Engineering Tripos Part IIB, 4B25: Embedded Systems for the Internet of Things, 2023-24

Module Leader

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Module Lecturer

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Timing and Structure

Lent term. 100% coursework. The course will be delivered using a combination of three activities: (1) pre-recorded content to be watched before timetabled meeting; (2) in-person lectures; (3) supplementary discussions on Microsoft Teams where specified.

Prerequisites

3B2 useful. Previous familiarity with using command-line tools on Unix required. The course uses an open source set of software tools available on github at https://github.com/f-of-e/f-of-e-tools. You are required to install these yourself on a Linux workstation or virtual machine for use during the course. The course uses a hardware kit that you are required to acquire and assemble yourself. The list of components in the kit is available online at https://f-of-e.org/course-hardware-kit

Aims

The aims of the course are to:

- Introduce students to the principles and practice of computation and sensing systems that interact with the physical world.
- Provide students an introduction to a Bayesian view of measurements, measurement uncertainty, sensors, and computing on sensor data that is synergistic with other research and teaching in the Department of Engineering at the University of Cambridge.

Objectives

As specific objectives, by the end of the course students should be able to:

- Define the role of uncertainty in measurements of physical signals and quantify measurement uncertainty for a given sensing system.
- Evaluate energy use in an embedded system using in-system current monitors.
- Define the role of noise in both measurements and displays and identify appropriate metrics to use in quantifying noise for a given design.
- Derive analytic relations underlying a Bayesian view of measurements, measurement uncertainty, sensors, and computing on sensor data.
- Design communication subsystems and the required electrical circuit support between a collection of I2C- or SPI-interfaced sensor integrated circuits and an ARM Cortex-M0 microcontroller.
- Numerically quantify measurement uncertainty and noise in outputs given a system design.
- Recall and explain the interaction between displays and the human visual system.

- Design modifications to sensing, communication, and display systems to improve their energy efficiency.
- Design the logical organization and required firmware for new systems built around an ARM Cortex-M0 microcontroller, and sensors or displays connected via I2C and SPI communication interfaces.

Content

The module will introduce students to the principles underlying sensor operation, signal acquisition, the role of measurement uncertainty and noise, common sensor communication interfaces and how they interact with modern embedded microcontrollers such as the ARM Cortex-M0 family. The module will link these concepts in the signal acquisition and processing chain to a study of output interfaces in embedded systems. This exploration of output systems will be built on a study of the principles of operation of OLED displays and how the flexibility of the human visual system enables interesting circuit- and algorithm-level techniques to reduce display power dissipation.

Syllabus

Lecture 1, Friday, 26th January 2024: System overview of sensing, computation, I/O, and displays in embedded systems; interpreting device and system datasheets. At the end of this lecture, students should be able to: Enumerate the important components in an embedded system design; read and interpret the datasheet for a component in a system or for an entire system; propose and design changes to a system to extend its uses.

Lecture 2, Friday, 2nd February 2024: Precision, accuracy, reliability, and measurement uncertainty. Noise sources in analog and digital systems; role of signal gain and restoring logic. At the end of this lecture, students should be able to: Define precision, accuracy, reliability, and measurement uncertainty; analyze a system design and quantify these properties for a design's components; enumerate the sources of noise and measurement uncertainty in analog and digital systems; propose design changes to improve the robustness of systems to noise.

Lecture 3, Wednesday, 7th February 2024: Low-level C and assembly language in embedded systems. At the end of this lecture, students should be able to: implement firmware that runs on a microcontroller or microprocessor in the abscence of an operating system and which contains a mixture of C and assembly code.

Coursework Activity #1 due 16:00, Friday, 9th February 2024.

Lecture 4, Friday, 9th February 2024: Sensors, embedded I/O interfaces, and noise: Commercial sensor integrated circuits; I2C, SPI (and I2S, I3C, MIPI DSI, and MIPI CSI); noise in integrated circuits (Johnson-Nyquist noise, shot noise, 1/f noise, random telegraph noise). At the end of this lecture, students should be able to: Enumerate the differences between the common embedded wired communication interfaces; select and substantiate a choice for an interface for a given design problem; enumerate the different potential sources of noise in integrated systems.

Lecture 5, Wednesday, 14th February 2024: A Bayesian view of measurements, measurement uncertainty, sensors, and computing on sensor data.

Lecture 6, Friday, 16th February 2024: Field-programmable gate arrays in low-power embedded systems; Verilog overview. At the end of this lecture, students should be able to: Describe and explain the basic architecture of FPGAs; use their understanding of the Verilog hardware description language and FPGA synthesis tools to modify an existing Verilog design.

Coursework Activity #2 due 16:00, Friday, 16th February 2024.

Lecture 7, Wednesday, 21st February 2024: Human color vision perception and its interaction with OLED displays: Their structure, interfaces, and techniques for energy-efficiency. At the end of this lecture, students should be able to: Enumerate the properties of OLED displays; propose changes to existing system designs that use OLED displays in order to improve their energy efficiency; enumerate the basic properties of human color vision that have a bearing on the design of displays for embedded systems.

Lecture 8, Friday, 23rd February 2024: Physical invariants in embedded systems. At the end of this lecture, students should be able to: Define physical invariants in the context of a sensor-driven system; apply concepts from Lagrangians, Hamiltonians, the Euler-Lagrange Equations, Noether's theorem, and recent research on inferring

Lagrangians and Hamiltonians from sensor data to embedded systems designs.

Lecture 9, Wednesday, 28th February 2024: Wireless communications using Bluetooth, 802.15.4/Zigbee, and LoRa; Bluetooth HCI interface. At the end of this lecture, students should be able to: Enumerate the differences between the major low-power radio interfaces available for embedded systems; propose energy-efficient choices for a wireless sensing system design given the application's design constraints.

<u>Coursework Activity #3 due 16:00, Friday, 1st March 2024.</u>

Lecture 10, Friday, 1st March 2024: Case study: Designing new embedded systems to solve a specified application need. At the end of this lecture, students should be able to: Propose an architectural design comprising sensing, computation, communication, and display to address a given application need, with the design implementable within the limitations of schematic capture and printed-circuit-board layout tools such as Eagle.

Lecture 11, Friday, 8th March 2024: Evaluating the efficacy of embedded computing systems: Power, performance, and noise measurements. At the end of this lecture, students should be able to: Quantify the time-performance, energy-efficiency, power-efficiency, and uncertainty in embedded computing systems. Adapt the design of embedded sensing and computation systems that are Pareto-optimal with respect to alternatives.

<u>Coursework Activity #4 due 16:00, Friday, 15th March 2024.</u>

Coursework

Coursework	Format	Due date & marks
Coursework activity #1: Embedded processor emulator exercise Use the GCC and Binutils tools to compile, link, and disassemble binaries and use an open-source embedded system emulator to run a few different programs written in a combination of C and assembly language. <u>Learning objective:</u> After successfully completing this exercise, students should be able to: • Write simple programs using combination of C and assembler • Compile and run programs directly on an embedded processor with no operating system (OS) • Create, use, and modify Makefiles and Linker Command Files • Use Linker Map Files and differentiate them from Linker Command Files	Individual. Source files, binaries, and PDF file with answers to questions. non-anonymously marked	16:00, Friday 2024 [20%]
Coursework activity #2: OLED display control over SPI exercise Obtain hands-on experience writing a device driver in C for an SPI peripheral, using the FRDMKL03 ARM board and the OLED display from the course hardware kit.	Individual. Source files, binaries, picture of working system, wiring diagram, and PDF file with answers to questions.	16:00, Frida 2024 [20%]

Coursework	Format	Due date & marks
Learning objective: After successfully completing this exercise, students should be able to: • Read a datasheet for an unfamiliar embedded hardware component such as an SPI peripheral and write a device driver in C to interface with the peripheral.	non-anonymously marked	
Coursework activity #3: Power measurement using TI INA219 I2C device exercise Obtain hands-on experience writing a device driver in C for an I2C peripheral, using the FRDMKL05 ARM board and the TI INA219 daughterboard from the course hardware kit. Learning objective: After successfully completing this exercise, students should be able to: • Read a datasheet for an unfamiliar embedded hardware component such as an I2C peripheral and write a device driver in C to interface with the peripheral.	Individual. Source files, binaries, picture of working system, wiring diagram, and PDF file with answers to questions. Non-anonymously marked.	16:00, Friday [20%]
Coursework activity #4: Project concept, design, implementation, and final report Present the problem addressed, approach employed, system implemented, and system evaluation. Learning objectives: After successfully completing the final project, students should be able to: • Design an embedded computing system that address a specified engineering challenge. • Prototype an embedded system design using a combination of sensors, microcontrollers, communication, displays, or FPGAs using the tools provided in the course kit. • Quantitatively evaluate an embedded sensing and computation system in terms of its time efficiency (performance), energy efficiency (battery life), and measurement and data processing accuracy.	Individual report, source files, binaries. Non-anonymously marked.	16:00, Frida 2024 [40%]

Booklists

The following books are relevant to the material in the course and will all be available from the Engineering Library.

1. *An Introduction to Uncertainty in Measurement*, ISBN: 978-0521605793
2. *Linkers and Loaders*, ISBN: 978-1558604964
3. *The Circuit Designer's Companion*, 3rd Edition, ISBN: 978-0080971384
4. *The Art of Electronics*, ISBN: 978-0521809269

5. *Color Science: Concepts and Methods, Quantitative Data and Formulae*, ISBN: 978-0471399186

Examination Guidelines

Please refer to Form & conduct of the examinations [2].

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Links
[1] mailto:ps751@cam.ac.uk
[2] https://teaching23-24.eng.cam.ac.uk/content/form-conduct-examinations