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Raising the Bar in Teaching Mechatronics

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Abstract— **In academia, our current strategies for teaching mechatronics in mechanical design curricula provide opportunity for improvement. We have undergone a revolution in evolving mechatronics content in our curricula from limited coursework in instrumentation to one or more courses in mechatronics. However, mechatronics or dynamic systems courses tend to use a few pre-defined examples that are narrow in training experience for the students. When multiple components are incorporated into a laboratory or project, these courses tend to focus on the interfacing problem at the expense of a system view. The issues concerning optimization of the complete system to meet given requirements is not well considered. Integration of the mechanical elements, the electronic elements, and frequently the embedded software to meet a system requirement are often not an emphasis.**

We believe that laboratory design exercises based on actual design cases are an opportunity to provide a more comprehensive exposure to mechatronics design. These laboratory exercises can be structured to provide experience and exposure in integration of mechanical and electronics systems, system level analysis and design, and application of network communications in mechatronic systems. Several case studies, which have been used as a catalyst to various mechatronics projects at Oklahoma State University, are discussed.

I. INTRODUCTION

IN academia, our current strategies for teaching mechatronics in mechanical design curricula provide opportunity for improvement. We have undergone a revolution in evolving mechatronics content in our curricula from limited coursework in instrumentation to one or more courses in mechatronics. In 2002, one of the authors described the evolution of current efforts in teaching mechatronics along with some sophisticated projects at Oklahoma State University and Kansas State University [12]. In addition, a modular set of courses supporting students from electrical and mechanical engineering as well as those from computer science was presented. However, across the country, current mechatronics elements in curricula are generally still somewhat limited. Existing mechatronics coursework may typically be characterized with some of the following descriptions.

Mechatronics or dynamic systems courses tend to use a few pre-defined examples that are narrow in training experience for the students. For the most part, this is a good thing. If dynamic behavior is to be investigated, it makes sense to study a system whose dynamics are not significantly complicated. If a control design is to be investigated, the interaction between the control structure plus gains and the controlled object should be tractable. An example might be an exercise to implement control of an inverted pendulum. See for example [9], [11], [13]. The mechanical system is typically a given element and the students exercise is to develop functional hardware for a given electronics platform. It is not unusual that the platform is a personal computer (PC). In some cases, perhaps because of the high cost of the experimental setup, PCs are used to interface the experiment with the Internet, providing remote access to students [3], [5].

Mechatronics courses also tend to focus on the interfacing problem at the expense of a system view. The issues concerning optimization of the complete system to meet given requirements is not well considered. Integration of the mechanical elements, the electronic elements, and often the embedded software to meet a system requirement are often not an emphasis.

Mechatronics courses do not provide students with significant experience in communications systems. Systems currently based on mechatronics technology increasingly rely on multiple electronic components that communicate with a local network. This distributed computing requires a network and integrating software to link the sensor, actuator, and control modules. One example is the use of Control Area Network (CAN) in automotive applications where in-vehicle networks are commonplace. Other examples are the use of wireless networks such as Bluetooth or ZigBee in home automation, security, or industrial control networks. This area of mechatronics design has for the most part been ignored in engineering academic coursework.

System co-design has also not found its way into the classroom in teaching mechatronics. It is common that different people do electronic hardware design and

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software development. Simultaneous adjustment of hardware and software to meet problem requirements is a natural part of what is done in commerce but we typically do not focus on this approach in teaching mechatronics [10].

Another topic that has not been well integrated into mechatronics teaching is hardware in the loop. Hardware in the loop systems are expensive and this cost prevents the technology from becoming well adopted in teaching. However, some progress can be made by making use of software such as MATLAB™ to provide the hardware response solution while the microcontroller (PIC) is used to generate the control inputs with communication taking place over a serial connection.

Control of functional quality is not typically an outward objective of coursework in mechatronics. Yet, quality failures in mechatronics systems are headline news in many of the systems that are developed. An example might be the Arianne 5 failure where a software misinterpretation caused a mission abort [7]. Similar well known functional quality problems occurred with NASA's Mars Polar Lander [4], and the Therac 25 medical linear accelerator [8]. There is a need to integrate quality control processes into the classroom work in Mechatronics. This may be too large a bite to ask of an academic environment, but it is something to think about as programs expand and mechatronics integration becomes more commonplace.

The increasing importance of mechatronics as a fundamental subject in mechanical design training reinforces the need to improve mechatronics teaching. We tend to think that coursework in machine design, vibrations, dynamics, materials, etc. are fundamental in teaching engineers to design mechanical systems. The extent of integration of electronics in contemporary mechanical systems requires that mechatronics become a more fundamental emphasis in mechanical design curricula. Training in mechatronics needs to address those design skills required in contemporary mechanical design. Hence, we propose a broader and more significant role for mechatronics in teaching mechanical design.

II. Strategies For Improving Mechatronics Education

We believe laboratory design exercises based on actual design cases are an opportunity to provide a more comprehensive exposure to mechatronics design. These laboratory exercises can be structured to provide experience and exposure in:

1. Integration of mechanical and electronics systems.
2. System level analysis and design.
3. Application of network communications in mechatronic systems.
4. Analysis of failure modes and focus on quality end results.

Presentation of the exercises as a case study, and as elements of the case provide the opportunity to place laboratory design exercises in the environment in which mechatronics design is normally conducted. The laboratory exercises are necessarily a part of the whole case and are much narrower or much more constrained than the actual cases. Presentation of the case and then the exercise as a part of the case provides context for the laboratory exercise. Context is necessary to allow students to make practical judgments regarding the more narrow or constrained element of the system that students are addressing as a part of a laboratory exercise. The case study approach also allows exercises to be developed that address various levels or aspects of design that may include system design and planning, communications, control issues as well as bottom-up issues like interfacing. Case studies that have the aspects presented above can be drawn from commercial applications but may also be derived from some of the competitive design contests in which students normally participate.

The following case studies and extracted laboratory exercises are given to illustrate this concept.

III. CASE STUDIES

A. *Fertilizer Applicator*

This case study describes a system that was designed and is currently being manufactured. References to manufacturers involved and proprietary details are intentionally omitted and any indirect reference is not intended.

An equipment manufacturer required the development of a system to apply liquid nitrogen fertilizer to agricultural crops. The system was designed to mount on an applicator vehicle and consists of a liquid nitrogen (UAN) fertilizer supply tank from which a pump draws liquid fertilizer and supplies it to a spray boom under pressure (Fig. 1). The spray boom is equipped with fixed orifice nozzles that are each engaged with a solenoid valve. The system uses a control valve divert flow from the pump either to the spray boom or to return to the fertilizer supply tank. Positioning this motorized valve adjusts the pressure of the fertilizer to the nozzles. The system is also equipped with a flow meter to measure flow rate to the spray boom and a pressure transducer to measure pressure at the spray boom.

The fertilizer applicator system uses three electronic control units (ECUs), an ECU for an operator interface, an ECU for pressure control and an ECU for application rate control. The machine is designed to allow the application rate of fertilizer per unit surface area to be varied to particular desired levels during operation of the machine. Pressure at the spray boom set to a particular level sets the flow rate through the nozzles. The pressure is increased or decreased to compensate for vehicle speed and allows the application rate per unit surface area to be constant with varying speed for a particular nozzle configuration. A Doppler radar is used to measure groundspeed. Nozzle sets can then be turned ON or OFF to select the desired application rate range.

Many laboratory exercises can be based on the problems in the design of this machine. Examples might include the following:

1) Propose a minimal user interface design that will allow the user to control the machine. The design should provide functions to turn the machine ON or OFF, allow setting application rate, allow for cleaning the machine, allow logging of when, where and what amounts of material are applied.

2) Design a set of messages for network communications that will allow the machine to provide the functions given in part 1.

3) Determine the potential failure modes of the system and assess the potential severity of the failures.

4) Develop software that uses an on-chip counter and on-chip timer to process the Doppler radar signals and produce a velocity signal with units of m/s. The radar produces 44 Hz/mph (27 Hz/kph) and the vehicle speed will range from 2 to 20 mph (3.2 to 32 kph).

5) Develop a control algorithm that may be used in the pressure controller ECU to manipulate valve position and control spray boom pressure.

6) Propose an H-bridge circuit and interface design for the valve control portion of the pressure controller.

7) Use MATLAB™ to simulate the pressure control circuit in the sprayer and determine the effect of selection of valves with response times varying between 1 s and 5 s open to fully closed.

8) Determine the optimum nozzle orifice sets to allow the sprayer to operate from 2 to 20 mph (3.2 to 32 kph) with pressures maintained above 20 psi (140 kPa) and below 45 psi (310 kPa). Assume three solenoid-operated nozzles at each 24 in. (0.61 m) location across the spray boom and desired application rates between 20 and 120 lb/acre (22.4 and 135 kg/Ha).

9) Propose a feed-forward control strategy for this machine that will compensate for pressure given known changes in nozzle orifice settings (see problem 7).

The examples above demonstrate the earlier point that comprehensive exposure may be provided by basing the problem on an actual design case. One of the difficult aspects in implementing the strategy is that a reasonably detailed case study must be found. The opportunity exists to secure design case studies from industries. These necessarily need to be stripped of proprietary material as in the case above, but can still provide breadth and context for classroom use. Another source of cases may be found in the laboratory work and student competitions that are a part of most educational institution activities.

B. Formula SAE Car

We have been using microcontroller-based hardware to teach our mechatronics courses at Oklahoma State University (OSU) for many years. The PC is used to edit, compile, and download executable code. It is also used to receive data via a serial cable or wireless network and to interface with an in-circuit debugger (ICD). A photograph of the Summer 2003 version of the OSU microcontroller target board along with a similar board (Fall 2004) from Custom Computer Services, Inc. and a quarter for scaling purposes is shown below. Microcontrollers in use are the 16F876 DIP package and the 16F877A surface mount package respectively from Microchip Technology, Inc.

We determined that it was advantageous for students to own their own hardware and software so that they could be independent of a fixed laboratory. Lab times were on their own schedules and if they "toasted " equipment, it did not adversely affect the other students in the class. This idea is similar to that described in a recent paper where students check out small laboratory kits to execute at home [6]. However, we have still not implemented all of the topics discussed in the introduction. We have, through the use of term design projects, allowed students to work in teams of one or two and on rare exceptions, three. In this manner students are able to work on more advanced projects than those used to teach the fundamental concepts.

One senior design project, the Formula SAE car, is associated with a national design contest sponsored by the Society of Automotive Engineers and incorporates many aspects of engineering [1]. Several students working on this project decided to apply their mechatronics training and implemented the schematic diagram shown below in Fig. 3 on the vehicle. The ignition, fuel injection, and data storage and retrieval systems were connected using PIC microcontrollers and a CAN network. Items shown as dashed lines on the schematic were not implemented by the end of the Spring 2004 semester but plans do exist to complete these items at the next course offering. This represents a very practical and realistic project that integrates electrical, mechanical, software and communication components into a functioning mechatronic system. Several projects could be partitioned from this very real case study. A group of one or two students could work on various parts of the design. New features could be added from semester to semester and old designs improved.

C. AIAA Design/Build/Fly Competition

Additional projects have emerged from a senior design course supporting the national Design/Build/Fly international competition sponsored by the American

Institute of Aeronautics and Astronautics (AIAA) Foundation, the Office of Naval Research (ONR), and the Cessna Aircraft Company.

Student teams will design, fabricate, and demonstrate the flight capabilities of an unmanned, electric powered, radio controlled aircraft which can best meet the specified mission profile. The goal is a balanced design possessing good demonstrated flight handling qualities and practical and affordable manufacturing requirements while providing a high vehicle performance [2].

The specified mission profile and design objectives change from year to year. However, this case study again represents a very real project, which must be partitioned into many different tasks. Some of the mechatronics related tasks in the past supporting this effort are as follows.

1) Build a microcontroller (PIC) – based dynamometer to measure propeller thrust along with overall propeller efficiency. In this project, input power to the DC motor is compared with thrust and airspeed measured in a wind tunnel to arrive at the overall efficiency. This instrument was used to evaluate various propeller designs over different operating ranges.

2) Design and implement an anti-lock braking system (ABS) for the aircraft. Used to rapidly stop the aircraft on the ground in the middle of a flying profile when the payload is exchanged.

3) Build and implement an on-board data logger. Used to measure battery life and aircraft performance data. Telemetry could be added to this project so that the data logger could communicate with a laptop PC on the ground to obtain data acquisition in real time.

4) Design and implement a microcontroller (PIC) – based autopilot. This is used during the design stage to enable the aircraft to fly a prescribed course and altitude. Couple with project 3) above to attain a complete testing environment.

5) Assess the potential failures that may be associated with the use of the autopilot and identify the best strategies to minimize the effects of the potential failures.

Again, this project represents a very practical and integrated mechatronic design, one that we think should be closer to the norm for student projects than those traditionally given.

IV. ASSESSMENT

Assessment is a constant concern these days in the education community. What are the outcomes? How can we measure the success of this approach? At Oklahoma State University our objective is clear. Can a student after taking one of our mechatronics courses design, implement, and test an electro-mechanical system utilizing embedded software at the appropriate level for the course? Does the student's design perform acceptably under the conditions for which it was designed to operate?

In our courses, students complete small projects taking a week to two weeks in duration. They are then evaluated through performance on written reports, microcontroller output for a given input, and/or a design portfolio. In some cases these small projects are demonstrated to the instructor or teaching assistant in the laboratory where they are thoroughly tested. The quality of the embedded software is evaluated. One to two term design projects are given where the student, in addition to a report, provides a working demonstration to his/her fellow classmates and the instructor and teaching assistant. Grades are assigned and are correlated to the outcomes listed above.

V. CONCLUSION

An argument has been presented that suggests that some of the laboratory experiments and projects associated with teaching mechatronics courses should be based on actual design case studies. The case study approach allows exercises to be developed that address various levels or aspects of design that may include system design and planning, communications, control issues as well as bottom-up issues like interfacing. Classical projects used to illustrate simple dynamics or control strategies and / or their interaction are still important and necessary to the overall teaching effort. However, these traditional projects do not provide the more comprehensive exposure to mechatronics design that is necessary in today's engineering environment. Essential knowledge and practice must include the integration of mechanical and electrical systems, system level analysis and design, and the application of network communications in mechatronic systems.

The three case studies discussed in this paper will continue to spawn many real-world design projects. Many more will be generated. Our students currently graduate and receive many job opportunities requiring them to analyze and design extremely complicated mechatronic system components. These tasks require the generation and integration of microcontroller and other processor software with highly sophisticated electro-mechanical systems. If we do not raise the bar in teaching mechatronics by providing a more comprehensive exposure to mechatronics design, we feel that the gap between the fundamentals we currently provide and those required for today's engineering environment will continue to widen.

ACKNOWLEDGMENT

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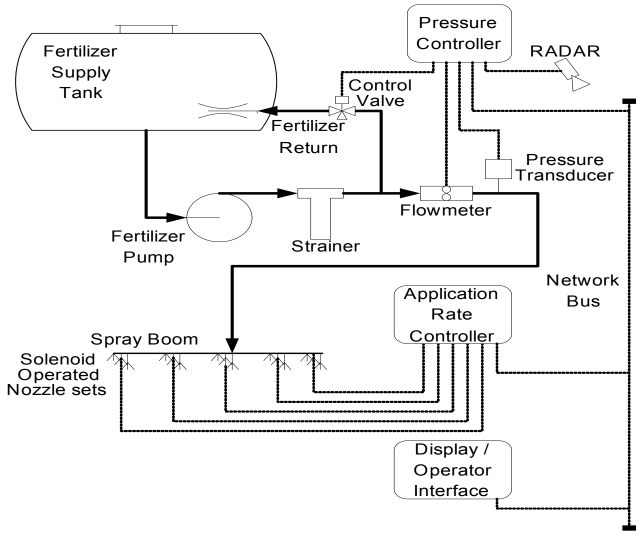

Fig. 1. Fertilizer applicator schematic.

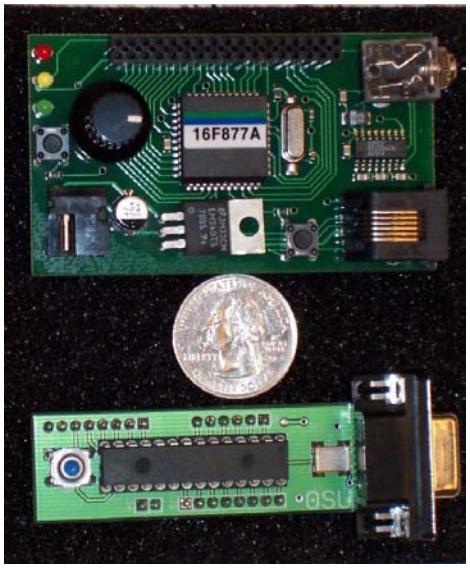

Fig. 2. OSU target board (bottom), quarter, and CCS target board (top).

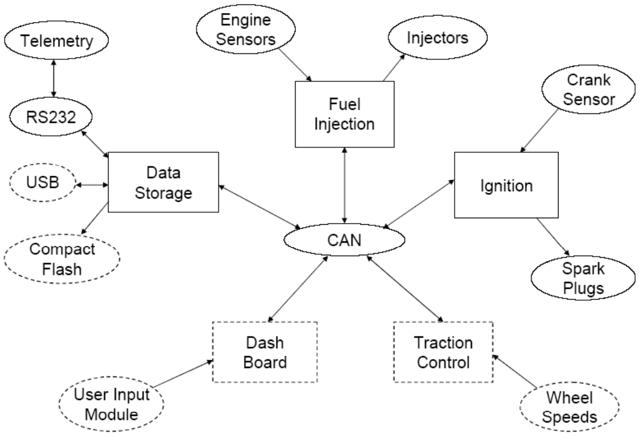

Fig. 3. Schematic of Formula SAE Vehicle.