

# Engineering Tripos Part IIB, 4B25: Embedded Systems for the Internet of Things, 2018-19

## Module Leader

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## Lecturer

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## Timing and Structure

Michaelmas term. 100% coursework

## Prerequisites

3B2 useful

## 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.

## 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.
- 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

measurement uncertainty and noise, common sensor communication interfaces and how they interact with modern **Engineering Topics Part II, 4825: Embedded Systems for the Internet of Things, 2018-19** signal acquisition and processing graduate research outputs/teaching 2017-2018. 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.

## Preliminary Syllabus

**Lecture 1:** 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:** 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:** C and assembly programming for embedded systems. At the end of this lecture, students should be able to: implement firmware that runs in the absence of an operating system and which contains a mixture of C and ARM assembly code.

**Lecture 4:** 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:** Case study.

**Lecture 6:** 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.

**Lecture 7:** 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:** 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:** 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 or Internet-of-Things systems; propose energy-efficient choices for a wireless sensing system design given the application's design constraints.

**Lecture 10:** Schematic capture and basic printed circuit board layout using Eagle. At the end of this lecture, students should be able to: create a design ready to be submitted for manufacturing (Gerber files) using the Eagle schematic capture and printed-circuit-board layout tools.

**Lecture 11:** 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.

## Further notes

## **Pictures of individual final project from previous years**

The pictures below are for a sample of the individual student projects, for students who gave consent for pictures of their final demo system to be used in future instances of 4B25.

**Pedometer (using 3-axis MEMS accelerometer, ARM Cortex-M0+, and 96x64 color OLED display from the course kit in custom laser-cut enclosure):**

**Bike theft alarm (using 3-axis MEMS accelerometer and ARM Cortex-M0+ from the course kit, in custom 3D-printed enclosure):**

**Pedometer (using 3-axis MEMS accelerometer, ARM Cortex-M0+, and color 96x64 OLED display from the course kit):**

**Plant health monitor using external conductivity, light, temperature, and humidity sensors together with the ARM Cortex-M0+ and color 96x64 OLED display from the course kit:**

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**Sensor fusion (GPS + velocity) using FRDM KL25Z and GPS module together with 3-axis MEMS accelerometer and 96x64 OLED display from the course kit:**

**Razor cut prediction (HDC1000 humidity sensor and force-sensing resistor together with 3-axis MEMS accelerometer and ARM Cortex-M0+ from the course kit):**

**RFID-based class attendance monitor (using INA219 current measurement board, ARM Cortex-M0+, and color 96x64 OLED display from the course kit):**

**Custom multi-layer PCB for sports injury detection, using the same KL03 Cortex-M0+ as in the course kit:**

**Electric bike controller (using INA219 current monitor, ARM Cortex-M0+, and color 96x64 OLED display from the course kit):**

**Pedometer (using a counter module attached to the ARM Cortex-M0+ and 3-axis MEMS accelerometer from the course kit):**

**Coursework**

Coursework	Format	Due date & marks
<p><b>Coursework activity #1:</b> Embedded processor emulator exercise</p> <p>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.</p> <p><u>Learning objective:</u></p> <p>After successfully completing this exercise, students should be able to:</p> <ul style="list-style-type: none"> <li>• Write simple programs using combination of C and assembler</li> <li>• Compile and run programs directly on an embedded processor with no OS</li> <li>• Create, use, and modify Makefiles and Linker Command Files</li> <li>• Use Linker Map Files and differentiate them from linker command files</li> </ul>	<p>Individual</p> <p>Source files, binaries, and text file with answers to questions.</p> <p>non-anonymously marked</p>	<p>Friday, 19th Oct</p> <p>[10%]</p>
<p><b>Coursework activity #1:</b> OLED display control over SPI exercise</p> <p>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.</p> <p><u>Learning objective:</u></p> <p>After successfully completing this exercise, students should be able to:</p> <ul style="list-style-type: none"> <li>• 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.</li> </ul>	<p>Source files, binaries, picture of working system, wiring diagram, and text file with answers to questions.</p> <p>non-anonymously marked</p>	<p>Friday, 26th Oct</p> <p>4)</p> <p>[15%]</p>
<p><b>Coursework activity #3:</b> Project proposal one-page report</p> <p>Identify an interesting engineering problem that can be addressed using an embedded system developed using the concepts, theory, techniques, and tools covered in this course.</p> <p><u>Learning objectives:</u></p> <p>After successfully completing this exercise, students should be able to:</p>	<p>Individual Report</p> <p>non-anonymously marked</p>	<p>Friday, 2nd Nov</p> <p>5)</p> <p>[5%]</p>

Coursework	Format	Due date & marks
<ul style="list-style-type: none"> <li>Identify an interesting and important engineering challenge that can be solved using a combination of embedded sensing, embedded computation, and possibly displays and communication.</li> <li>Present a clear list of design objectives for solving the engineering challenge using an embedded system.</li> </ul>		
<p><b>Coursework activity #4:</b> Power measurement using TI INA219 I2C device exercise</p> <p>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.</p> <p><u>Learning objective:</u></p> <p>After successfully completing this exercise, students should be able to:</p> <ul style="list-style-type: none"> <li>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.</li> </ul>	<p>Source files, binaries, picture of working system, wiring diagram, and text file with answers to questions.</p> <p>non-anonymously marked</p>	<p>Friday, 9th Nov 2018 (6)</p> <p>[15%]</p>
<p><b>Coursework activity #5:</b> Project interim report</p> <p>Present progress made towards final project goals, evaluate lessons learned so far, and obtain feedback and guidance on necessary plan adaptation.</p> <p><u>Learning objectives:</u></p> <p>After successfully completing the interim project report, students should be able to:</p> <ul style="list-style-type: none"> <li>Identify and present progress made towards final project.</li> <li>Identify and present potential challenges and propose necessary changes to project plan.</li> </ul>	<p>Individual Report</p> <p>non-anonymously marked</p>	<p>Friday, 23rd Nov 2018 (week 8)</p> <p>[10%]</p>
<p><b>Coursework activity #6:</b> Project concept, design, implementation, and final report</p> <p>Present the problem addressed, approach employed, system implemented, and system evaluation.</p> <p><u>Learning objectives:</u></p> <p>After successfully completing the final project, students should be able to:</p> <ul style="list-style-type: none"> <li>Identify an interesting and important engineering challenge that can be solved using a combination of embedded sensing, embedded computation, and possibly displays and communication.</li> <li>Design an embedded computing system that address the engineering challenge.</li> </ul>	<p>Individual report, source files, binaries, in-person demonstration at final feedback session.</p> <p>non-anonymously marked</p>	<p>Friday, 18th Dec 2018 (Term)</p> <p>[45%]</p>

Coursework	Format	Due date & marks
<ul style="list-style-type: none"><li>• Prototype an embedded system design using a combination of sensors, microcontrollers, communication, displays, or FPGAs using the tools provided in the course kit, and potentially design a custom PCB implementing the design.</li><li>• 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.</li></ul>		

## Booklists

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

1. *Introduction to Embedded Systems, A Cyber-Physical Systems Approach*, ISBN: 978-0262533812
2. *An Introduction to Uncertainty in Measurement*, ISBN: 978-0521605793
3. *Linkers and Loaders*, ISBN: 978-1558604964
4. *The Circuit Designer's Companion*, 3rd Edition, ISBN: 978-0080971384
5. *The Practice of Programming*, ISBN: 978-0201615869
6. *Expert C Programming*, ISBN: 978-0131774292
7. *C: A Reference Manual* (5th Edition), ISBN: 978-0130895929
8. *Bluetooth Low Energy: The Developer's Handbook*, ISBN: 978-0132888363
9. *Programming Embedded Systems: With C and GNU Development Tools*, 2nd Edition, ISBN: 978-0596009830
10. *Embedded Systems Dictionary*, ISBN: 978-1578201204
11. *The Art of Designing Embedded Systems*, Second Edition, ISBN: 978-0750686440
12. *The Art of Electronics*, ISBN: 978-0521809269
13. *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://teaching26-27.eng.cam.ac.uk/content/form-conduct-examinations>