CS-454 / CS-654 Spring 2023

Embedded Systems Development

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Lectures: Tuesday & Thursday, 9.30 am - 10.45 am, CAS 426

Labs: (A2) Wednesday, 9.05 am - 9.55 am, CCDS 1012 (Lab Space)

(A3) Wednesday, 10.10 am - 11.00 am, CCDS 1012 (Lab Space)

Webpage: `http://cs-people.bu.edu/rmancuso/courses/cs454_654-sp23/`

This syllabus represents a guideline on the intended pace of the course. As such it is subject to unpredictable yet moderate changes throughout the semester.

1 Course Description

We do not always realize it, but we live surrounded by machines that augment our abilities by shaping the physical world around us at the press of a button. What supports our modern society and ordinary life is a computing infrastructure (cyber-) that is strongly intertwined with the real world (-physical). These referred as Cyber-Physical Systems (CPS). From toasters to defibrillators; from laundry machines to fighter jets; from elevators to a Mars lander. When dealing with CPS development, programming abandons the cyber-space and touches on the "real world". In this course, we focus on the "brain" behind CPS, namely embedded platforms. As opposed to traditional computing systems, embedded systems are often powered by simple yet powerful micro-controllers. Embedded systems directly interact with the surrounding physical space via sensors and actuators. They are responsible for the timely acquisition, processing and deliberation of actuation decisions. More in detail, CS-454 / CS-654 explores topics in efficient and portable embedded programming. It provides a general introduction to real-time programming, explores topics in sensor data acquisition and processing, design principle for time-sensitive firmware design, and asynchronous event handling. The course also dives into I/O interfacing, and into design and tuning of feedback control strategies. As such, this course can be considered as a gateway for practical development of medical devices, engine control applications, flight control systems, automated assembly lines, industrial controllers. It can also be handy in case you simply want to put a car in Sun's orbit[1].

[1] See `http://www.spacex.com/careers/position/213492`

Prerequisite(s):

1. CAS CS-210: Programming and basic software/hardware interface concepts.
2. CAS CS-350 (highly recommended): Basics of system modeling and performance analysis; understanding of resource scheduling.
3. Please contact the instructor(s) ahead of time if you do not satisfy any of these prerequisites.

Credit Hours: 4

Course Material: *POSIX.4 Programmers Guide - Programming for the Real World* by Bill Gallmeister[2]. A detailed introspection into programming for systems that interact with the real-world.

Course Objectives: The typical know-how that students are expected to acquire with this course should allow them to:

1. how to interact and develop applications for a micro-controller;
2. how to handle A/D and D/A conversions;
3. how to program and handle interrupts;
4. how to interface with external controllers, sensors and actuators via standard I/O interfaces (e.g. I^2C, UART, USB);
5. how to develop real-time applications in a POSIX-compliant systems and on a bare-metal system;
6. how to use and program timers and periodic functions;
7. how to use synchronization and message passing in real-time applications;
8. how to perform signal filtering and processing;
9. how to design feedback loop control systems using PIDs;
10. how to debug logic and temporal behavior of firmware on micro-controllers.

2 Grading

Grading will be determined by your performance on the assignments, the labs, the exams, and according to your participation to the lectures. Grading (except for the midterm and final exam) is done by a number of class graders, under the direct supervision of the Teaching Fellow(s). If you have an issue with a grade (homework or exam), please contact the Teaching Fellow(s). If your issue is not resolved, then (and only then) please contact me. In doing so, please note that (to ensure fairness and grading consistency) it is seldom the case that I will overrule a Teaching Fellow. This class is not graded on a curve, i.e., there is no prescribed proportions for specific grades. This means that if everybody's performance in the class deserves an A, then everybody will get an A. The converse is also true! Therefore, don't be satisfied with an "average" grade because that average could well be less than what you expect. You should expect this class to be competitive. Thus, make sure you work hard from the very beginning.
An instructor is not allowed to give W (withdrawal) grades. One can get such a grade only by dropping this class by the deadline specified by the registrar office for withdrawals with or without a W grade (check the registrar's office calendar for the exact date). Also, an instructor is not allowed to give an I (incomplete) grade except if a student misses completing assignments and/or misses taking tests due to circumstances beyond their control.

[2] `http://www.oreilly.com/catalog/posix4/index.html`

Grade Distribution:

Class Participation	5%
Lab assignments	35%
Homework assignments	10%
Midterm	20%
Final	30%

3 Course Policies

The following is a summary of the main course policies.

- **General**
  - Attending lectures is mandatory and will account for a portion of the final grade.
  - Students are responsible for all missed work, regardless of the reason for absence. It is also the absentee's responsibility to get all missing slides/materials.
  - Quizzes and exams are closed book, closed notes.
  - **No makeup quizzes or exams will be given.**
  - Conflict exams can be scheduled as needed, but it is up to the student to schedule the exam at least 2 weeks before the date of the conflicting exam.
- **Grades**
  - As mentioned above, grading does not follow a curve. You will earn the grade that is directly proportional to your performance.
  - Grade corrections should be requested no later than 3 weeks after the corresponding assignment due date or exam date.
- **Homework Assignments**
  - Students are expected to work individually. Students involved in plagiarism will be heavily penalized according to the Academic Code of Conduct. Please carefully review the Academic Code of Conduct below. Discussion amongst students is encouraged, but when in doubt, direct your questions to the professor, or to a Teaching Fellow.
  - **No homework will be accepted if late by more than one class**. The only exception to this policy are certified medical excuses.
  - Homework assignments will be posted online at the end of each week, typically on Fridays.
  - Solutions to homework assignments that are handwritten should be scanned and uploaded electronically on Gradescope.
- **Labs**
  - Labs represent micro-projects that are intended to be solved in team. Solving a lab entails producing the code that can reliably produce an expected result on the target micro-controller.

- Successful completion of a lab is confirmed during the weekly lab session by the TF(s).
- Solutions to labs will not be accepted if successful demonstration to the TF(s) is not achieved within the corresponding weekly lab session.
- *All-team-present* policy: when demonstrating a successful solution, ALL the members of the team are expected to be present. Credits for the completion of the lab will be given only to the team members who are present at the time of the deamo.
- Exceptions to the *all-team-present* policy are confined to documented medical emergencies and a make-up demonstration should be scheduled by the absent team member(s) with the TF(s).

4 Interaction with Course Staff

In the context of this course, there are four main ways to interact with the course staff:

1. Lectures;
2. Office Hours;
3. Lab sessions;
4. Piazza Online Platform.

4.1 Lectures

As mentioned above, attendance to lectures is mandatory and overall in-class participation contributes to 5% of the final grade. Attendance will be sampled via random quizzes announced in class. These quizzes will consist in straightforward questions related to the material presented in class.
Each student is responsible for **any** material covered in class, regardless of whether or not it is covered in the lecture notes or in any supporting material provided by the instructors. A good rule of thumb is: if it was mentioned in class, you are supposed to know it.
The length of each class is about 1 hour and 15 minutes. The last 10 minutes of each class may be used to answer questions about the material presented in previous lectures. As an instructor/TF is wrapping-up after the class is officially over, you are welcome to hang around and ask additional questions about the course material or about administrative matters.

4.2 Office Hours

Office hours are meant to answer specific questions about the papers and/or to receive directions on how to progress on your labs and assignments. Only the instructor will hold office hours for the course, so these office hours are best suited to receive clarification on the class material.

4.3 Piazza

In the context of this course, we will use Piazza as the official platform to extend the in-class interaction outside the scheduled lectures and office hours. Students are welcome to establish other ways to interact with each other online outside of Piazza. However, they should expect the instructor and TF(s) to interact only on Piazza posts.

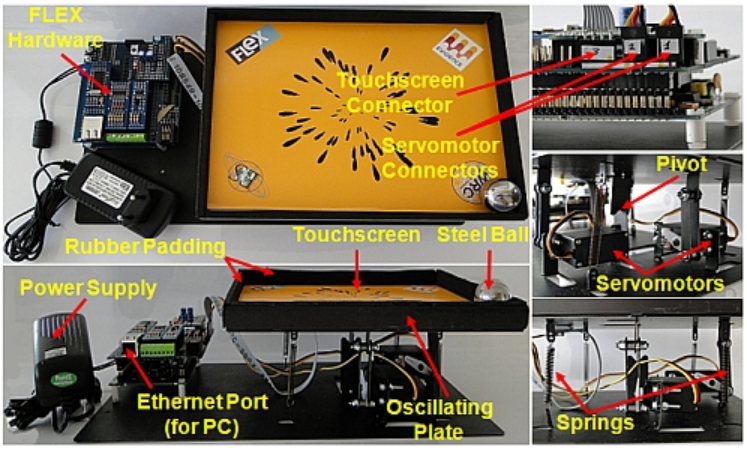

Figure 1: Overview of Amazing Ball 2D Seesaw development platform.

Piazza will be used to post various course resources, including the most up-to-date version of this document, as well as to release weekly assignments, labs and supporting material. On top of that, Piazza will be used to communicate important announcements, post solutions to assignments, provide lengthy answers to questions that were not completely addressed in class, and the like. As such, every student is strongly encouraged to regularly check the official CS-454 / CS-654 Piazza page.
Although constructive opinions about the lectures and the material are welcomed, everyone should make an effort in keeping the discussion on a professional tone and to the point.
It is severely prohibited to share code snippets that constitute a solution or a partial solution to lab assignments. See Academic Code of Conduct.

5 Labs and Lab Assignments

The CS-454 / CS-654 labs are designed to supplement the material covered in lecture. Throughout the semester students will build components required to control a 2D seesaw[3]. Figure 1 provides an overvbiew of the development platform used for your lab assignments. The last two lab projects will then be: (1) to assemble the components and keep the seesaw balanced in real time, and (2) to practice in the lab basic theory about Rate Monotonic Scheduling.
Each lab assignment is intended to be completed in a week after its release date. The code developed to solve the lab should be directly tailored to the considered 2D seesaw system. Successful completion of a lab assignment is determined by the TF(s) during lab hours.
Attendance is required for all labs, since the groups will demo their work to the TF(s) each week. For each submitted lab assignment, each student will receive a *lab score* and no score will be awarded to students who are absent from their group demo. Lab groups that have finished the assignment and satisfactorily demonstrated it to the TA are excused until the start of the next lab assignment. If you have a planned absence, make arrangements with the members of your group and email your TF at least four days prior to the lab that will be missed.
Students will have access to the Embedded Systems Lab and will need to work with their team outside of lab time to complete some assignments. Access to the lab should

[3]See `http://www.evidence.eu.com/products/amazing-ball.html`

be unrestricted for all the students enrolled in the course, albeit some EMA building access restrictions might apply.
Each lab will be generally comprised of two parts. The first part of each lab needs to be completed and will be graded for students taking both the undergraduate (CS-454) and graduate (CS-654) version of this course. The second part of each lab (if present) is only intended to be completed by graduate students taking CS-654. Appropriate directions in each of the labs will be provided.

6 Homework Assignments

Homework assignments are intended to assess student understanding on theoretical concepts that will be later applied in the context of labs and lab assignments. Unlike lab assignments, homework assignments are intended to be solved individually.
Completed homework assignments are to be handed in electronically, typically using Gradescope. You will receive an invitation to join Gradescope if you have enrolled in this class before the firt day of class. If you enrolled later, use the following code to join the Gradescope class: XV7RGW. If your submission is composed in part by handwritten answers, you will need to scan all your answer sheets and submit them electronically. If you do not have a personal scanner, scanning capabilities are available at various university libraries and also through the main CS office on the first floor of MCS—keep in mind that they have well defined business hours. Alternatively, you can use mobile apps (e.g. CamScanner) to scan documents using your phone camera. When doing so, please make sure that the resulting PDF file is readable. Once you have an electronic copy of your answers, use Gradescope to complete the submission process. Regrading requests can be submitted directly via Gradescope. **To be considered valid, a regrading request should clearly explain why your answer was graded incorrectly**.
It is strongly recommended to double-check the class schedule at the end of this document for homework assignments handout and due dates. Assignments submitted after the deadline incur a hefty 25% penalty.

7 Exams and Quizzes

This course includes two exams: a midter exam and a final exam. Quizzes and challenges can also be given through the semester to probe attendance, to give an opportunity for extra credits, or both.

7.1 Midterm Exam

There will be a single in-class exams. The exam will be worth 20% of the final grade, and will cover the material presented from the beginning of the semester up to the last lecture before the exam. Please check the class schedule for the specific dates of these exams.

7.2 Final Exam

The course final exam is worth 30% of the final grade, and will cover the material offered throughout the semester. Please check the class schedule for date and time. The place for the final exam is typically the same as that of the lecture (and will be announced in due time, if different).

7.3 Missed and Conflict Exams

Please mark the exam dates on your calendar (and remember them when you make your recess and end-of-semester travel plans!) There will be absolutely no make-up exams, except for medical emergencies.
Conflict exams can be arranged, as long as the student who has the conflict can communicate the need and arrange the exam at least 2 weeks before the date of the troubling exam. A conflict exam can be scheduled up to two days after the original date of the exam, and needs to be properly motivated. Once arranged, it is severely forbidden to obtain any detail from other students about the content of the original exam before taking the conflict exam.

8 Additional Material for CS-654 Students

Graduate students who take this course as CS-654 will be required to complete extra workload. The additional workload for CS-654 students is comprised of two types: (i) lab assignments; and (ii) readings.

8.1 Additional Lab Assignments

As mentioned above, each lab assignment will be structured in two parts. The first part of the lab is mandatory for all the students. The second part is only optional for students taking this course as CS-454 (i.e. it could be counted for extra credits, but only if and in the form explicitly specified by the instructor). It is however mandatory and regularly graded for students taking this course as CS-654. For instance, as we study USB interfacing, CS-654 students will implement a host-side USB driver for a simple USB device.

8.2 Additional Readings

In order to complete some of the additional lab assignments, students taking this course as CS-654 will be prompted to perform additional readings. These readings will be a combination of: (i) recent research papers on techniques to better implement control and/or communication strategies in embedded software; and (ii) book chapters to deepen their understanding of some of the basic techniques covered in the class material.

9 Academic Code of Conduct

It is expected that each and every student taking CS-454/654 complies with the directives and regulations provided in the Academic Code of Conduct. The full body of the code is available online at `https://www.bu.edu/academics/policies/academic-conduct-code/`. Students taking the CS-654 version of this course also need to abide to the GRS Academic Conduct Code, available at `http://www.bu.edu/cas/files/2017/02/GRS-Academic-Conduct-Code-Final.pdf`. Hereafter we highlight those portions of the codes about which the students should be particularly aware.

9.1 Academic Misconduct

Academic misconduct is conduct by which a student misrepresents his or her academic accomplishments, or impedes other students' opportunities of being judged fairly for their academic

work. Knowingly allowing others to represent your work as their own is as serious an offense as submitting another's work as your own.

9.2 Violations of The Code

Violations include, but are not limited to:

- Cheating on examination;
- Plagiarism;
- Misrepresentation or falsification of data presented for surveys, experiments, reports, etc.;
- Theft of an examination;
- Unauthorized communication during examinations;
- Knowingly allowing another student to represent your work as his or her own;
- Forgery, alteration, or knowing misuse of graded examinations, quizzes, grade lists, or official records of documents;
- Theft or destruction of examinations or papers after submission;
- Submitting the same work in more than one course without the consent of instructor;
- Altering or destroying another student's work or records, or altering records of any kind;
- Violation of the rules governing teamwork; Unless specifically authorized, the following rules apply to teamwork:
    1. No team member shall intentionally restrict or inhibit another team member's access to team meetings, team work-in-progress, or other team activities without the express authorization of the instructor;
    2. All team members shall be held responsible for the content of all teamwork submitted for evaluation as if each team member had individually submitted the entire work product of their team as their own work.
- Failure to sit in a specifically assigned seat during examinations.
- Attempting improperly to influence the award of any credit, grade, or honor.
- Intentionally making false statements to the Academic Conduct Committee or intentionally presenting false information to the committee.
- Failure to comply with the sanctions imposed under the authority of this code.

9.3 Authorship

The student must clearly establish authorship of a work. Referenced work must be clearly documented, cited, and attributed, regardless of media or distribution. Even in the case of work licensed as public domain or Copyleft, (See: http://creativecommons.org/) the student must provide attribution of that work in order to uphold the standards of intent and authorship.

9.4 Declaration

Online submission of, or placing one's name on an exam, assignment, or any course document is a statement of academic honor that the student has not received or given inappropriate assistance in completing it and that the student has complied with the Academic Honesty Policy in that work.

9.5 Consequences

According to the Academic Code of Conduct, sanctions may be imposed on the student that has been deemed in violation of the code. Sanctions may vary depending upon the gravity of the misconduct. For minor violations, any of the instructors may require to: (i) redo a homework assignment; (ii) complete a different assignment than what originally given; assign a grade of zero or "F" for a single assignment or for the course. Major and/or repeated violations can result in official reprimands, disciplinary probation, suspension, or expulsion in agreement with the official code of conduct.

9.6 Personal Takeout

The whole point is: do your best to be a good student. You are here to learn, but in the meantime also to become a better citizen of the world.

10 Tentative Course Outline

The weekly coverage might change to adapt to the progress of the class, and to react to unforeseen circumstances. Hence, the table below may not reflect the latest changes to the course schedule.

Lecture	Unit	Lecture Topic	Lab Coverage	Homework
Thu 1/19	Background	Introduction and Course Overview	Lab 0	
Tue 1/24	Background	The Amazing Ball Platform: LCD and Joystick	Lab 1	
Thu 1/26	Embedded Programming	Interrupts	Lab 2	
Tue 1/31	Embedded Programming	Timers and Counters, I/O (UART)	Lab 2,3	
Thu 2/02	Embedded Programming	I/O (SPI and I2C), DACs and ADCs	Lab 3,5	
Tue 2/07	Embedded Programming	Implementation of Periodic Tasks	Lab 9	HW1 Out
Thu 2/09	Sensing & Control	Sampling Jitter, Real-Time POSIX	Lab 4	
Tue 2/14	Sensing & Control	Signals and filtering (I)	Lab 5,6	
Thu 2/16	Sensing & Control	Signals and Filtering (II)	Lab 5,6	HW1 Due
Thu 2/23	Sensing & Control	Practical Control (I)	Lab 7,8	HW2 Out
Tue 2/28	Sensing & Control	Practical Control (II)	Lab 7,8	
Thu 3/02	Sensing & Control	Practical Control (III)	Lab 7,8	
Tue 3/14	I/O Interfacing	Touchscreen and Servomotors	Lab 5,6	
Thu 3/16	I/O Interfacing	USB Communication and LibUSB	654 Lab	
Tue 3/21	I/O Interfacing	LibUSB Programming	654 Lab	HW2 Due
Thu 3/23	**Exams**	**Midterm Exam**		HW3 Out
Tue 3/28	Real-Time Programming	POSIX Messages and Shared Memory		
Thu 3/30	Real-Time Programming	Real-Time Scheduling		
Tue 4/04	Real-Time Programming	Analysis of Periodic Systems		HW3 Due
Thu 4/06	Real-Time programming	Practical Application Issues		HW4 Out
Tue 4/11	Real-Time programming	Handling Aperiodic Events		
Thu 4/13	Real-Time programming	Real-Time Synchronization (I)		
Tue 4/18	Real-Time programming	Real-Time Synchronization (II)		HW4 Due
Thu 4/20	Real-Time programming	FreeRTOS Design	Lab 9	HW5 Out
Tue 4/25	Real-Time programming	Real-Time Networking		
Thu 4/27	Recaps	Putting Everything Together		
Tue 5/02	Recaps	Curse Wrap-up and Exam Review		HW5 Due
Tue 5/8–12	**Exams**	**Final Exam — Time & Room TBA**		

11 Tentative Lab Schedule

Below is a table of the topic covered in each lab. Labs are due during lab hours. Each group is required to provide a live demo of their code to the TF.

Demo	**Lab**	**Lab Topic**	**Due**
Wed 1/25	Lab 0	Introduction to the Lab	2/01
Wed 2/01	Lab 1	LCD Module and Digital I/O	2/08
Wed 2/08	Lab 2	Interrupts and Timers	2/15
Wed 2/15	Lab 3.1	Serial Communication (Part 1)	2/22
Wed 2/22	Lab 3.2	Serial Communication (Part 2)	3/01
Wed 3/01	Lab 4	Linux Timers and Singals	3/15
Wed 3/15	Lab 5	Joystick, ADCs and Servomotors	3/29
Wed 3/29	Lab 6	Touchscreen Interfacing	4/05
Wed 4/05	Lab 7	Balancing Ball in 1 Dimension	4/12
Wed 4/12	Lab 8	Balancing Ball in 2 Dimensions	4/26
Wed 4/26	Lab 9	PID Controller in FreeRTOS	4/03