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Engineering Concepts: Exploiting a Systems and Control Perspective

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Abstract— **Introductory courses in engineering can be developed that satisfy multiple objectives. They can motivate and excite students who have already decided to study engineering or provide an introduction to engineering for students with primary interests in other fields. Developing such courses based on the theme of systems and control is very effective. These courses can present multidisciplinary problems, emphasize the systems viewpoint, and introduce engineering problems, principles, practices and solutions. Application areas can be chosen that have special appeal to students from diverse backgrounds. Theory, simulations and experiments can be interwoven through interesting projects. In this paper we discuss such an introductory engineering course developed and taught at Mt Holyoke College. The course pays special attention to the fact that Mount Holyoke College is an all-female liberal arts institution having a 3-2 engineering program in association with several engineering colleges.**

I. Introduction

It is evident throughout history that society has continually placed demands on the scientific and engineering community. Even though the needs over the centuries have changed the push to overcome new obstacles and improve the standard of living remains the same. Demands on the profession filter down to expectations that shape the educational systems. Currently there is serious debate about what the engineer of the 21st century should look like and how best she/he can be educated [4]. New engineering problems have emerged that require engineering students to acquire basic knowledge in non-traditional areas. These problems are multidisciplinary and require a basic understanding of many fields. At the same time non-engineering students should learn more about engineering concepts, principles and practices. Building such bridges between engineering and other fields would enhance the solution of such multidisciplinary problems and improve the educational experience of many students.

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Engineering educational reform is a very broad topic that involves many disciplines and active debate is taking place within different circles and at all levels. It goes without saying that as we proceed with these innovations it is important to recognize that any change should be implemented in a way that preserves the integrity of current successful engineering programs. In other words we should not destroy programs that continue to serve our needs while creating new possibilities. Failure to maintain this balance will be quite unproductive. We believe that such curriculum innovations can be introduced that increase flexibility while maintaining this balance.

In this paper we argue that introducing engineering by exploiting a systems and control perspective is a very promising approach. We are not suggesting that this is the only way but in view of the fact that many of the new engineering problems have systems and control components the approach is quite powerful. Consider the next generation of intelligent transportation problems or the next generation of sensor networks for weather prediction. They all have a very strong "systems" flavor. The introductory course we discuss in this paper should be part of an integrated curriculum that seeks to make connections with other courses offered during the same time frame as well as more advanced courses offered during succeeding years.

In addition to technical and pedagogical reasons for choosing systems and control as the vehicle for this introduction to engineering, there is also a "pragmatic" reason that supports our argument. This is especially true in the context of the US educational system. Systems and control educators are naturally dispersed among different engineering disciplines and for years have been working on multidisciplinary problems. Their presence in different departments can provide the common ground on which such a course can be built. In suggesting changes to the curriculum one must remain always cognizant of the fact that implementation of new ideas needs "political" support.

Recently there has been a resurgence of interest in the systems and control community in undergraduate education. References [5, 6] provide a wonderful description of recent activities at all levels of the spectrum. Over the last decade we have been advocating that systems and control provide a powerful vehicle for introducing engineering to students [1, 2]. Initially we had developed a five-week automatic control module and last year presented some general

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thoughts on curriculum reform and the creation of new programs geared towards engineering students [3]. We also suggested how an introductory engineering course might be structured in that context. Here we focus on a version of such an introductory course, argue that such a course can have a much wider appeal and discuss a collaborative effort underway at Mt Holyoke College. A prototype course, Engineering Concepts I-102, was developed and taught during the Spring '05 term for the first time. Mt. Holyoke is an all-female liberal arts institution that recently developed a 3-2 engineering program with several engineering colleges. Students complete a five-year program of study and at the end of the program earn a BA degree in some field as well as a BS degree in a particular engineering discipline. Even though this course is focused on this group of students we believe that it is a positive educational experience for students who just want to get a "taste of engineering."

It is interesting to point out that in addition to the educational dimension there are issues related to "changing the status quo." Mt Holyoke College is a premier liberal arts institution and this is the first time that an "engineering course" was co-developed and co-taught by instructors from the two institutions. The preliminary discussion about the course and its content took two years and involved several College faculty from different disciplines and a number of engineering faculty from the University of Massachusetts in Amherst. We do not want to underestimate the effort required to build such bridges across disciplines or non-traditional collaborations.

In section II we discuss course objectives as they relate to general program outcomes. In section III we provide details about course structure and content. In section IV we discuss an automated railway project that helps students develop new skills (e.g., interfacing sensors/actuators to microcontrollers). In section V we talk about dynamic models, feedback and automatic control. The students work on the design and implementation of a feedback controller in a collision avoidance application. In section VI we discuss the concept of distributed collaborative adaptive sensing and show the importance of sampling and feedback.

II. A New Introductory Course

Engineering is an exciting and multi-faceted field whose essence cannot be captured in a single course. Even if one concentrates on a single discipline (e.g., electrical engineering) one cannot provide a comprehensive and all-encompassing introduction within the confines of a semester, as one can choose to focus on theoretical concepts, or principles and practices, or applications and implementation. However difficult as this task may be it is important to start somewhere but always keep in mind that any introduction will only be the first step. A further complication arises because engineering as a field is evolving and so is engineering education. Engineers have always been faced with changing challenges in service to humanity and the new century poses a new set of problems. Nanotechnology, logistics, biotechnology, high-performance computing and sensor networks are areas of intense research interest with "high payoff." Of course all of this is taking place in the context of a global economy where the lines of design, development, manufacture, marketing, and finance have been completely re-drawn. The face of engineering and engineering education is changing and this generation of students will take part in the debate and have the opportunity to shape it.

We have argued that an introduction to engineering based on a "systems and control" viewpoint has distinct advantages. Because of our background most of the examples we will use have an electrical engineering and computer science flavor. Students get to see throughout the course that the systems view is quite powerful and has a very wide range of applicability. The material presented is quite relevant to almost all engineering disciplines and is at the core of many of the problems engineers are being asked to solve.

As educators we should continually be mindful of broad educational goals. In particular, we should be concerned about the structure and content on any course and its relation to overall "program outcomes." Listed below are some program outcomes that we believe are very important in the training of "problem solvers." In the US one would recognize that these are "typical" ABET program outcomes. This of course is a partial list.

Program Outcomes

1. Knowledge of advanced mathematics and physical sciences, and the ability to apply these to engineering problems.
2. An ability to design and conduct experiments, as well as to analyze and interpret data.
3. Experience in working productively in a team environment on technically diverse problems.
4. An ability to identify, formulate and solve engineering problems.

As we developed our introductory course outline and set our course objectives we wanted to ensure that they were consistent with our program outcomes. We list below our course objectives and in the matrix that follows relate the two lists.

Course Objectives

a. Motivate and excite the students about engineering
b. Introduce a number of engineering problems
c. Introduce basic concepts, engineering principles, practices and solutions
d. Demonstrate the advantages of a "systems" approach to the solution

e. Conduct laboratory experiments with basic electronic and electromechanical components
f. Introduce basic programming
g. Interface sensors to computers
h. Integrate theory, computer simulations and physical experiments through projects.

A "Y" in the appropriate cell indicates that the course objective has some impact on the corresponding program outcome and an "N" indicates it does not.

Course Objectives / Program Outcomes	a	b	c	d	e	f	g	h
1 Knowledge, ability to apply to engineering problems	Y	Y	Y	Y	Y	Y	Y	Y
2 Identify, formulate, solve engineering problems	Y	Y	Y	Y	Y	Y	Y	Y
3 Conduct experiments, analyze interpret data	Y	Y	N	N	Y	Y	Y	Y
4 Work in teams on multidisciplinary problems	Y	N	N	N	Y	Y	Y	Y

III. Course Structure and Content

We have decided to exploit the "systems viewpoint" and chose to focus mostly on electromechanical systems as the application area. Since this is an introductory course perhaps the most important course goal is to motivate and excite the student about engineering. There is no question that having students work on "fun projects" is very important. Finding the solution of a differential equation or applying Kirchoff's laws to a circuit to obtain voltages and currents is "not fun" for other than the most dedicated student. Working with a team of robots that play soccer is fun. Here lies the fundamental challenge: Develop a course that teaches fundamentals and is fun at the same time. On the one hand we want students to get a better understanding about the "big picture" and have them work on interesting projects. On the other, students must begin to learn the fundamentals and make connections with "hands-on" projects. Developing a course that strikes a balance between these competing goals is crucial. We do not want to have students complete an introductory course and think they have become "engineers" just because on the surface their projects look like senior design projects.

In order to achieve this balance we have developed a course that consists of three elements: 1) Components and Circuits, 2) Software and Interfacing and 3) Systems. These are integrated through "fun" projects. In the sequel we will briefly talk about these elements and in the next three sections focus on some projects.

Components and Circuits: The students are given a very basic introduction to electric circuits. They are exposed to Kirchoff's Voltage and Current Laws for resistive circuits. They construct simple circuits, make basic experimental measurements and make comparisons with theoretical models (using PSpice). The students are also introduced to capacitive and inductive circuits and use Kirchoff's laws to develop simple differential equation models. In the same way Newton's Laws are introduced to develop similar models for simple mechanical systems.

Software and *Interfacing*: The students are taught basic programming skills with MATLAB. Students learn about vectors, matrices, operations, plotting, functions, m-files, for-loops, if-then statements, etc.. They are also given a basic introduction to SIMULINK for use in computer simulation of dynamic systems. The Handy Board is used as a platform for carrying out hardware experiments. It provides a very easy way to interface sensors and actuators with a microcontroller. The programming language for the Handy Board is Interactive C.

Systems: The students are introduced to dynamical systems. Simple mechanical systems are considered for which models are developed (simple differential equation models). Discrete-time models are also introduced as well as system properties like linearity. Exact solutions of simple differential equations computed and compared with numerical solutions. SIMULINK is used to compare results. System behavior is discussed as well as performance. The concept of feedback is introduced and shown how it can be used to improve system performance.

These components are integrated through the completion of projects. Students, working in teams, are asked to complete a number of projects. In the laboratory sequence, the students will use the components from their lab work to automate a small (model) railway system. In a classroom project, students get a first hand appreciation of feedback, the design controllers for CIMCAR, and the implementation using the Handy Board. A final lab demonstration is inspired by a research problem currently being investigated by the Collaborative Adaptive Sensing of the Atmosphere (CASA) NSF Engineering Research Center. CASA is developing a distributed, collaborative, and adaptive system for the sensing of the atmosphere. The actual system being constructed is composed of a network of distributed radars that will allow for the unprecedented collection of data used for weather prediction. The students work with a "laboratory version" of such a system that exposes them to issues associated with data collection using a sensor network. In the next three sections we discuss in more detail these three projects.

IV. AUTOMATED RAILWAY SYSTEM

We wanted a hands-on lab sequence that would have students solder components, experiment with sensors, and program the Handy Board. To give the components section a focus, students work on a sequence of labs that lead to one where they work as a group to design a sensor/control network to run a small automated railway project using HO gauge equipment. This lab sequence takes advantage of ideas from a robotics course taught in Fall '04 at Mt. Holyoke where we discovered that concentrating on automation rather that autonomous, mobile robots would allow more to be accomplished with less programming on the part of students. The system is just complex enough that multiple Handy Boards are needed to be in communication to handle sensing, switching, and motor control.

V. FEEDBACK IN COLLISION AVOIDANCE

We believe that the concept of "feedback" is fundamental not only in an engineering or technical context but much more broadly. Control engineers have used it to solve problems for centuries. For a number of years (see references) we have been advocating that "systems" and "feedback" is a perfect vehicle for an introductory engineering course. In fact, we have developed a five-week introduction to automatic control [2]. In view of the constraint imposed by the duration on the module only one component of the puzzle could be presented. In this course we have an entire semester to tell a more complete story. We are now able to present enough theory, teach appropriate programming skills and have students work on interesting feedback design projects.

The theme of systems and control was presented around "collision avoidance" project involving CIMCAR [1]. Whereas the original version of CIMCAR implemented the controller on a 8051 microcontroller a new version of CIMCAR was built around the versatile Handy Board platform. For the student this is a much easier platform for implementing embedded systems. Students can program with relative ease, incorporating sensors and actuators and provide a solution to the entire project. The exercise gives a pretty accurate picture of more sophisticated and professional embedded system platforms. Its limitations are not severe enough to prevent the demonstration of important systems concepts. In fact, the limitations can be used to point out to students what they need to learn. Simplicity does come at a price.

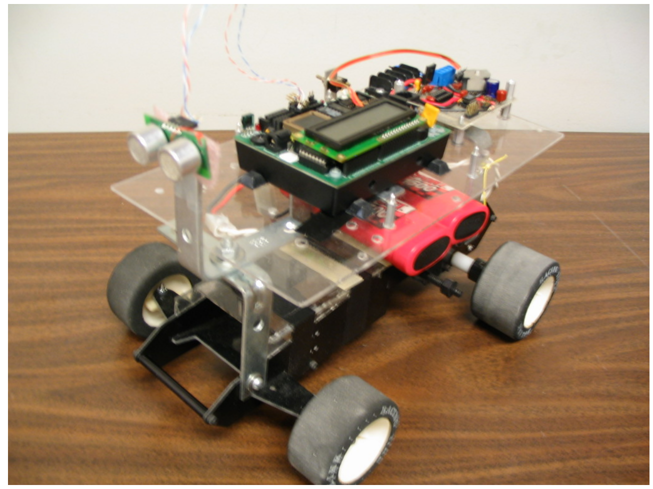

Figure 1: Handy Board CIMCAR

Listed below is a set of topics and theoretical concepts that were discussed in the "systems" portion of the course:

i) Introduction to dynamic systems

ii) Models of simple dynamic systems, discrete time difference equations, continuous time differential equations first and second order

iii) Analytical solutions of first and second order differential equations

iv) Inputs, Outputs, Linearity, Non-linearity, Transfer Functions, Interconnections of Systems, Complexity

v) Numerical solutions of differential equations using SIMULINK

vi) Stability and Performance

vii) The use of feedback for stability and improved system performance using CIMCAR

viii) Sensor Networks (CASA)

The collision avoidance project allowed students to integrate theoretical knowledge about systems and the software tools they were exposed to. They were given the CIMCAR transfer function and were be asked to design a simple gain controller that allows CIMCAR to complete the following movement: CIMCAR should start eight feet away from a wall, move toward the wall and come to a stop three feet away from it. The performance specifications are:

- the car should be at 3 feet plus-or-minus 3 inches within 3 seconds
- the car should come to a stop 3 feet away from the wall without “overshooting” this target and certainly without crashing into the wall

They were given enough technical knowledge to design a gain controller that achieves the desired performance. They tested the controller using SIMULINK and then implemented this controller on the Handy Board CIMCAR. They had enough background knowledge to interface the sonar sensor and drive the actuator. They wrote the program in Interactive C, download it and test it. In so doing the students were able to provide a *complete* solution to an engineering problem working on a "fun" project. Even though they did not have a complete understanding of every component there was enough balance between "fundamentals" and "fun." They were able to verify the theoretical predictions with experimental results. We continually reminded students that even though they had enough knowledge to complete this project they needed to develop appropriate depth in every area for a more complete understanding.

We realize that focussing on a specific application area is restrictive and may not appeal to every student in the class. In view of this fact, at every opportunity we told these students that the feedback theory used, the methodology for design and the microcontroller implementation would be exactly the same, if we were working on an automatic pump that delivers insulin to a diabetic. All the steps used in the design of this and many other problems are the same. The CIMCAR platform is simply much easier to work with.

VI. DCAS PROJECT

In the collision avoidance experiment students were able to see how feedback was used to control the operation of a system. This is but one example of the use of feedback. The DCAS (Distributed Collaborative Adaptive Sensing) Project has been inspired by another application and is a demonstration of the use of feedback at a different level. In what follows we will briefly describe the real application and discuss the DCAS system under development. We then discuss a "laboratory version" of this system.

Current observation platforms for weather prediction work open-loop and are not networked. In the USA, NEXRAD is a system or weather radars that are distributed around the country (approximately 160), usually placed near metropolitan areas and airports that "sit and spin." Each is a radar whose antenna spins about azimuth and elevation axes following specified trajectories. The data collected is processed and sent out to appropriate agencies where meteorologists take it, combine it with other data, feed this information to weather prediction algorithms and develop forecasts. Researchers of CASA argue that weather prediction could be vastly improved if many smaller radars (with overlapping coverage areas) were networked and if feedback was used to re-task them based on observations. In other words if storm activity is detected in some sector, radars could focus resources there while at the same time "keeping an eye" at all areas. Clearly, resources need to be allocated appropriately so that no important weather activity is missed.

This very exciting example provides the inspiration for a classroom version of a network of sensors. Depicted below is a "Sonar Sensing Station, (S3)".

Figure 2: Sonar Sensing Station

A slip ring allows for 360° rotation in azimuth and a sonar sensor is mounted on a board that rotates in elevation. The station can collect position data of objects placed in its observation area. Currently we have a functioning network consisting of two "nodes" which is being expanded to one with four nodes.

A fundamental issue in actual weather prediction is space-time observations. In other words, one needs to collect data in time and space so that all important atmospheric dynamic phenomena are observed. If the radar node is not looking in the right sector at the right time or is collecting data samples too slowly, important weather information may be missed. The process of collecting data using a network of sensors can be very easily demonstrated using the S3 network. An entire array of experiments can be conducted that demonstrate key components of the data collection process. Demonstrating the limitations associated with slow sampling, showing that one has to deal with "noisy" data, demonstrating the importance of data collection by a network of sensors, exploiting feedback in re-tasking nodes are but a few examples.

Consider an experiment where two sensor nodes observe the movement of an inverted pendulum that is swinging back and forth. One node is placed in the plane of motion of the pendulum and the other on an axis perpendicular to it. The two nodes are thus 90° apart and the pendulum swings at a period of .2 Hz. Figure 3 shows the results where "Servo 4" is the node in the plane of motion and "Servo 6" is on an axis perpendicular to this plane. The sampling rate is "high enough" and the results are as one would expect. One can see that the period of oscillation is reasonably detected from the raw data of Servo 4. However, the data is noisy and it is not easy to detect what is happening by looking at the raw data of Servo 6.

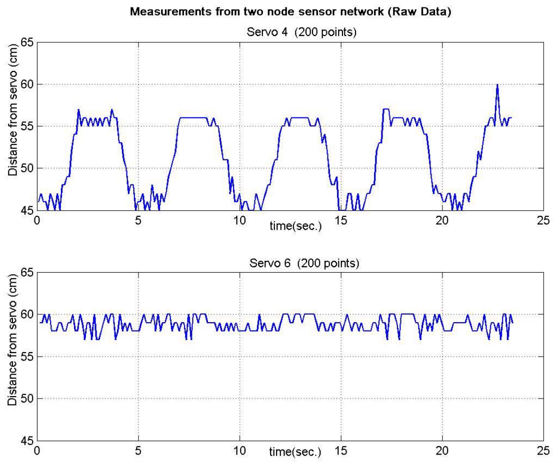

Figure 3: Two-node Sensor Network Data

A moving average filter is used to "clean" the data and results are shown in Figure 4. Looking at the experiment from two vantage points allows one to have a better understanding of what is actually taking place.

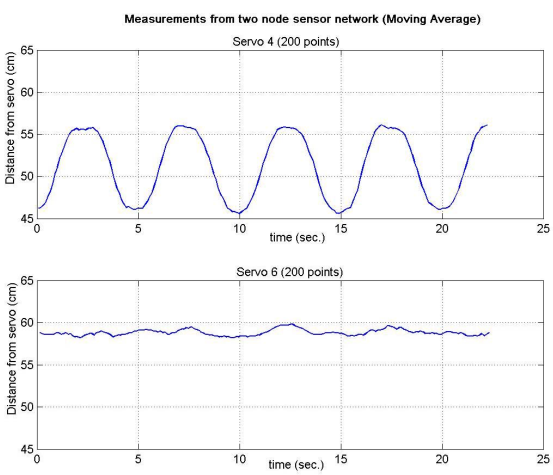

Figure 4 Filtered Data

One can envision many other experiments that can be conducted with the network that would allow one to demonstrate the power of feedback and the advantages of network observations. A demonstration of the operation of this network was made for the students. As the structure and functionality of this sensor network is improved it will become a platform for numerous experiments.

VII. Conclusions

In this paper we argued that systems and control can provide an excellent vehicle for introducing engineering concepts, principles and practices. We have argued that their multidisciplinary character provide a natural foundation for the solution of many new engineering problems. We then described the structure and content of a new introductory course developed and taught at a four-year liberal arts college. The students (all women) had generally positive comments to say about the course. They really appreciated the experience of working with hardware and making connections with theory. These students had a physics or a computer science background and were very interested in "robotics" applications. One of them continued this work as part of a "research experience for undergraduates" at UMass Amherst made possible by CASA. The course will again be taught at Mt. Holyoke College in Spring '06.

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