EXPLORING ROBOTICS THROUGH SENSOR INTEGRATION AND MEASUREMENT APPLICATIONS

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Abstract

This article presents a novel approach to the teaching of robotics. By first examining sensors and measurement, and by providing real world and tangible examples of robotics technology but in a sensing and measurement context, it is put forward that students will be better prepared for and better acquire the standard robotics pedagogy. Student feedback has been especially positive due to the use of robotics examples in lectures and in exams, as well as in the use of a "Hands-on Fridays" whereby students are able to examine robotic components and other devices, which contain the sensors previously discussed in class, thereby reinforcing the lecture material.

Introduction

Robotics is a large field, composed of many interdisciplinary components. Traditionally, robotics is taught from the perspective of kinematics and dynamics (Mechanical Engineering), controls (Mechanical or Electrical Engineering), or behavioural / artificial intelligence (Computer Science). Here, we examine an aspect that is generally overlooked in the teaching of robotics: sensors and measurement.

Robots are required to perform actions. Except in the simplest cases, this requires that they know something about the world around them, whether it's a factory, living room, or outer space. This means that they must sense and interpret their environment. Without this, they generally cannot produce meaningful results.

Therefore, it is proposed here that before robots can be studied or designed, the sensing and measurement aspect needs to be addressed. It is in this context that ELE 604 Sensors and Measurement, a course offered in the third year of the Electrical Engineering program at Ryerson University in Toronto, Canada, ispresented.

Motivation

Being able to sense internal and external phenomena and to draw clear conclusions about these phenomena is one of the fundamental requirements for robotic and mechatronic devices. Without a clear sense of what is to be measured and the degree to which the measurement can be trusted, other aspects of robotics, which often implicitly rely on these two points, cannot be examined. For this reason, it is put forward here that a course in sensing and measurement should precede most general robotics courses.

Survey of the Literature

Microcontroller and embedded systems has traditionally been an area reserved for electrical and mechanical engineers but is now becoming a multidisciplinary field and can be found in other areas such as biomedical engineering. A curriculum with a focus on electronics, computers, and integration helps students prepare for their final year projects as well as prepare them for real world problems encountered in their careers. Factors such as noise and electromagnetic interference can hinder useful sensor readings and students will learn necessary techniques to determine engineering solutions to tackle these problems.

There is a wide range of academic literature available that discusses embedded and hardware structures in their curriculum. This section lists some of the more recent literature found in education-related conferences as well as from online search results from universities that teach instrumentation and measurement techniques using microcontroller and embedded system tools.

Current Hardware Architectures

In modern embedded systems, a microcontroller is a fundamental component in the hardware architecture that maintains system wide control of the processes that allow it to interact with its environment. The rapid miniaturization in microcontroller technology has led to increasing complexity of these devices and with an increasing amount of features that help expand its application range [1].

However, the fundamentals of hardware interfacing remain unchanged and what is important is the skill set that the student learns in extracting useful information from the sensors and actuators that connect to the system. Useful data acquisition is crucial in developing robust and dynamic systems as the microcontroller requires this information in order to interact effectively to its surroundings. Table 1 lists representative microcontroller requirements currently or recently used in Canadian and US institutions.

Reese and Jones had found that 67% of US schools emphasized on an assembly-only approach [1] as this was the standard approach taken by most textbooks written in the previous 20 years. Microcontroller programs had to be highly optimized due to limited on-chip memory space and limited C compiler resource tools. However, assembly language gives a student insight on deterministic clock cycle execution times per instruction of their written source code whereas C compilers abstracts this step and outputs the final optimized assembly code.

The same report also discovered that 78% of the embedded courses from the survey used Freescale (formerly Motorola) processors which are mainly due to Motorola's dominance in the embedded market in the late 80s and 90s. Modern microcontrollers are continuously improving in both increasing processing power, lower power consumption as well as reducing the cost in production. Furthermore, the memory and performance of these devices allow greater flexibility in application development. Some examples of modern microcontroller manufacturers that are prominent in embedded microcontroller sales include the Microchip, Atmel, and Renesas. Microchip and Atmel are especially popular in the hobby electronics field. Reese and Jones conclude that modern microcontrollers now have large amounts of memory, program space, and clock speed that allow C code implementation to be feasible [1].

Table 1. Some Current Microcontroller Requirements at Various Institutions (adapted from [1] and [19]).

Institution	Course	Processor
Ryerson University	ELE/COE538 Microprocessor Systems ELE604 Sensors and Measurement ELE744 Instrumentation	Freescale HC11
University of British Columbia	EECE 259 Introduction to Microcomputers	MCS-51
University.of Toronto	ECE 243 Computer Organization	Altera NIOS II/DE2
Queen's University	ELEC 274 Computer Architecture	Freescale HC11
University of Waterloo	ECE 324 Microprocessor Systems and Interfacing	Altera Excalibur Dev. Board
University of Kentucky	EE 383 Embedded Systems	Freescale HC12
Embry-Riddle Aeronautical University	CEC 320 Microprocessor Systems	Freescale 68000
Florida State University	EEL 4746 Microprocessor Based Sys. Design	Freescale HC11
University of Florida	EEL 4744C Microprocessor Applications	Freescale HC12
North Carolina State University	ECE 306 Intro. To Embedded Sys.	Renesas M16C/16P

C code can provide greater code clarity when compared to assembly programming. However, the C compiler also abstracts out the importance of teaching students about low level clock cycle execution. By programming in assembly, students will gain a better appreciation for code optimization and learning about determinism. Deterministic insight enables the student to program more efficiently and also help them during hardware-software interfacing where sensor sampling time and instruction execution can be critical in the overall performance and requirement of the system.

Teaching Instrumentation

Different institutions implement different design tools and different hardware architectures in their curriculum. The overall objective is the successful integration of analog and digital computer components and software. This entails proper signal filtering of noise issues as well as performance matching the system to specifications outlined in the project requirements. Instrumentation and measurement courses typically cover basic operational amplifiers and progress into analog sensor integration, signal amplification, noise conditioning, and A/D and D/A conversion. The basic laboratory setups are usually a series of individual labs each focusing on a specific topic mentioned above. The following are a few notable universities that have implemented the topics described above into final course projects or competitions with an objective in order to increase student interest and motivation.

U.S. Air Force Academy

The U.S. Air Force Academy uses robotics as their methodology in teaching instrumentation and measurement. The curriculum uses a two level approach in which the first level teaches the fundamentals such as A/D and D/A conversion, sensor operation and interfacing, I/O interfacing and programming (assembly and C languages) [2]. Some typical sensors used in the course include IR sensors, wheel encoders, GPS, and SONAR. At the advanced level, the students learn to develop subsystem integration, testing and debugging.

In ECE 382 "Microcomputer Programming" students learn the basics of assembly language and learn the skills required in hardware interfacing and debugging [3]. Students are provided with a mobile robot in which to conduct their lab experiments. In ECE 383 "Microcomputer System Design I" and ECE 387 "Introduction to Robotic Systems," students expand the functionality of the microcontroller, hardware and software interfacing, and also learn about deterministic timing analysis [2]. A final embedded microcontroller system project allows the student to pursue their interests in developing their engineering and design skills.

It was found that a robot is a great facilitator to engaging students in electronic and instrumentation development. The robot encouraged team collaboration skills as well as solving complex goals by dividing the task into smaller and manageable subtasks. More importantly, robots can provide students with an immediate feedback on hardware and software behavior.

University of Nebraska

University of Nebraska offers a course (ELEC 400/800) in electronic instrumentation with an emphasis on instrumentation design and development [4]. The topics covered include basic analog and digital circuits, filters and oscillators, linear and switching power supplies, low-noise techniques, phase-locked loops (PLLs), transducers, grounding and shielding, thermal analysis, vibration analysis, electronic packaging, wiring and cabling, and engineering economics [5].

The first group of topics that is covered is basic circuit analysis and designs as well as amplifier and transistor circuit designs. The course then transits into the advanced group of topics which include: low-noise filtering techniques, digital circuits (TTL/CMOS), A/D-D/A conversion, PLLs, transducers, and signal processing techniques. The special topics group electromagnetic (EM) coupling and interference are covered as well as thermal and vibration analysis and human factors engineering.

It was determined that the course was successful based on an increasing student enrollment over five consecutive years and through positive student feedback. It was found that students were particularly interested in the special topics group in the course. Students were also given the opportunity to submit design reports rather than homework problems throughout the semester.

Ryerson University

Ryerson University has traditionally taught its students instrumentation and measurement through a two level approach. COE 538 "Microprocessor Systems" is the first level and it engages its students into microcontroller fundamentals (via the Freescale HC11) [6] Through a series of labs, the students learn about assembly programming, hardware and software timing, interrupt service routines (ISRs), use of development tools, and testing and debugging.

Upon completion of COE 538, Electrical Engineering students used to immediately take ELE744 "Electronics and Instrumentation" where the Freescale HC11-based IPB development board was used to teach the students about hardware-software design and interfacing [7]. The course objectives include the following: building, programming, and calibrating a microprocessor-based instrumentation system, dynamic range, noise filtering techniques, A/D conversion techniques, signal conditioning, transducer circuits, and grounding/shielding of wires and PCB layout design. In the past, ELE744 also introduced students to sensors and measurement concepts. The final project requires students to design and development a microcontroller based instrumentation device to meet the required electrical, mechanical and functional specifications.

Since 2008, the sensors and measurement aspect of ELE744 have been moved to an intermediate course between COE538 and ELE744: ELE 604 Sensors and Measurement.

Curriculum Structure

All Electrical Engineering students at Ryerson University take common courses in their first and second years, as well as the third year course, COE 538 Microprocessor Systems, in which the students learn about microcontrollers in hands-on labs. In the second semester of third year, the Robotics Option (see the table below for the course content of the Option) begins to diverge from the regular program. At this point, students can select the ELE 604 Sensors and Measurement course. The following is a list of classes that define the Robotics Option:

- Third year:
  - ELE 632 Signals and Systems II
  - One of :
    - ELE 604 Sensors and Measurement
    - ELE 637 Energy Conversion

- Fourth year:
  - ELE 700 Engineering Design
  - ELE 709 Real-Time Computer Control System
  - ELE 792 Digital Signal Processing
  - ELE 829 System Identification
  - CEN 800 Law and Ethics in Engineering Practice
  - ELE 800 Design Project
  - ELE 809 Digital Control System Design
  - ELE 869 Robotics
  - ELE 888 Intelligent Systems

The ELE 604 Sensors and Measurement syllabus reads as:

"The course will cover the theory and principles of sensors and transducers (electrical, chemical and mechanical). The topics covered include transduction techniques, linear/non-linear signal processing, low noise amplifiers, instrumentation amplifiers, data converters. There will be small design projects for the labs to reinforce sensor/transducer interfacing."

Effectively, ELE604 provides a basis for measuring phenomena in a number of applications, whether it is industrial, consumer, scientific or educational. In robotics and mechatronics, it is often assumed that the sensed data is of a perfect nature. In this course, students discover important sensor modalities and, just as importantly, the limitations of the technology to sense these modalities.

Learning Objectives

The general objective of the course is to have the students understand the basic theory of sensors and transducers. Specifically students are to learn transduction techniques, linear and non-linear signal processing, the use and design of amplifiers and methods of data conversion.

Description of the Lecture Material

The lecture material currently revolves around the textbook "Principles of Sensors and Measurement" by Bentley, [8] with selected material derived from other major sources (e.g. [9, 10]). Supplementary material is derived from sources related to particular sensor modalities [14, 15] or application types, such as mobile robotics [4].

Initial lectures concentrate on the Scientific Method (i.e. Observation, Hypothesis, Experiment and Conclusion) as a framework for doing meaningful scientific and engineering work. This framework helps focus the students in the experimental work that they will do, because without observations and hypotheses, experiments are a poor vehicle for understanding the world, regardless if the experiments are variational, validational, pedagogical, or explorational [9].

Sensors and measurement are applied at two distinct points in the Scientific Method: at the observational stage and in the experimental stage. Knowing this, the students can devise technological solutions which help formulate and answer the hypothesis.

Furthermore, by understanding the nature of the various sensor modalities covered in class, and the limitations of both the modalities and the applicable technologies, students will be better able to formulate meaningful hypotheses. By knowing limitations in accuracy and precision of the sensors and related signal conditioning and processing hardware and software, the students can determine *how well* the experiments help answer the hypotheses.

Subsequent lectures focus on both theoretical and applied topics. Laplace transforms are covered in the context of building frequency domain representations of different sections of a measurement system, including signal conditioning and display elements. Another section of the lectures is devoted to noise and interference, their theoretical basis and the practice of reducing and eliminating them. For instance, principles (Lenz's Law and Faraday's Law of Electromagnetic Induction) are explained in the context of how technologies such as twisted pair wire are applied in interference reduction. Proper shielding and grounding technique are discussed. This is especially relevant for embedded or robotics systems containing electric motors [16] or gasoline engines [17,18].

"Hands-on Fridays"

While the laboratory component of a standard engineering class is considered to be the time and place for "hands-on" learning, standard lecture time can also be devoted to tactile reinforcement of concepts. Therefore, a short session is held about once a week in which particular sensor hardware is demonstrated and discussed. Examples include Hall Effect sensors

Table 2 lists the order of topics covered in ELE604.

Table 2 Lecture Topics.

Week	**Topic**
1	Introduction, Sci. Method, Accuracy and Precision
2	Static Characteristics: range, nonlinearity, sensitivity, hysteresis, resolution, error band, repeatability, and tolerance.
3	Dynamic Characteristics: transfer functions, step/sinusoidal response, dynamics identification, dynamic errors and compensation
4	Loading and 2-port Systems: Thevenin and Norton, electromechanical systems, thermo and hydraulic systems
5	Signals and Noise: electrostatic and inductive sources, noise reduction and compensation
6	Midterms
7	Reading Week
8	Sensing Elements: strain gauges, resistive, capacitive and inductive sensing elements, pH and Hall Effect sensors
9	Sensing Elements: Ultrasonics, inertial measurement sensing (accelerometers, gyroscopes), odometry, quadrature encoding, rotary potentiometers
10	Signal Conditioning: Wheatstone Bridges, AC carrier systems, operational amplifiers, instrumentation amplifiers, filtering
11	Signal Processing: quantization, encoding, ADCs, DSP
12	Review

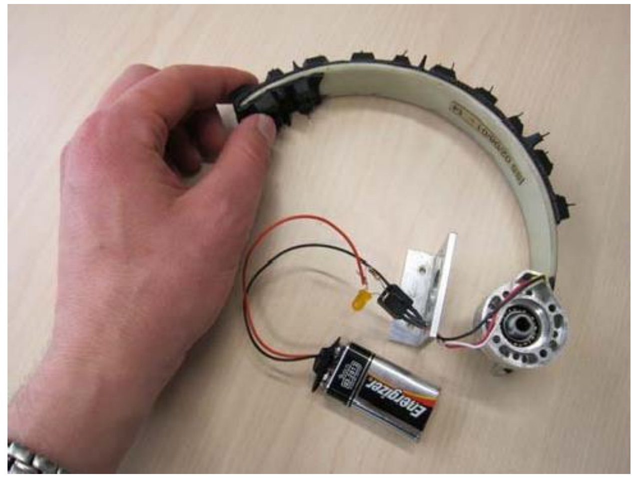


Figure 1. **"**Hands-on Fridays": Here, the students are examining the Hall Effect "home" sensor in a RHex robot leg [16].

mounted on robot legs (see Figure 1), quadrature encoders in computer mice and ElectroCardioGram (ECG) measurement systems. The principles of operation are discussed and then the students are given the opportunity to try it out. Because it is generally done in a less formal context than the standard laboratory or lecture, students can explore and observe the device without the pressure or formality of these other venues.

Description of the Lab Design Project

The lab focuses on the development of a microcontroller-based measurement system. The students program a Freescale HC11 8-bit microcontroller to gather and process signals from a MEMS accelerometer and a load cell. The two-axis accelerometer's digital output is pulse-width modulated and the load cell's output is analogue. The students design support circuitry to signal condition the load cell's output.

In the case of the MEMSIC 2125 accelerometer, the students place it on a test rig designed to vary angular position of a mechanical arm. Using the accelerometer, the students are able to read the digital output and determine the angle of the arm.

In the case of the load cell, the students design circuitry including a Wheatstone bridge. The students must then calibrate the system. Finally, they generally implement noise-reduction circuitry to obtain a relatively clean analogue signal.

The completed project requires that the students design and implement a complete system which can respond in a deterministic fashion, much like the requirements for many robotic systems. This is especially challenging considering that the students use a relatively low-powered (computationally speaking) 8bit Freescale HC11 to collect and process the analogue and digital signals, as well as the user generated commands from a set of buttons. A sample experimental setup is shown in Figure 2.

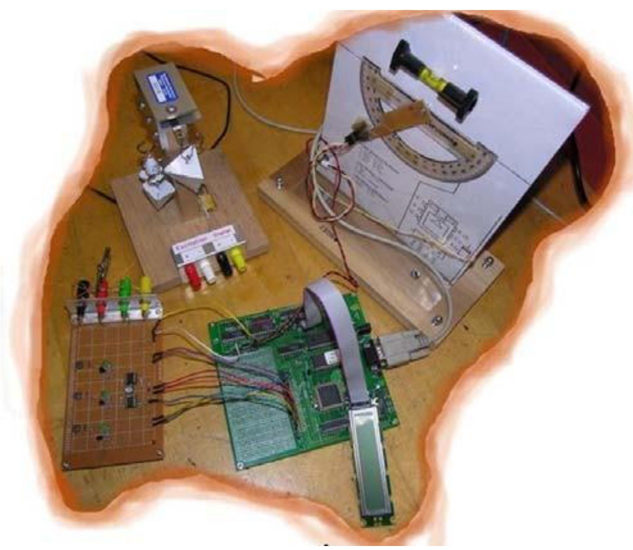


Figure 2. The lab setup. Clockwise, from upper right: the accelerometer/angular test jig, the HC11 electronics board and display, the analogue electronics and switches, and the load cell test rig. (photo courtesy of Ryan Snow and Krisztian Futo).

Assessment

Students are assessed on a combination of theoretical and practical design components. A midterm exam, which concentrates on the first half of the course, is worth 20% of their grade. A final exam, concentrating on the second half of the semester, is worth 30%. Two quizzes, worth 10% of their grade are conducted prior to and after the midterm exam. This ensures that the students are assessed throughout the semester on various components of the course, including lecture, homework problems and lab material. The final 30% of the grade is based on the lab component of the course. Since the lab work is team-based, the marks are generally shared equally between partners, hence the need to include a small portion of assessment of lab material in the formal exams and quizzes.

The exams and quizzes are designed to exam theoretical and practical aspects of sensors and measurement. Generally, 30 – 50% of the questions model problems they have seen in the book, while another 30 – 40% are challenging variations of the same material. This permits all students to be fairly assessed and to receive a good grade if they have a good understanding of the material. Finally, the remainder are more holistic extensions of the classroom material, allowing students who have mastered the concepts to demonstrate this.

Sample Exam Questions

Many of the exam questions reflect the robotics examples given in class. Figures 3 and 4 reflect the robotics applications for sensing and measurement systems.

Student Feedback

The robotics examples in the exams have proven to be popular with the students. While correcting a recent exam one of the authors found “Cool!” scribbled across an illustration of the Boston Dynamics Big Dog robot [17] used in one of the problems.

The Hands-on Fridays were especially well received when the course was offered at 9am on Friday mornings. Attendance increased immediately once word got out that there were demonstration items available to try out.

Sample Final Exam Question

Question

The PAW legged robot, shown in the figure below, has four legs and is currently being tested on flat concrete surfaces. Its feet are equipped to sense the ground reaction force using a longitudinally-mounted strain gauge (the "Force Sensor" shown in the diagram). The feet, located at the ends of the legs, have a cross-sectional area of 10^{-2} m^2. The feet are comprised of a material having a Young's modulus of $2*10^{10}$ Pa and a Poisson's Ratio of 0.2. The unstrained resistance of the strain gauge is 120 Ohms. The Gauge Factor is 2. As one foot contacts the ground it "feels" a force coming from the ground. This is the ground reaction force.

PAW Robot shown jumping (photo: James A. Smith)

a) What kind of force is the ground reaction force? Tensile or Compressive? Answer in one word. *[1 mark]*
b) During ground contact the strain gauge reports a resistance of 119.99 Ohms. What was the applied force, assuming that it is along the longitudinal axis of the toe? *[2 marks]*

Note: ***show all calculations****!* ***Circle*** *your final answers.*

Figure 3. First sample exam question, emphasizing the use of sensors in real-world robotics applications.

Future Directions

The course has been held twice since 2008. This year, the course is undergoing a revamping, focusing on improving the lab curriculum. The microelectronics hardware will be changed from the Freescale HC11 to the Freescale 9s12 [12, 13]. Compatibility between the devices will permit us to reuse our best pedagogical material, and technological improvements in the 9s12 should permit a wider range of projects to be examined at a reduced cost. In-lab software development will be updated from Assembler-only to mixed C and Assembler. This will permit more modern structuring the of the main software code, while also permitting time-critical code (like Interrupt Service Routines) in Assembler. The two major sensors used, the accelerometer and the load cell will remain. Finally, a special effort will be made to better coordinate and complement the material presented in class with the lab schedule, so that the relevance is driven home more effectively.

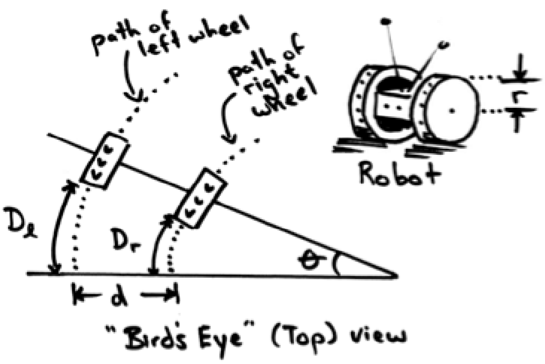
Sample Final Exam Question

Question

A Segway-like robot turns on an arc, shown in the figure below. The actual angle of the turn, θ, is unknown and must be determined. The wheels are 0.25 in radius (r) and are assumed to be rigid (i.e. they don't compress due to weight of the robot or deform due to shear loading).

Each wheel is driven by a geared motor. The motors run at 24 volts and have a maximum output torque (before the gear) of 1 Nm. The gearhead is used to convert the torque to a maximum of 90 Nm at the wheel. Directly attached to the motor shaft (not the output of the gearhead) is a quadrature encoder. The encoder disc has 500 holes per revolution.

The microcontroller which controls the robot has read and interpreted the quadrature signals coming from the left and right motors (which are driving the left and right wheels). The right count is 206264 and the left count is 229183.



a) What is the distance traversed on the ground by each wheel, D_l and D_r? [2 marks]
b) Knowing that the wheelbase, d, is 0.5m, calculate the angle that the robot has traversed. [2 marks]

Note: ***show all calculations****!* ***Circle*** *your final answers.*

Figure 4. Second example question, illustrating how to combine multiple subcomponents in a robot in an odometry application.

Conclusions

The ELE604 class on Sensors and Measurement provides an excellent opportunity to examine fundamentals of robotics prior to embarking on the more traditional courses in mobile or manipulator robotics. The Hands-On Fridays have proven to be very successful and popular with the students. Furthermore, the robotics examples in the examination and in the lecture materials reinforce real-world applications of the concepts. Future developments will maintain these positive elements and build on them through the use of more modern lab hardware and closer ties between the lab and class material.

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