Mechatronics and Systems Instruction Across Graduate, Undergraduate, and Research Applications Using Rapidly Reconfigurable Hardware

Abstract

A challenge with the development of any new mechatronics, systems, and/or controls laboratory is the cost-effective use of hardware resources. This work discusses the development of a reconfigurable data-acquisition architecture across three different application areas in university instruction: undergraduate education, graduate education, and graduate-level research. An analysis is offered of the different operational and educational requirements across these different levels of instruction. In many cases, these educational tiers present non-complementary requirements including different expectations on ease of use, durability, compatibility, software complexity, and performance. The historical solution at many educational institutes is simply to purchase and support distinctly different hardware data-acquisition solutions between undergraduate, graduate, and research areas. Not only is this expensive, but also it artificially breaks a natural continuum of instrumentation education across levels of instruction. This work presents solutions to assist in balancing research and teaching while simultaneously fostering new activity in both areas. Case studies drawn from each area illustrate the main points.

Introduction

Motivation for hands-on learning: While interactive laboratory experiments and problem-based learning (PBL) have always been known to foster learning, only recently have large-scale studies appeared in the literature that unquestionably support the validity of such activities[1]. Additionally, there are a very large number of articles in the particular area of control systems, mechatronics, and dynamics, in the literature on the development and use of laboratory hardware[2-27].

Background to our system: Starting in 2004 and with development continuing to 2005, the Department of _________ Engineering and ____(corporate sponsor)_______ jointly sponsored the development of a new graduate-level course, "Advanced Mechatronics" at _________________ University focused on immersive learning via in-class development of high-performance embedded robot systems. Central to the class teaching structure was the use of intensive laboratory experiences in which students developed code and hardware necessary to operate mobile robots for advanced tasks. An example of an advanced task, for example, would be vision-based tracking and recovery of a soda can. In 2005 to 2006, the same sponsors supported the generalization of the hardware to serve as the base system for the department's undergraduate systems and control courses. Over this same timeframe, this same system platform was externally adopted for graduate research in vehicle dynamics.

Overview of paper structure: This iterative and cross-use development cycle has led to a number of insights and "lessons learned" that are conveyed in this paper and organized as follows: First, a description of the capability requirements of graduate, undergraduate, and research-grade data-acquisition equipment are described focusing on the conflicting and synergistic aspects of each requirement. Next, an overview of the system is given focusing on technical specifications and development hurdles. Case studies are next presented in the three following sections, organized in a manner that parallels the three areas of development at ______ University: graduate course deployment, undergraduate deployment, and research. The findings are summarized in a Discussion section that presents student and faculty feedback on the system, particularly focusing on topics that may affect similar system development at other institutes.

Capability Requirements: A Three-Tier Problem
Description of capability needs: The instrumentation needs of undergraduate education, graduate education, and research in control theory are driven by the project or educational goals. For mechanical control systems which are the focus area of this discussion, there are commonalities in all stages. However, the criteria for a successfully designed data-acquisition system is remarkably different depending the application, leading to conflicts. Both the synergies and conflicts are summarized below:

Synergies: All data-acquisition systems share the following needs and desirable features:
- Low cost of ownership and purchase,
- Simplicity in the interface,
- High performance, at least as measured by the mechanical systems controlled by the system.
- Flexible usage

Conflicts:
- The relative importance of cost and performance is relative. If a research project is only feasible with the use of a very expensive piece of equipment, then that equipment will almost always be procured. The opposite is generally true of an undergraduate lab equipment.
- Reliability is judged by the expertise of the user. Graduate students are generally able to cope with (and sometimes expected to fix) equipment failures. Undergraduates do not have the time available.
- Portability of the equipment is often required for undergraduate laboratory exercises and in-class demonstrations. This constraint generally doesn't exist to such an extent for graduate classes or graduate research, where the small number of students allows more direct access to the equipment, e.g. everyone can "crowd around."
- There are a very large number of undergraduates to use the equipment, moderate number of graduate students, and a few research project. Hence, the students least likely to be trained in use or repair of the system are most often using (and hence breaking) the system.

The discussion that follows presents solutions that focused on synergies between different platform needs, while at the same time addressing *some* of the above core conflicts, particularly how these conflicts map to constraints in equipment design and setup.

Equipment Overview
Technical specifications: Among the conflicts listed above, the performance needs of graduate research are paramount. If these are not met, then there is little chance of usage of equipment within graduate research, and hence little chance of faculty interest in supporting the equipment to a level described in this work. Therefore, the first task in equipment selection was to identify the most constraining research usage of the equipment. For the activities described herein, the most constraining data-acquisition event was the coordinated control of a real-time vision system

with a mechanical control loop. The use of an embedded vision system requires extremely high data transfer rates and processing speeds.

To address the performance issues primarily, the hardware platform used throughout the discussion of this article is a Digital Signal Processor (DSP), namely the TMS320C6713 by Texas Instruments mounted on a developer's kit (DSK) component board manufactured by Spectrum Digital. The processor operates at 225 MHz with many key mathematical operations occurring in a single processor cycle. This particular processor was attractive for vision systems because of its low cost (free to university programs supporting education in this area), and capability to support direct memory access (DMA) for automated image acquisition.

Why a robot platform?: One of the key constraints for the system was an ability to be deployed in the classroom. Additionally, many of the authors research projects required mobile, stand-alone embedded systems that consume little power (e.g. vehicles, aircraft, robots, etc.). The mobile robot was chosen as a teaching and hardware platform because it encapsulated these needs while at the same time providing an accessible and familiar system concept to the students.

Development hurdles: Without question, one of the largest hurdles in deploying an advanced toolset such as a DSP for student use is the lack of resident expertise in such systems at the onset of development. While many students and faculty in the department are familiar with microprocessor-based systems such as the Stamp or Atom series by Parallax, or the Microchip PIC systems, Atmel processors, or the Motorola series, there are relatively few students or faculty trained in DSPs at a level allowing creation of an embedded hardware system and supporting software.

Transplanting Expertise From Elsewhere: The author was fortunate to have worked on nearly identical platforms as a student at ____(University)________. This university graciously donated code and example laboratories that served as the framework for the new developed described here.

Fortunately, the issue of lack of expertise on a system architecture is a problem that largely fixes itself as deployment into classrooms proceeds. However, this key issue did affect the nature of system deployment and which courses were targeted first. This is discussed shortly.

Graduate Deployment

Advanced Mechatronics Class: Construction of the robot began during the Summer of 2004, a time period corresponding to the hire of the first graduate student in the author's research group (not a coincidence). Working closely with the graduate student, the author taught the principles of circuit board layout, robot construction, and shared previous mechatronic designs - and mistakes! - from the author's previous institution. The graduate student then constructed the first prototype of the mobile robot (Fig. 1), and based on this experience developed subsequent designs of the system.

Fig. 1: (Left) Construction of first prototype, (Right) Final system

Course structure: From the beginning, the focus of the course design was on breaking the typical classroom style of focusing on many topics (particularly in Mechatronics), then exploration of only one or two topics in a single project. This is opposite in nature of the typical industrial project, where the focus is solely on one project, but where work that project invariably isolates (or "snags on") one or two topics of key importance. The goal of the course development was therefore move away from the notion of flexible laboratories supporting challenging lecture content, and instead use flexible lecture content to support very challenging labs.

After construction of the robot, eight graduate-level laboratory activities were developed that focus on stages of the robot construction encountered during the robot build (these are listed shortly). The labs in total occupied approximately 32 one-hour lecture periods. Each lab was designed to be completed in either two or four class periods, depending on the complexity of the task. Each lab period began with approximately 10 to 15 minutes of lecture to guide activity, and an additional lecture was provided before each lab segment to allow introduction of lab content.

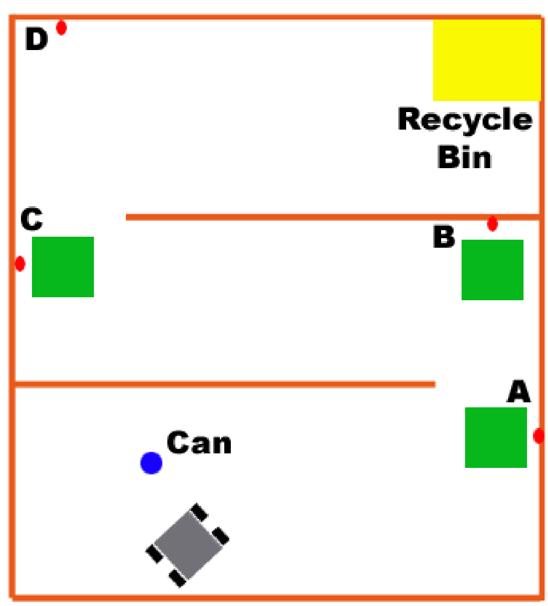

Fig. 2: Final lab contest maze

An additional 3 class periods were allowed for a final contest-style lab assignment that did not include any new hardware or software material, but did require synthesis of all topics in the class. An example final contest is shown in Fig. 2. In this contest, students applied previously learned techniques to program their robot to autonomously find a soda can in a maze, and carry it to a 'recycle bin'. The bin's position varied, but was always found under a light in the top section of a maze. The robot was required to pass over certain "detection pads" (A,B,C) to turn on the recycle bin light.

The final 8 lectures of the course were dedicated to class content of the student's choosing which generally consisted of integration of course material into research. Because nearly all the students taking the course were first-year graduate students, many were initiating research endeavors requiring new equipment or instrumentation setups. Students were encourage to meld their research tasks with laboratory tasks, a synergy that led to many class-to-research project synergies discussed shortly.

Typical Lab setup: The typical lab setup focused on directed questioning techniques in the lab write up. To use one example, Lab 6 had the following task: "Using only two sensors, make the robot do right-wall following around the classroom's outer wall edge at the fastest possible speed." To engage the students, questions were asked such as: Can you do it faster than your neighbor? Students were then asked to define the task before doing anything, again with directed questioning including: What aspects of the system design that they think will most limit their speed? What aspects do they plan to study? What are they assuming? Where do they place their sensors? What are the tradeoffs with each sensor? Students were then encouraged to explore freely: How do you intend to investigate design space? As exploration commenced, students were asked which of their previous questions appear to be more important? This led to planning, where students were asked to write down and commit to a methodology that will quantitatively answer their questions. They then solved their problems by completing their measurements (takes ~ 1 hour). Finally, the lab asked students to evaluate themselves. For example, how sensitive was their algorithm to wall conditions i.e. will it work with non-right angled rooms? Were their assumptions reasonable? What was the single largest limiting factor limiting their speed?

Listing of Lab Activities: The above represents the design structure for one of eight labs listed and summarized below:

1. BIOS: Students learn how to compile programs, comprehend basic compiler mistakes, review binary logic, etc.
2. GUI's / Networking: Students learn how to design MATLAB GUI's, comprehend serial ports protocol, apply protocols to their robot.
3. Daughter cards: Students synthesize and fabricate a new I/O card (!).
4. Glue Logic: Students analyze an existing parallel interface to an analog output device, and synthesize a new one for analog input.
5. DC Motor Control: Synthesize a method to control velocity of robot while compensating for friction, evaluate two different control techniques to steer the robot.
6. Sensors: Students demonstrate knowledge of basic feedback control by synthesizing a method for the robot to navigate an arbitrary maze (often an arbitrary room) using only two sensors
7. Actuators: Students find and pick up a soda can evaluating different methods to sense and pick up the can the fastest.
8. Vision: Synthesize an algorithm to find and approach a light, and set the can directly under the light
9. Maze: Apply previous techniques to have your robot find a soda can in a maze, and carry it to a 'recycle bin', found under a light in an different location in the maze

Undergraduate Deployment

The success of deployment of the previous graduate-level course led directly to interest in similar usage at an undergraduate level. Many of the above labs were converted directly to undergraduate final projects. The interest in this soared until it was felt necessary to develop a separate set of tools and equipment specific to undergraduate education.

Pendubot Project and Final Project for Dynamic Systems: In 2006, a laboratory project was developed to provide a hands-on learning component to engineering students in ____________(course name here)________ by use of a non-linear, unstable system. Effective modeling and control of this system requires derivation of system equations with Lagrangian methods, linearization of these equations for analysis with ME 440 tools, understanding of state feedback control theory and familiarity with MATLAB/Simulink software.

With the assistance of an undergraduate senior project group, the author developed and tested several concepts for instructional use. These concepts evaluated the reliability, durability, and aesthetics of the system. The final design is a double pendulum system called the Pendubot, which is shown in Figure 3 below. The Pendubot is an under-actuated two link robot. Its main components are two vertically mounted links, a motor, and two encoders. The motor is mounted at the shoulder joint and provides the driving torque for the system, while the two encoders provide system feedback. One is mounted on the motor and provides the angular position of link1. The other encoder is mounted at the elbow joint (top of link2) and provides the relative angular position of link2 with respect to link1.

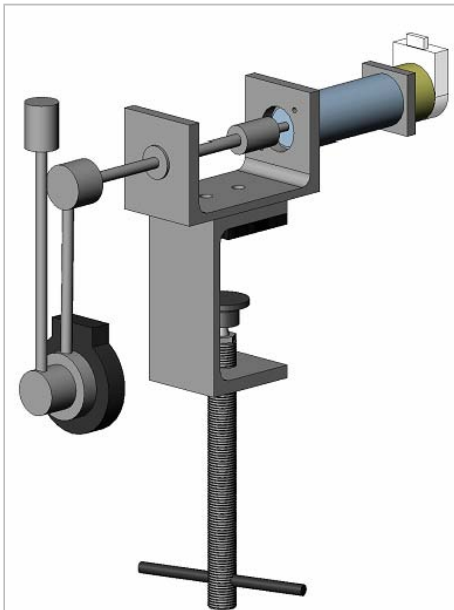

Fig. 3: Pendubot system

The students were then asked to control the Pendubot to stay in the unstable "down-up" position shown in figure 3 where link1 balances in front of link2. In order to do this, they had to derive and linearize the system model, then apply state feedback control via a Simulink to the DSP.

To implement this project with the aforementioned data-acquisition system, the DSP was programmed to interface to a PC system through the parallel port as an external data acquisition system. This allowed real-time, high speed (1 kHz) sampling rates, and additionally allowed the students to avoid programming the system in C code as used in the graduate course, but instead design and test their system directly in Simulink.

Student testing of the system resulted in positive results. Students in the course ______(class name)____ were able to complete the pre-lab worksheet within 2-3 hours, complete the lab activity itself within around 2 hours. So positive were the results, that one of the members of the student group developing the equipment recently told the author that he sleeps with a picture of this system over his bed!

Research Deployment
After use in the graduate course, the DSP-based system was deployed in a research setting to instrument a test vehicle for a research project. All hardware used duplicate configurations to the equipment found in the graduate and undergraduate courses. Because the DSP system was relatively low cost ($1000) and highly integrated with MATLAB and Simulink through a parallel-port interface, the extension to a vehicle, Differential GPS system, and steering sensors was relatively straightforward. The architecture is shown in Fig. 4.

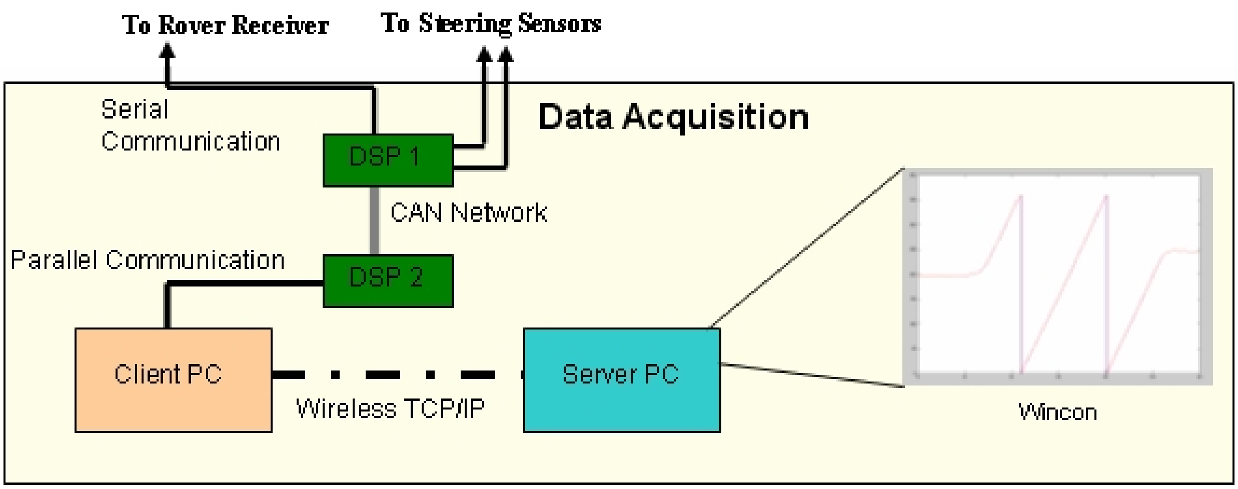

Fig. 4: Vehicle instrumentation architecture using DSP architecture similar to the course usage.

The dual Texas Instrument DSP's are the heart of the current data acquisition system. Interfacing with the DSP chips is accomplished through standard address and data-bus pin headers. The pin headers allow for expansion via custom designed daughter cards such as the Digital I/O and CAN boards used in this project. The TI DSP's allow for the boards to be programmed via Code Composer Studio (CCS) – a standard C-code programming suite included with the developer's kit.

Discussion:
An unanticipated benefit of the above integration is the cross-training between graduate and undergraduate students and co-use of equipment. If a laboratory system stopped working, not only was research hardware on hand to substitute for that equipment, but graduate students highly trained in the equipment were often the TA's for the undergraduate course. In this manner, many system faults and bugs were readily worked out with minimal assistance from the author after setup.

Another unanticipated benefit of the integration efforts described here were the number of serendipitous meetings between faculty of other students and the author, in order to set up new research projects and learning activities. So heavy is the demand for such capability that the author is now often having to turn away interested parties due to possible over-commitment of equipment resources.

An unanticipated challenge to the system usage is the need to support industry-level development tools. These tools, namely the compiling software, require computing permissions not typical of the normal student, or even the normal faculty. Because undergraduates are not normally allowed administrator privileges on campus machines, workarounds had to be found to allow some of the software systems that assumed these privileges to be available to operate.

In summary, having completed development of such a complex system, the author would strongly encourage others to foster such a tight integration of data-acquisition capabilities within their respective research and teaching endeavors.

Acknowledgements

The author wishes to thank _________ from ___________ for all his support in developing this system. Without his expertise, guidance, and shared code, a project endeavor of this magnitude would not have been possible for a single faculty or even department worth of faculty!

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