In this lab, you will implement a PID (**P**roportional **I**ntegral **D**erivative) controller to make the car drive parallel to the walls (or better, at the middle) of a corridor at a fixed distance. At a high level, you will accomplish this by taking laser scan distances from the LiDAR that attached on top of your car, computing the required steering angle and speed (drive parameters), and publishing these to the VESC to drive the car. Before starting this lab, review the learning materials on PID and LiDAR to ensure you are familiar with the materials.

2.1 A quick review of discrete-time PID control

A PID controller is a way to maintain certain parameters of a system around a specified set point. PID controllers are used in a variety of applications requiring closed-loop control, such as in the VESC speed controller on your car. The general equation for a PID controller in the time domain, as discussed in lecture, is as follows:

$$u(t) = K_p \, e(t) + K_i \int_0^t e(t') \, dt' + K_d \, \frac{d}{dt}(e(t))$$

Here, K_p, K_i, and K_d are constants that determine how much weight each of the three components (proportional, integral, derivative) contribute to the control output $u(t)$. $u(t)$ in our case is the steering angle we want the car to drive at. The error term $e(t)$ is the difference between the set point and the parameter we want to maintain around that set point.

You will implement the PID controller in a computer machine, so the PID controller should be discretized in time. Below is the Pseudocode of a PID controller in the discrete time domain:

```
previous_error := 0
integral := 0
loop:
    error := reference - measured_value
    integral += integral + error x dt
    derivative := (error - previous_error) / dt
    output := Kp * error + Kd * derivative + Ki * integral
```

2.2 Data from your LIDAR

To learn how a LiDAR sensor works with ROS and to understand the scan data obtained from a LiDAR sensor in ROS, read the LiDAR tutorial on http://wiki.ros.org/laser_pipeline/Tutorials/IntroductionToWorkingWithLaserScannerData, in particular the section **the Laser Scan Message* and the two tutorial videos at the bottom of the page.

- Video 1: http://www.youtube.com/watch?v=tEayzulupxE
- Video 2: http://www.youtube.com/watch?v=kze3Z8rTkZo

The format of a `sensor_msgs/LaserScan` (click for ROS page) is as follows:

```
# Single scan from a planar laser range-finder

Header header
# stamp: The acquisition time of the first ray in the scan.
# frame_id: The laser is assumed to spin around the positive Z axis
# (counterclockwise, if Z is up) with the zero angle forward along the x axis

float32 angle_min # start angle of the scan [rad]
float32 angle_max # end angle of the scan [rad]
float32 angle_increment # angular distance between measurements [rad]

float32 time_increment # time between measurements [seconds] - if your scanner
# is moving, this will be used in interpolating position of 3d points
float32 scan_time # time between scans [seconds]

float32 range_min # minimum range value [m]
float32 range_max # maximum range value [m]

float32[] ranges # range data [m]
#(Note: values < range_min or > range_max should be discarded)

float32[] intensities # intensity data [device-specific units].
```

The angle range of each LiDAR scan image is from `angle_min` to `angle_max` (in radians), with `angle_increment` being the step-wise increment of the sensing angle as the LiDAR rotates. All of the measured distances (in meters) to surrounding objects are stored in the `ranges` field, which is a list of real numbers. The list of distances `ranges` is ordered in increasing angles from the minimum angle to the maximum angle, with a constant step size of `angle_increment`.

In this lab, you will need to use `LaserScan` messages from the LiDAR sensor to measure the distance of your car to surrounding objects. Use `rostopic echo /scan` to see the realtime messages from the LiDAR of your car (`/scan` is the topic that the LiDAR publishes to). It might be different in your car, so you need to **verify it first!**.

2.3 One side wall following

In the context of our car, the desired distance to the wall should be our set point for our controller, which means our error is the difference between the desired and actual distances to the wall. This raises an important question: how do we measure the distance to the wall, and at what point in time? One option would simply be to consider the distance to the right wall at the current time t (let's call it D_t). Let's consider a generic orientation of the car with respect to the right wall and suppose the angle between the car's x-axis and the wall is denoted by α. We will obtain two laser scans (distances) to the wall: one at an angle θ ($0 < \theta \leq 70$ degrees), and another at an angle of 0 degrees relative to the car's x-axis. Suppose these two laser scans return distances a and b, respectively. See the diagram in the figure.

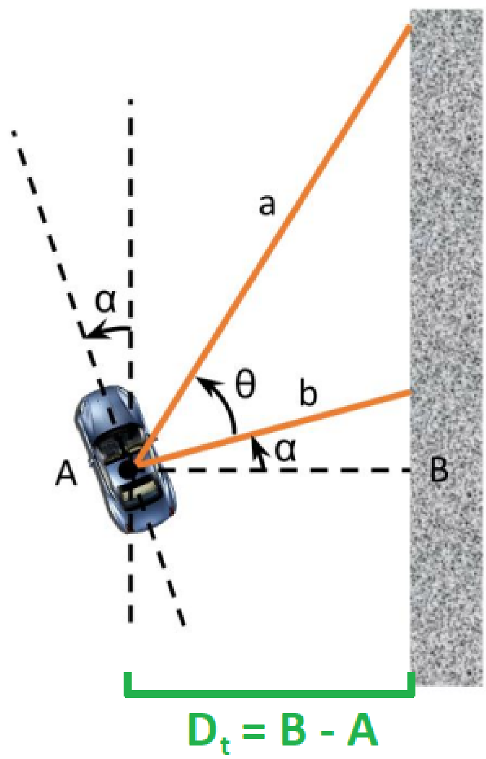


Figure 1: Distance and orientation of the car relative to the wall

Using the two distances a and b from the laser scan, the angle θ between the laser scans, and some trigonometry, we can express α as

$$\alpha = tan^{-1}\left(\frac{a\ \cos(\theta) - b}{a\ \sin(\theta)}\right)$$

We can then express D_t as $D_t = b\ \cos(\alpha)$ to get the current distance between the car and the right wall. What's our error term $e(t)$, then? It's simply the difference between the desired distance and actual distance! For example, if our desired distance is 1 meter from the wall, then $e(t)$ becomes $1 - D_t$.
However, we have a problem on our hands. Remember that this is a race: your car will be traveling at a high speed and therefore will have a non-instantaneous response to whatever speed and servo control you give to it. If we simply use the

current distance to the wall, we might end up turning too late, and the car may crash. Therefore, we must look to the future and project the car ahead by a certain lookahead distance (let's call it L). Our new distance D_{t+1} will then be

$$D_{t+1} = D_t + L\ \sin(\alpha)$$

See the figure on the future distance. In this lab, we will fix the rate of sending driving messages (that is the control frequency) at `freq` (Hz). Thus, you can estimate L as the distance that your car will travel in one sampling period at the current speed.

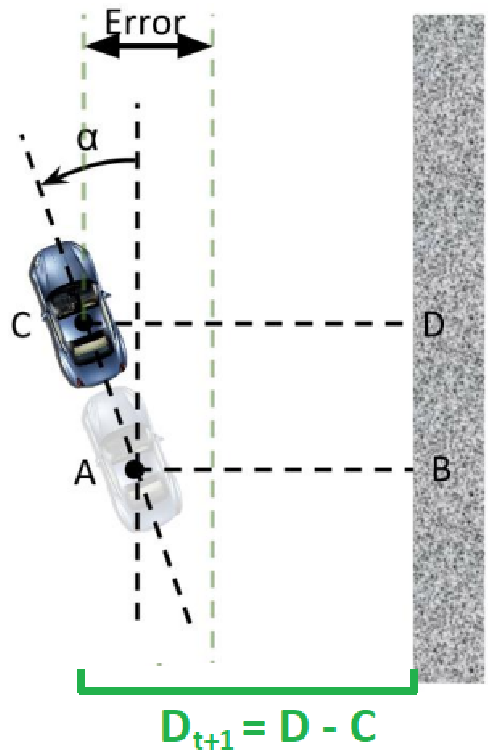


Figure 2: Finding the future distance from the car to the wall

We're almost there. Our control algorithm gives us a steering angle for the VESC, but we would also like to slow the car down around corners for safety. We can compute the speed in a step-like fashion based on the steering angle so that as the angle exceeds progressively larger amounts, the speed is cut in discrete increments. For this lab, we would like you to implement the following speed control algorithm for the **simulator**:

- If the steering angle is between 0 degrees and 10 degrees, the car should drive at 1.5 meters per second.
- If the steering angle is between 10 degrees and 20 degrees, the speed should be 1.0 meters per second.
- Otherwise, the speed should be 0.3 meters per second.

We would also want to limit the steering angle to a certain range so that the car will not turn too sharply. So, in summary, here's what we need to do:

1. Obtain two laser scans (distances) a and b, with b taken at 0 degrees and a taken at an angle θ ($0 < \theta \leq 70$)
2. Use the distances a and b to calculate the angle α between the car's x-axis and the right wall.
3. Use α to find the current distance D_t to the wall, and then find the estimated future distance D_{t+1} to the wall.
4. Run D_{t+1} through the PID algorithm described above to get a steering angle.
5. Use the steering angle you computed in the previous step to compute a safe driving speed.
6. Saturate the calculated steering angle if it is out of the given range.
7. Publish the steering angle and driving speed to the VESC.

2.4 Implementation of wall following for the simulator

If you haven't studied or don't understand the theory explained above, stop and go back to the top of this document. If you do understand it, you can continue.

1. At the beginning of this lab, you have copied the template code in `wall_follow` to your working Catkin workspace and created a ROS package for it. Your task, as explained later, is to complete the code and and test your algorithm with the `f110_simulator`.
2. Edit the file `wall_follow.py` in `wall_follow/scripts` and follow the instructions therein to complete the code. The instructions are placed in the comments, often marked with the keyword `TODO`. Most of the places which you must complete are marked with three dots `...`. Below are some general instructions.
   a. Pay attention to the constructor of the class `WallFollow`. It initializes important variables and constants that you will use throughout the implementation, including the parameters and variables of the PID controller.
      - `min_angle` and `max_angle` are the minimum and maximum values of the steering angle that the car can accept. For the real car, you will need to find these bounds by sending different steering angle values to the car's driving topic (see Lab 3) and seeing how your car respones. The real car may also need an offset, in the variable `servo_offset`, to the steering angle so that the steering is accurate. This offset value may need to be calculated and set for your real car. For the simulator, the offset is set to 0 and the angle bounds have the default values.
      - The scan data contain range values for different increasing angles. It's unlikely that you will find the exact measurement for an arbitrary angle. However, you can find the measurement for the angle closest to a specific angle; but the measurement can be noisy. Therefore, it is more accurate and stable to use the average value of several measurements around the specified angle, which are the measurements with indices in the range `[index - window_size, index + window_size]`, where `index` is the index of the measurement of the closest angle. Set a reasonable value for `window_size`.
      - You also need to create and initialize the `AckermannDriveStamped` message to be published to the drive topic of the car (to control it).

   b. The method `lidar_callback` is the main function in which you will implement the wall following procedure mentioned above. It will set the speed and steering angle commands in the `AckermannDriveStamped` message. This function calls the following methods to complete its task.
      - The method `rawDistances` calculates the values a and b which are used to calculate the distances to the left wall and the right wall. It will calculate the indices of the range measurements of the angles involved, then use `numpy.nanmean()` to calculate the average value in the range `[index - window_size, index + window_size]` (ignoring NaN values, which may happen during a scan).
      - The method `distanceSide` calculates the distance D_{t+1} from the car to the wall on either side. Use the equations described in the previous section to implement this method.
      - The method `selectVel` selects the suitable speed for a given steering angle following the above discrete increment rule.
      - The method `limitAngle` saturates a given steering angle if it is outside the allowed range `[min_angle, max_angle]`.
      - The method `pidControl` implements the PID control algorithm for the steering angle `angle`, then calculates an appropriate speed using `selectVel`.
3. Test your wall following code with the car simulator
   - Make your `wall_follow.py` file executable, run `catkin_make` on your workspace and source the setup file again.
   - The launch file `simulator_levine_blocked.launch` will start a new car simulator with an appropriate map for testing your driving code. To use it, run the following command in a terminal.

     ```
     $ roslaunch wall_follow simulator_levine_blocked.launch
     ```

   - Run the `wall_follow.py` file with `rosrun`.
   - If you do all the steps correctly, the node you have implemented will start controlling the car to drive autonomously. However, it may not work well and crash. Your task now is to tune the PID gains to make the car drive well and safely. When tuning the PID gains, tune the proportional term first until the car quickly approaches its set-point, followed by the derivative term to reduce oscillation and smoothen the response. You can implement a PD controller by setting $K_i = 0$. The integral term may improve the driving performance (but may also degrade the performance); however, since the steering angle may be saturated, an anti-windup mechanism for the integral term must be implemented. If you are going to use the integral term, refer to the lecture and the learning materials on PID control for details.

2.5 Both side wall following

If you successfully implement the controller for one-side wall following (in the previous section), the simulated car should be able to drive itself safely, including making safe turns. However, the car would not be able to complete the track as we intentionally designed a special structure on the track that can "trap" the car and make it crash. In this section, you will improve your algorithm to avoid that trap. A good solution is to make the car always drive at the center of the lane. To do that, you need to calculate the distances from the car to both sides, calculate the center position, and control the car to track that position (instead of keeping a constant distance from the wall on one side). Specifically, you will need to

- Calculate the distances to the walls on both sides.
- The main difference between one-side following and both-side following is the driving reference (i.e., the reference distance from one side) in the variable `self.D`. As you now want the car to be at the center of the lane, `D` needs to be the mean of the real-time distances to both sides.
- `error` is now the difference between `D` and the current distance to either of the sides (left or right). You may need to re-tune the PID gain values.
- The rest are the same.

Copy the file `wall_follow.py` to a new file named `wall_follow_both_side.py` and implement the above both-side wall following strategy in the new file. Repeat the simulation with the new Python file to test the new code. How does the driving performance change? Can the car avoid the trap?

3 Submit your lab

Each team has already been assigned a GitHub repository on https://github.com/FF1RR-NAU-Spring-2020. If you haven't, clone your team's repository to your machine. Copy the directory `wall_follow` with your completed code for the above exercises to your team's repository, then commit it (with the commit message "Submission of Lab 5") and push the changes to your team's GitHub repository. This will be your team's submission of this lab.

4 Wall Following In the Real World

If you have successfully implemented the both-side wall following algorithm, you will be allowed to test the code with your car. What you need to do is writing a launch file that starts the `teleop.launch` file in the `racecar` package and the node `wall_follow_both_side.py` you have implemented. Note that you have been publishing driving messages to the `/drive` topic of the car simulator, so you need to use `remap` in the launch file to remap it to one of the `.../nav_X` topics of the real car. Also remember that driving the real car with code can only be enabled by holding the `RB` button of the gamepad.

IMPORTANT: You MUST lower the speed of your car to avoid crash damages caused by your algorithm's failure. Use `[0.3, 0.4, 0.6]` as the discrete increment values first and then gradually increase them up to 1 if your algorithm works well.

College of Engineering, Informatics & Applied Sciences
School of Informatics, Computing, and Cyber Systems

Term	Class No.	Section	Units	Days & Times	Room	Mode
Spring 2021	EE 222	002	3	Tu & Th 9:35 - 10:50AM	ENG-106	NAUFlex

Department/ Academic Unit:
School of Informatics, Computing, and Cyber Systems

Course prefix, Section number and Title:
EE 222, Section 002, Intermediate Programming

Term/ Year: Spring 2021

Total Units of Course Credit: 3

Course Pre-requisite(s), Co-requisite(s), Co-convened, and/or Cross-Listed Courses:
MAT 136 and (CS 122 or CS 122H or CS 126) with grades of C or better.

Mode of Instruction: NAUFlex.

Course Website: http://bblearn.nau.edu

Instructor: Dr. Truong Nghiem
Office: Room 303, SICCS Building #90, 1295 S. Knoles Drive
E-mail: truong.nghiem@nau.edu
Office Hours: **Online only through BB Collaborate link**
Tuesday 4:00 - 5:00 PM, and by appointment (always write "EE222" in the subject line).

Teaching Assistant: No.

Reading and Materials:

Required text:

In this course, we will use the interactive electronic zyBooks *"Programming in C"* at the link https://www.zybooks.com/catalog/programming-in-c/. **Each student is required to purchase a subscription to this textbook**, following the instruction below:

1. Sign in or create an account at https://learn.zybooks.com
2. Enter zyBook code: **NAUEE222NghiemSpring2021**
3. Subscribe using your NAU email address

Important notes:

- A subscription is $77 and lasts until May 21, 2021.
- Students get free access to the first chapter and can ask for a deferral for two weeks for financial aid (email support@zybooks.com to request).
- Students get a full refund for dropping the course (email support@zybooks.com to request).
- Students who do not pass the course can retake the course for free (email support@zybooks.com to request).

Recommended text:

- Etter, "Engineering Problem Solving With C", 4th Ed. Pearson, 2013. ISBN 9780136085317.
- Shaw, "Learn C the Hard Way", Pearson, 2002. ISBN 9780131103627.

- Harbison and Steele, "C: A Reference Manual", 5th Ed. Pearson, 2016. ISBN 9780321884923.
- Kernighan and Ritchie, "The C Programming Language", 2nd Ed. Prentice Hall, 1988. ISBN 9780131103627.

Course Purpose:
Beginning with a review of basic program design and programming style, we will explore writing programs in C. The student will learn to write structured programs, use makefiles to build applications, and use headers to organize their code. C language features such as pointers will be covered.

Course Student Learning Outcomes (Course Objectives): Upon completion of this course, students will be able to:

- Develop an algorithmic solution to a problem.
- Translate an algorithm into C code.
- Use the C compiler
- Create an organized project using makefiles.
- Correctly use data types and pointers.
- Implement sorts and searches in C code.

Assignments/Assessment of Course Student Learning Outcomes:
The interactive online textbook (zyBooks) includes many practice and assessment activities: *participation activities* (basic activities for learning), *challenge activities* (intermediate activities / problems for reinforcing knowledge and skills), and *labs* (longer and more difficult problems to test skills). Following are the assignments / assessment in this course.

- **Textbook Participation Activities**: Students must complete these activities while reading the weekly assigned sections.
- **Textbook Challenge Activities**: Students must complete these activities while or after reading the weekly assigned sections.
- **Textbook Labs**: Students must complete each assigned lab by the corresponding deadline.
- **Project**: each student will be required to complete a programming project during the semester. The project will be due near the end of the semester (before the final exam week).
- **Final Exam**: There will be a comprehensive final exam on all topic covered in the semester.

Grading System: Final letter grades will be assigned as follows:

A:	≥ 90%;
B:	≥ 80% and < 90%
C:	≥ 70% and < 80%
D:	≥ 60% and < 70%
F:	< 60%

Course grades will be calculated as follows:

Textbook Participation:	10%
Textbook Challenges:	20%
Textbook Labs:	30%
Projects:	20%
Final Exam:	20%

Class Outline:

Although the lectures will generally follow the material in the text, we will occasionally skip certain material and may include supplementary topics. The schedule is tentative and is subject to changes, including due dates for homework and lab assignments. Updates will be posted on BBLearn; check BBLearn frequently for updates. We'll decide firm exam dates at least two weeks in advance.

Week	Dates	Topic
Week 1	Jan 12 (Tue) Jan 14 (Thu)	Course Introduction, Introduction to C
Weeks 2-3	Jan 19 (Tue), Jan 21 (Thu) Jan 26 (Tue), Jan 28 (Thu)	Variables, Data types
Week 4	Feb 2 (Tue), Feb 4 (Thu)	Branches and Operations
Week 5	Feb 9 (Tue), Feb 11 (Thu)	Loops
Week 6-7	Feb 16 (Tue), Feb 18 (Thu) Feb 23 (Tue), Feb 25 (Thu)	Arrays and Strings
Week 8-9	Mar 2 (Tue), Mar 4 (Thu) Mar 9 (Tue), Mar 11 (Thu)	User-defined Functions
Week 10	Mar 16 (Tue), Mar 18 (Thu)	Structs
Week 11-12	Mar 23 (Tue), Mar 25 (Thu) Mar 30 (Tue), Apr 1 (Thu)	Pointers
Week 13-14	Apr 6 (Tue), Apr 8 (Thu) Apr 13 (Tue), Apr 15 (Thu)	Input / Output Recursion
Week 15	Apr 20 (Tue), Apr 22 (Thu)	Project, Review

Class Policies:

<u>Assignments (Textbook activities and labs):</u>

- **Assignments are due when specified** and should be submitted electronically as instructed.
- **Late submissions will not get credit**.
- University disciplinary procedure will be invoked if any form of cheating is detected. Plagiarism and cheating are subject to the Arizona Board of Regents Code of Conduct procedures as outlined in the NAU Student Handbook.

<u>Exams:</u>

- Exams are open book, open notes, and conducted through an online service. Measures will be taken to prevent cheating, including but not limited to: randomized questions, combination of multiple-choice questions and long-answer questions, timed exam, displaying questions one-by-one without the ability to re-visit a previous question.
- All exams are individualized, meaning that questions may be different between students.
- **No makeup exams will be given** except by prior arrangement in exceptional or emergency situations at the discretion of the instructor and will require a documented emergency supported by a class missed memo from Student Life (https://nau.edu/student-life/classes-missed-memos/)

and with approval from the instructor. Make-up exams may be considerably different than the original exam.

Grading:

- Grades will be entered in BBLearn but your final grade will be calculated in Excel using the grading system described above and then entered in LOUIE. Your final course grade will not necessarily appear in BBLearn. Please check LOUIE for your final grade.
- Grades will be calculated based not only on technical content but also on the presentation of your work.
- No other grading accommodations will be made, with the exception of extreme cases where the university administration becomes involved, such as extended hospitalization.
- University policy for grade appeals (applied only to the final course grade) can be found at https://www5.nau.edu/policies/Client/Details/437.

Attendance and in-class participation:

- As stated in the Class Attendance policy in the NAU Academic Policies, students are expected to assume the responsibility for regular class attendance. When absence is unavoidable, students should report the reason to the instructor and assume the responsibility for any work they miss. Instructors are under no obligation to make special arrangements for students who have been absent.
- Class attendance will be recorded. Students should make every effort to be in their seats (if in-person) or logged in online (if remote) and ready when class begins. In the rare cases where being tardy is unavoidable, a student should enter the class or the virtual classroom as quietly as possible so that other students are not disturbed. Students with tardiness or attendance problems may have points deducted from their grade and might not be allowed to join a class in progress.
- You are encouraged to ask relevant questions and actively participate in the class.
- Attendance / Participation grade is part of the final grade of a student and includes: class attendance, participation in in-class / online / textbook activities, participation and performance in pop quizzes and mini-problems during lectures.

Extenuating Circumstances:

- Exceptions to the late homework, attendance, class activity, and examination policies may be made only under certain extenuating circumstances such as a serious illness or an institutional excuse, and will require valid written verification.
- A valid medical excuse must state that you are unable to attend classes due to the severity of the illness or the risk of spreading it and should clearly state the dates that you should be absent from the university. A written medical note that simply states that you visited a clinic or were seen by a doctor or nurse is not valid and will not be accepted.
- Students should inform the instructor of an institutional excuse or any significant scheduled events – such as religious ceremonies, away games for NAU athletes, weddings, conference travel, etc. – in writing at least 5 working days prior to the absence. Given these conditions, make-up work may be assigned and due before the student leaves for the event.
- Be aware that neither medical nor institutional excuses absolve you of making up any required work or exams. Remember also that you can always turn in an assignment early.
- Details of the student institutional excuses policy can be found in https://nau.edu/university-policy-library/wp-content/uploads/sites/26/Student-Institutional-Excuses.pdf

Communication: Email to the instructor and teaching assistants must be respectful and professional. Specifically, all emails should:

- Use a subject prefixed with "EE222" so that the message can be easily identified or placed in an auto-folder. The subject should also use lower case and upper case correctly.
- Contain a formal salutation: "Dear Dr. Nghiem"
- Contain a closing, (for example, "Best, Jane Doe")
- The body should contain complete sentences and correct grammar including correct usage of lowercase and uppercase letters. Composing emails on a mobile device is **not** an excuse for poor writing.
- The body of your message should also be respectful and explain the full context of the query.
- Although email will typically be answered quickly, you should allow up to three (3) business days for a response.
- If you have a question that would require a long response or you have a lot of questions, please come to office hours or schedule an appointment with the instructor.

Other means of electronic communication are also used in this course, which will be described by the instructor.

Academic Integrity:

- See the *NAU Academic Integrity Policy* for more information: https://policy.nau.edu/policy/policy.aspx?num=100601 and https://in.nau.edu/academic-affairs/academic-integrity/
- Keep in mind that exceptionally high standards of honor and integrity are fundamental and essential to the study and practice of engineering.
- Every student should fully understand and comply with the *NAU Academic Integrity Policy*. To foster such understanding and compliance, every student must submit his/her certificate of completion of the *Academic Integrity Workshop* on BBLearn within four weeks from the start of the course.

Academic Dishonesty:

- Academic dishonesty, including cheating and plagiarism, will not be tolerated in this class and could result in failing the course or even expulsion from the college and university. If you are charged with academic dishonesty, you are subject to the procedures established in the *NAU Academic Integrity Policy*. See the policy document for more information.
- The immediate consequence of academic dishonesty on an assignment, project, or examination will be a zero grade, and possibly a failing grade in the course.
- Not knowing that certain activities qualify as academic dishonesty is not a defense to a charge of academic dishonesty.
- Keep in mind that engineering is considered to be an ethical profession, and engineering students are expected to display the highest ethical standards.

Learning:

- You are expected to read the textbook and do all the activities therein. Not all topics are covered in depth in lectures. To be able to do the assignments and exams, it is not sufficient to rely only on the in-class lectures; you should invest your study time in reading the textbook on the topics covered in this course.
- Students are strongly encouraged to complete all assignments to prepare for the examinations.

- Students are strongly encouraged to seek assistance for their learning either from the instructor and/or the TA(s) and other campus' resources. The Academic Success Centers offer free tutoring and academic support to improve students' study skills and review course material in a number of engineering and math courses. Students can schedule an appointment by visiting http://nau.edu/asc, calling the Academic Success Center at 928-523-7391 or visiting Dubois Center - Room 140.

Cell Phone, Laptop, and Other Electronic Device Policies:

- In class: Electronic device usage must support learning in the class. Laptop computers and tablets may only be used for class activities during class time. All cell phones, PDAs, music players and other entertainment devices must be turned off (or in silent mode) during lecture, and may not be used at any time. Texting and phone calls are not allowed during class. If you do receive an emergency call, ask to be excused so that you can take it outside the classroom.

Emergency Textbook Loan Program: Eligible students can apply for assistance with acquisition of textbooks for the semester. More information can be found at: https://in.nau.edu/dean-of-students/course-materials-assistance-program/

COVID-19 Requirements and Information

The following statements in red set forth in this document's first section are specific to NAU's response to the COVID-19 situation. The requirements outlined below are mandatory until further notice. They are based upon current public health conditions and guidance and may change as circumstances warrant or new information becomes available. Additional information about the University's response to COVID-19 is available from the **Jacks are Back!** web page located at https://nau.edu/jacks-are-back/lumberjack-responsibilities.

FACE COVERING AND PHYSICAL DISTANCING REQUIREMENTS
Appropriate face masks or other suitable face coverings must be worn by all individuals when present in classrooms, laboratories, studios, and other dedicated educational spaces. To maximize the benefits of physical distancing as an important strategy to help reduce community transmission of the SARS-CoV-2 virus, instructors may implement mandatory student seating arrangements or specific seat assignments. Instructors may remove students who do not cooperate with these requirements from the instructional space in the absence of an approved accommodation arranged through Disability Resources. Failing to comply with these requirements may constitute a violation of the university's *Disruptive Behavior in an Instructional Setting* policy available at https://nau.edu/university-policy-library/disruptive-behavior.

USE NAUFLEX TO HELP MAINTAIN PHYSICAL DISTANCING
NAUFlex (available at https://nau.edu/nauflex/student) is designed to help all students actively participate in their coursework during the required day and time of a course when they are not physically present in the classroom. This course design model allows students to be fully engaged with faculty and peers and receive the high-quality educational experience for which NAU is known.

CLASS SESSION RECORDINGS FOR STUDENTS AND FACULTY USE ONLY
Certain class sessions may be audio or video recorded to help reinforce live instruction during the COVID-19 pandemic. These recordings are for the sole use of the instructor and students enrolled in the course. Recordings will be stored in approved, accessible repositories. By enrolling, students agree to have their image and classroom statements recorded for this purpose, to respect the privacy of their fellow students, and university-owned intellectual property (including, but not limited to, all course materials) by not sharing recordings from their courses. Questions regarding restrictions on the use of classroom audio or video recordings may be addressed to the appropriate academic unit administrator.

Syllabus Policy Statements

ACADEMIC INTEGRITY
NAU expects every student to firmly adhere to a strong ethical code of academic integrity in all their scholarly pursuits. The primary attributes of academic integrity are honesty, trustworthiness, fairness, and responsibility. As a student, you are expected to submit original work while giving proper credit to other people's ideas or contributions. Acting with academic integrity means completing your assignments independently while truthfully acknowledging all sources of information, or collaboration with others when appropriate. When you submit your work, you are implicitly declaring that the work is your own. Academic integrity is expected not only during formal coursework, but in all your relationships or interactions that are connected to the educational enterprise. All forms of academic deceit such as plagiarism, cheating, collusion, falsification or fabrication of results or records, permitting your work to be submitted by another, or inappropriately recycling your own work from one class to another, constitute academic misconduct that may result in serious disciplinary consequences. All students and faculty members are responsible for reporting suspected instances of academic misconduct. All students are encouraged to complete NAU's online academic integrity workshop available in the E-Learning Center and should review the full *Academic Integrity* policy available at https://policy.nau.edu/policy/policy.aspx?num=100601.

COURSE TIME COMMITMENT
Pursuant to Arizona Board of Regents guidance (ABOR Policy 2-224, *Academic Credit*), each unit of credit requires a minimum of 45 hours of work by students, including but not limited to, class time, preparation, homework, and studying. For example, for a 3-credit course a student should expect to work at least 8.5 hours each week in a 16-week session and a minimum of 33 hours per week for a 3-credit course in a 4-week session.

DISRUPTIVE BEHAVIOR
Membership in NAU's academic community entails a special obligation to maintain class environments that are conductive to learning, whether instruction is taking place in the classroom, a laboratory or clinical setting, during course-related fieldwork, or online. Students have the obligation to engage in the educational process in a manner that does not interfere with normal class activities or violate the rights of others. Instructors have the authority and responsibility to address disruptive behavior that interferes with student learning, which can include the involuntary withdrawal of a student from a course with a grade of "W". For additional information, see NAU's *Disruptive Behavior in an Instructional Setting* policy at https://nau.edu/university-policy-library/disruptive-behavior.

NONDISCRIMINATION AND ANTI-HARASSMENT
NAU prohibits discrimination and harassment based on sex, gender, gender identity, race, color, age, national origin, religion, sexual orientation, disability, or veteran status. Due to potentially unethical consequences, certain consensual amorous or sexual relationships between faculty and students are also prohibited as set forth in the *Consensual Romantic and Sexual Relationships* policy. The Equity and Access Office (EAO) responds to complaints regarding discrimination and harassment that fall under NAU's *Nondiscrimination and Anti-Harassment* policy. EAO also assists with religious accommodations. For additional information about nondiscrimination or anti-harassment or to file a complaint, contact EAO located in Old Main (building 10), Room 113, PO Box 4083, Flagstaff, AZ 86011, or by phone at 928-523-3312 (TTY: 928-523-1006), fax at 928-523-9977, email at equityandaccess@nau.edu, or visit the EAO website at https://nau.edu/equity-and-access.

TITLE IX
Title IX is the primary federal law that prohibits discrimination on the basis of sex or gender in educational programs or activities. Sex discrimination for this purpose includes sexual harassment, sexual assault or relationship violence, and stalking (including cyber-stalking). Title IX requires that universities appoint a "Title IX Coordinator" to monitor the institution's compliance with this important civil rights law. NAU's Title IX Coordinator is Elyce C. Morris. The Title IX Coordinator is available to meet with any student to discuss any Title IX issue or concern. You may contact the Title IX Coordinator by phone at 928-523-3515, by fax at 928-523-0640, or by email at elyce.morris@nau.edu. In furtherance of its Title IX obligations, NAU will promptly investigate and equitably resolve all reports of sex or gender-based discrimination, harassment, or sexual misconduct and will eliminate any hostile environment as defined by law. Additional important information about Title IX and related student resources, including how to request immediate help or confidential support following an act of sexual violence, is available at https://in.nau.edu/title-ix.

ACCESSIBILITY
Professional disability specialists are available at Disability Resources to facilitate a range of academic support services and accommodations for students with disabilities. If you have a documented disability, you can request assistance by contacting Disability Resources at 928-523-8773 (voice), 928-523-6906 (TTY), 928-523-8747 (fax), or dr@nau.edu (e-mail). Once eligibility has been determined, students register with Disability Resources every semester to activate their approved accommodations. Although a student may request an accommodation at any time, it is best to initiate the application process at least four weeks before a student wishes to receive an accommodation. Students may begin the accommodation process by submitting a self-identification form online at https://nau.edu/disability-resources/student-eligibility-process or by contacting Disability Resources. The Director of Disability Resources, Jamie Axelrod, serves as NAU's Americans with Disabilities Act Coordinator and Section 504 Compliance Officer. He can be reached at jamie.axelrod@nau.edu.

RESPONSIBLE CONDUCT OF RESEARCH

Students who engage in research at NAU must receive appropriate Responsible Conduct of Research (RCR) training. This instruction is designed to help ensure proper awareness and application of well-established professional norms and ethical principles related to the performance of all scientific research activities. More information regarding RCR training is available at https://nau.edu/research/compliance/research-integrity.

MISCONDUCT IN RESEARCH

As noted, NAU expects every student to firmly adhere to a strong code of academic integrity in all their scholarly pursuits. This includes avoiding fabrication, falsification, or plagiarism when conducting research or reporting research results. Engaging in research misconduct may result in serious disciplinary consequences. Students must also report any suspected or actual instances of research misconduct of which they become aware. Allegations of research misconduct should be reported to your instructor or the University's Research Integrity Officer, Dr. David Faguy, who can be reached at david.faguy@nau.edu or 928-523-6117. More information about misconduct in research is available at https://nau.edu/university-policy-library/misconduct-in-research.

SENSITIVE COURSE MATERIALS

University education aims to expand student understanding and awareness. Thus, it necessarily involves engagement with a wide range of information, ideas, and creative representations. In their college studies, students can expect to encounter and to critically appraise materials that may differ from and perhaps challenge familiar understandings, ideas, and beliefs. Students are encouraged to discuss these matters with faculty.

NORTHERN ARIZONA UNIVERSITY

College of Engineering, Informatics & Applied Sciences
School of Informatics, Computing, and Cyber Systems

Term	Class No.	Section	Units	Days & Times	Room	Mode
Spring 2023	EE 599	003	3	MW 2:20PM - 3:35PM	SBS-Raul H. Castro, Rm 210	In person

Department/ Academic Unit:
School of Informatics, Computing, and Cyber Systems

Course prefix, Section number and Title:
EE 599, Section 003, Modern Control Systems

Term/Year: Spring 2023

Total Units of Course Credit: 3

Course Pre-requisite(s), Co-requisite(s), Co-convened, and/or Cross-Listed Courses:
Knowledge of feedback control theory (equivalent to EE 458/558 with a grade of C or better); Knowledge and skills in calculus, differential equations, and linear algebra (equivalent to MAT 316 or EE 325 with a grade of C or better); Good programming skills in Matlab/Simulink, Python, Julia, or another suitable programming language and tool.

Mode of Instruction: In person.

Course Website: http://bblearn.nau.edu

Instructor: Dr. Truong Nghiem
Office: Room 303, SICCS Building #90, 1295 S. Knoles Drive
E-mail: truong.nghiem@nau.edu
Office Hours: Wednesday 11:30 AM – 12:30 PM in office. Additional appointments can be made via email.

Teaching Assistant: N/A.

Course Purpose: This course develops an understanding of the theory and applications of modern control systems. Together with EE 458/558 which focuses on classical control theory, this course will provide students with the advanced knowledge and skills expected in careers in robotics, industry automation, autonomous systems, and other complex systems. The topics include modeling, analysis, design, and simulation of modern control systems in state space, in both continuous time and discrete time; optimal control design with LQR and LQG methods; and an introduction to model predictive control and its applications.

Course Student Learning Outcomes (Course Objectives): Upon completion of this course, students will:

LO1) Be able to recognize and describe the widespread application of modern control, especially in electrical and mechanical systems.

LO2) Understand, choose, practice, and demonstrate methods for developing models of physical systems in state space, linearization, conversion between transfer functions and state-space models, and solutions of state-space models.

LO3) Understand the concepts of, apply methods for, analyze, and evaluate the performance and design of feedback control systems in state space, including: stability, controllability, observability, full-state feedback, output feedback, observer design, LQR.

LO4) Understand the basic concepts of, formulate problems for, and implement standard algorithms for continuous mathematical optimization and model predictive control (MPC).

LO5) Use Matlab, Simulink, Matlab's Control System Toolbox, Matlab's Optimization toolbox, Matlab's Model Predictive Control toolbox, and other relevant software tools for modeling, simulation, analysis, and design of state space control systems, optimal control systems, and MPC.

Assignments/Assessment of Course Student Learning Outcomes:
The following methods of assessment are designed to evaluate a student's mastery of the materials in this course for the learning outcomes LO1-LO5.

- **Quizzes (assessing learning outcomes LO1, LO2, LO3, LO4)**: Short quizzes will be assigned on a regular basis to test the student's basic understanding of the topics discussed in the lectures. The lowest quiz grade will be dropped in the calculation of the final grade.
- **Homework (assessing learning outcomes LO1, LO2, LO3, LO4, LO5)**: Homework assignments will be assigned on a regular basis and will typically be due one week after being assigned (unless specified otherwise by the instructor). Some assignments may involve programming and reporting code, computation results, and plots. Homework assignments are submitted online to the LMS site of the course.
- **Midterm exam (assessing learning outcomes LO2, LO3)**: There will be a midterm exam on all topics covered before the exam.
- **Final exam (assessing learning outcomes LO1, LO2, LO3, LO4) or course project (assessing learning outcomes LO2, LO3, LO4, LO5)**: There will be a comprehensive final exam on all topic covered in the course. Alternatively, a student may opt to do a semester-long course project, a project presentation, and a project report to replace the final exam. Potential project topics, their logistics, and sign-up will be discussed at the beginning at the course. A student may also do a course project and take the final exam, and will receive the higher score of the two for the final.

Grading System: Final letter grades will be assigned as follows:

A:	≥ 90%;
B:	≥ 80% and < 90%
C:	≥ 70% and < 80%
D:	≥ 60% and < 70%
F:	< 60%

Course grades will be calculated as follows:

Quizzes:	10%
Homework:	20%
Midterm Exam:	20%
Final Exam / Course Project:	40%

Participation:	10%

This course does not grade students relative to each other. There is no grading curve. Please address concerns regarding the grading of your assignments during office hours, or by appointment. Do not ask about your grade before, during, or after class.

Reading and Materials:

There is no required textbook. Course materials, including slides and reading materials, will be provided.

Suggested References:

- K. Astrom and R. Murray. *Feedback Systems: An Introduction for Scientists and Engineers*, First Edition, Princeton University Press, 2008. This text is publicly available for download from http://www.cds.caltech.edu/~murray/amwiki
- R.C. Dorf and R.H. Bishop. *Modern Control Systems*, Prentice Hall, 13th Edition, 2016.
- N.S. Nise. *Control Systems Engineering*, 7th Edition, Wiley, 2015.
- K. Ogata. *Modern Control Engineering*, 5th Edition, Prentice Hall, 2010.
- Francesco Borrelli, Alberto Bemporad, Manfred Morari. *Predictive Control for Linear and Hybrid Systems*, Cambridge University Press, 2017.
- Rawlings, James Blake, David Q. Mayne, and Moritz Diehl. *Model predictive control: theory, computation, and design*, Vol. 2, Madison, WI: Nob Hill Publishing, 2017. This text is publicly available at https://sites.engineering.ucsb.edu/~jbraw/mpc/.

Students will also need access to a computer with a recent version of Matlab/Simulink and the required toolboxes, available as part of NAU's standard software distribution and in most computer labs.

Class Outline:

Although the lectures will generally follow the topics listed below, we will occasionally skip certain material and may include supplementary topics.

1. Part 1: Control systems in state-space
   - State-space modeling: ODE, linearization, continuous-time / discrete-time, simulation (ODE solving)
   - System identification
   - Analysis in state space: solution in time domain, stability, controllability, observability
   - Control design in state space: full state feedback, output feedback, observer design, Kalman filter
   - Optimal control: LQR, LQG
2. Part 2: Introduction to Model Predictive Control (MPC)
   - A crash course on optimization: general optimization formulation, different types of optimization problems, solving unconstrained optimization, numerical optimization with computer tools
   - General MPC approach: the basic concept and formulation
   - Overview of theoretical topics in MPC: stability, recursive feasibility
   - Implementation and practical applications of MPC

Tentative Schedule:

Important:

- The schedule is tentative and is subject to changes, including due dates for assignments. Updates will be posted on the LMS. Please check the LMS frequently for updates.

Week	Topics
Weeks 1-2	Introduction to course. Review of linear algebra.
Week 3	State-space modeling.
Weeks 4	Analysis of state space control systems.
Week 5-7	Control design in state space.
Week 8	Review, Mid-term
Weeks 9-10	Introduction to mathematical optimization. Applied numerical optimization.
Weeks 11-12	Introduction to model predictive control.
Weeks 13	Practical model predictive control.
Weeks 14-15	Project. Final Review.

Class Policies:

Syllabus Adjustments: Everything in this syllabus is subject to change. If it becomes necessary or prudent for me to change something, I will try to do so fairly and transparently.

Copyright Notice: The instructor holds the copyright for all slides, instructor lecture notes, assignments, and exams for this class. You may not redistribute these materials to anyone, including others in the class, without **written permission** from the instructor. Students enrolled in the class are encouraged to obtain their own copies of available materials from the course website. Violation of this policy constitutes academic misconduct and may further result in criminal or civil penalties for copyright violation.

Attendance:

- The Class Attendance policy in the NAU Academic Policies requires students to assume the responsibility for regular class attendance. When absence is unavoidable, students should report the reason to the instructor and assume the responsibility for any work they miss. Instructors are under no obligation to make special arrangements for students who have been absent.
- Students should make every effort to be in their seats (if in-person) or logged in online (if remote) and ready when class begins. In the rare cases where being tardy is unavoidable, a student should enter the class or the virtual classroom as quietly as possible so that other students are not disturbed. Students with tardiness or attendance problems may have points deducted from their grade and might not be allowed to join a class in progress.
- You are responsible for all materials covered by the assigned reading and during the classes, whether you attend or not. I am happy to answer any questions you have about a missed lecture, but I will not repeat it for you.

Academic Integrity:

- Every student should fully understand and comply with the *NAU Academic Integrity Policy*: https://policy.nau.edu/policy/policy.aspx?num=100601 and https://in.nau.edu/academic-affairs/academic-integrity/
- Academic dishonesty, including cheating and plagiarism, will not be tolerated. All academic integrity violations are treated seriously. All work you submit for grading must be your own. You are encouraged to discuss the intellectual aspects of assignments with other class participants. However, each student is responsible for formulating responses and solutions on their own and in their own works. Academic integrity violations will result in penalties including, but not limited to, a zero on the assignment / project / exam, a failing grade in the class, or expulsion from NAU.
- Not knowing that certain activities qualify as academic dishonesty is not a defense to a charge of academic dishonesty.
- If you are charged with academic dishonesty, you are subject to the procedures established in the *NAU Academic Integrity Policy*. See the policy document for more information.

Homework assignments:

- Homework assignments, whether typed or handwritten, must be neat and legible. Students are encouraged to type the assignments.
- Assignments must be completed outside of class and submitted through the LMS. Assignments submitted by email or in person will not be accepted. Illegible submissions (for example, low scan quality) will not be graded.
- On all assignments, any sources of information that are not the original creation of the author nor taught in class nor in the textbook must be cited in sufficient detail that the instructor can locate and verify the sources. If you are repeating this class, you may not use previous work that you completed for a previous class.
- University disciplinary procedure will be invoked if any form of cheating is detected. Plagiarism and cheating are subject to the Arizona Board of Regents Code of Conduct procedures as outlined in the NAU Student Handbook.

Quizzes:

- Quizzes are given to increase student participation in classes and enhance student learning. There will be no make-up quizzes.
- Quizzes are in both the form of multiple choices and the form of written answers to be submitted online through the LMS.
- The following policy is designed to account for unexpected, emergency life events that may happen to some students, while maintaining fairness for all students: The lowest quiz grade will be dropped in the calculation of the final grade.

Exams:

- If conducted in-person: exams are closed book and closed notes. You may use dedicated calculators, unless mentioned otherwise, but you are not allowed to use laptops and cell phones. Calculator software is not allowed.
- If conducted online: exams are open book, open notes, and conducted through an online service (such as the LMS). Measures will be taken to prevent cheating, including but not limited to: randomized questions, combination of multiple-choice questions and long-answer questions,

timed exam, displaying questions one-by-one without the ability to re-visit a previous question, and online proctoring.

- All exams are individualized, meaning that questions are different between students.
- No makeup exams will be given except by prior arrangement in exceptional or emergency situations at the discretion of the instructor and will require a documented emergency supported by a class missed memo from Student Life (https://nau.edu/student-life/classes-missed-memos/) and with approval from the instructor. Make-up exams may be considerably different than the original exam.

Late submissions:

- The following late submission policy is designed to account for unexpected, emergency life events that may happen to some students, while maintaining fairness for all students.
- For all exams and quizzes, late submissions will not be accepted and will result in zeros for the grades.
- For all assignments, students are highly encouraged to submit their works before the deadlines.
- The penalty for a late submission of an assignment, unless permitted otherwise in advance by the instructor, is determined as follows (the late time is calculated relative to the deadline):
    - Late by 0-1 day (0-24 hours): deduct 20 percentage points absolute (not relative) from the earned grade; for example: if your earned grade is 85% but it was submitted 10 hours late, then your grade is 85% - 20% = 65%.
    - Late by 1-2 days (24-48 hours): deduct 50 percentage points absolute (not relative) from the earned grade; for example: if your earned grade is 85% but it was submitted 30 hours late, then your grade is 85% - 50% = 35%.
    - Late by more than 2 days (48 hours): grade is zero; for example: if your earned grade is 85% but it was submitted 50 hours late, then your grade is 0%.

Grading:

- Grades will be entered in the LMS but your final grade will be calculated in Excel using the grading system described above and then entered in LOUIE. Your final course grade will not necessarily appear in the LMS. Please check LOUIE for your final grade.
- Grades will be calculated based not only on technical content but also on the presentation of your work. The presentation should be neat, legible, clear, using standard technical terms and symbols.
- Most problems in homework and exams will be graded using the following scale: a first quarter of available points for formulating a solution (identifying the technique/equations necessary for the solution); a second quarter of available points for carrying out the solution but a major error is found in the work; a third quarter of available points for a correct solution; and a fourth quarter of available points for a good presentation. Full or half points can be subtracted for small errors. Illegible answers will have no points.
- No other grading accommodations will be made, with the exception of extreme cases where the university administration becomes involved, such as extended hospitalization.
- University policy for grade appeals (applied only to the final course grade) can be found at https://www5.nau.edu/policies/Client/Details/437.

Extenuating Circumstances:

- Exceptions to the late homework, attendance, class activity, and examination policies may be made only under certain extenuating circumstances such as a serious illness or an institutional excuse, and will require valid written verification.

- A valid medical excuse must state that you are unable to attend classes due to the severity of the illness or the risk of spreading it and should clearly state the dates that you should be absent from the university. A written medical note that simply states that you visited a clinic or were seen by a doctor or nurse is not valid and will not be accepted.
- Students should inform the instructor of an institutional excuse or any significant scheduled events – such as religious ceremonies, away games for NAU athletes, weddings, conference travel, etc. – in writing at least 5 working days prior to the absence. Given these conditions, make-up work may be assigned and due before the student leaves for the event.
- Be aware that neither medical nor institutional excuses absolve you of making up any required work or exams. Remember also that you can always turn in an assignment early.
- Details of the student institutional excuses policy can be found in https://nau.edu/university-policy-library/wp-content/uploads/sites/26/Student-Institutional-Excuses.pdf

Communication: Email to the instructor and teaching assistants must be respectful and professional. Specifically, all emails should:

- The subject should be prefixed with "EE599" so that the message can be easily identified or placed in an auto-folder. The subject should also use lower case and upper case correctly.
- Contain a formal salutation: "Dear Dr. Nghiem"
- Contain a closing, (for example, "Best, Jane Doe")
- The body should contain complete sentences and correct grammar including correct usage of lowercase and uppercase letters. Composing emails on a mobile device is **not** an excuse for poor writing.
- The body of your message should also be respectful and explain the full context of the query.
- Although email will typically be answered quickly, you should allow up to three (3) business days for a response.
- If you have a question that would require a long response or you have a lot of questions, please come to office hours or schedule an appointment with the instructor.

Other means of electronic communication are also used in this course, which will be described by the instructor.

Learning:

- You are expected to read the textbook, and watch the posted lecture / supplementary videos, to learn the material and achieve the objectives in the course. This includes reading and working the example problems in detail. Not all topics are covered in depth in lectures, nor can examples be done for each type of problems you may encounter in the homework. To be able to do the homework assignments, exams, and labs, it is not sufficient to rely only on the in-class lectures; you should invest your study time in reading the textbook on the topics covered in this course.
- Students are strongly encouraged to complete all assignments to prepare for the examinations.
- Students are strongly encouraged to seek assistance for their learning either from the instructor and/or the TA(s) and other campus' resources. The Academic Success Centers offer free tutoring and academic support to improve students' study skills and review course material in a number of engineering and math courses. Students can schedule an appointment by visiting http://nau.edu/asc, calling the Academic Success Center at 928-523-7391 or visiting Dubois Center - Room 140.

Cell Phone, Laptop, and Other Electronic Device Policies:

- In class: Electronic device usage must support learning in the class. Laptop computers and tablets may only be used for class activities during class time. All cell phones, PDAs, music players and other entertainment devices must be turned off (or in silent mode) during lecture, and may not be used at any time. Texting and phone calls are not allowed during class. If you do receive an emergency call, ask to be excused so that you can take it outside the classroom.
- During an exam: Cell phones, pagers and other electronic devices MUST be turned off. Their use is prohibited during an exam. You may use a dedicated calculator, not calculator software on a device such as smartphone or tablet.

Emergency Textbook Loan Program: Eligible students can apply for assistance with acquisition of textbooks for the semester. More information can be found at: https://in.nau.edu/dean-of-students/course-materials-assistance-program/

EE 599 – Spring YYYY
Homework X
Due: Time and Date

Instructions:

- Total score: 44 points.
- Each answer must be worked out in detailed steps. Writing only the final answer is incomplete.
- Write your answers neatly and legibly.

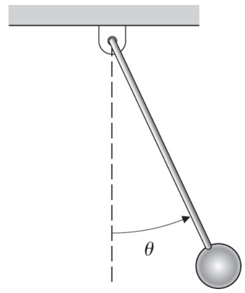
Have you read and fully understood the **"Instructions for All Homework Assignments"** on the "Course Information" page on BBLearn? Failure to follow the instructions, including how to submit the homework and the quality requirements of the electronic submission, may result in a grade reduction or a zero for this homework. Acknowledge below that you have read and fully understood the instructions?

☐ **I acknowledge that I have read and fully understood the instructions.**

Prob 1 | The linearized equations of motion of the simple pendulum in the figure below are

$$\ddot{\theta} + \omega^2\theta = u$$

where $\omega > 0$ is a parameter (unknown but constant).



The output is the pendulum angle θ.

a) (2 points) Choose the state variables as $x_1 = \theta$, $x_2 = \dot{\theta}$, and the output variable as the measured angle θ of the pendulum. Write the equations of motion in state-space form.

b) (2 points) Verify if the system is controllable.

c) (2 points) Show that the system is observable for all ω.

d) (4 points) Assume $\omega = 5$rad/sec. Design a state-feedback controller (that is, determine the state feedback gain matrix K) so that the roots of the closed-loop characteristic equation, i.e., the closed-loop poles, are at $s = -4 \pm 4i$. Verify that the closed-loop poles with the designed controller are at the desired locations. **Show the steps, not just the final result.**

e) (4 points) Design a state observer that reconstructs the state x of the pendulum given measurements of θ, so that the observer's poles are at $s = -20 \pm 4j$. The observer's gain matrix L is in terms of the parameter ω.

f) (2 points) Write the state-space model of the observer, given its inputs being u (the plant's input) and y (the plant's output, which is θ). The observer's state is $\hat{x}$, which is the estimate of the plant's state x.

g) (2 points) A full state feedback controller was designed with the gain matrix $K = \begin{bmatrix} 32 - \omega^2 & 8 \end{bmatrix}$. Write the state space model of the observer-based controller in the form $\dot{\hat{x}} = \hat{A}\hat{x} + \hat{B}y$ and $u = \hat{C}\hat{x}$. Note that the controller's input is the measured plant's output y, and the controller's output is the plant's input u.

Prob 2 | Consider an LTI system with the transfer function

$$G(s) = \frac{Y(s)}{U(s)} = \frac{10}{s(s+1)}.$$

a) (2 points) Define state variables $x_1 = y$ and $x_2 = \dot{x}_1$. Write the state space model of the system.

b) (4 points) Find state feedback gain matrix $K = [K_1, K_2]$ so that $u = -Kx = -K_1x_1 - K_2x_2$ yields closed-loop poles with a natural frequency $\omega_n = 3$ and a damping ratio $\zeta = 0.5$. **Show the steps, not just the final result.**

c) (4 points) Design a state observer for the system that yields observer's poles with natural frequency $\omega_n = 15$ and damping ratio $\zeta = 0.5$. **Show the steps, not just the final result**.

d) (2 points) What is the state-space model of the output feedback (observer-based) controller obtained by combining parts (a) and (c)? The controller's model must have the form $\dot{\hat{x}} = \hat{A}\hat{x} + \hat{B}y$ and $u = \hat{C}\hat{x}$. *Hint: see the first problem.*

Prob 3 | Consider a system with state matrices

$$A = \begin{bmatrix} -2 & 1 \\ 0 & -3 \end{bmatrix}, \qquad B = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \qquad C = \begin{bmatrix} 1 & 3 \end{bmatrix}.$$

a) (4 points) Use feedback of the form $u(t) = -Kx(t) + Nr(t)$, where N is a nonzero scalar, to move the poles to $-3 \pm 3j$. **Show the steps, not just the final result.**

b) (2 points) Choose N so that if r is a constant, the system has zero steady-state error, that is $y(\infty) = r$. In other words, the steady-state tracking error is zero. **Show the steps, not just the final result.**

c) (4 points) The system steady-state error performance can be made robust by augmenting the system with an integrator and using unity feedback, that is, by setting $\dot{x}_I = r - y$, where x_I is the state of the integrator. Compute a state feedback controller of the form $u = -Kx - K_I x_I$ so that the poles of the augmented system are at -3, $-2 \pm j\sqrt{3}$. You can use Matlab to design the feedback gain matrix (with the command `acker` or `place`). **You must show the steps, not just the final result.**

d) (4 points) Suppose that the plant's model used for control design has an error: the actual state matrix of the plant is

$$\hat{A} = \begin{bmatrix} -2.5 & 1 \\ 0 & -3 \end{bmatrix}.$$

Note the first element was changed from -2 to -2.5. Calculate the actual DC gain of the closed-loop control system with this new state matrix $\hat{A}$ in two cases: (1) the feedback control design resulted from parts (a) and (b); and (2) the feedback control design with integral action resulted from part (c). Which design still has zero steady-state tracking error and is therefore robust to model error?