DEVELOPMENT OF A MECHATRONICS AND INTELLIGENT SYSTEMS LABORATORY FOR TEACHING AND RESEARCH

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Abstract

This paper reports the development of a laboratory for undergraduate and graduate level teaching and research in the areas of Mechatronics and Intelligent Systems in the Department of Mechanical Engineering at Georgia Southern University. The laboratory covers mechatronic instrumentation, control and mobile robotics. The broad topics include sensors, actuators, data acquisition, modeling, simulation, analysis, design and implementation of controllers, and swarm robotics. The laboratory provides an integrated hardware and software environment from basic instrumentation to rapid control prototyping, hardware-in-the-loop investigations, and intelligent robotic systems.

Introduction

Recently there is a growing emphasis on multidisciplinary education and research, especially involving science, technology, engineering and mathematics (STEM), both within and outside the US[1-8]. The shift in emphasis from traditional discipline-specific to multidisciplinary domains, specifically in the US, is due to a host of factors that include budgetary pressure and the need to retain competitive edge of US in innovation through STEM education and research for the 21st century. Multidisciplinary research is viewed as a means to revitalize STEM education providing real-world, hands-on research experiences to students for better recruitment, retention, progression and graduation[9-17]. Education research also supports and advocates the learning centered environment for engineering education in the 21st century[18-24]. Mechatronics, Robotics and Computational intelligence (CI), derived from inspirations from the nature, can be used as important tools for multidisciplinary education and research[25-36].

Mechatronics and Robotics integrate multidisciplinary concepts leading to application-based systems that can be made adaptive and intelligent. Such systems have to act proactively in view of the predicted system status in an unknown, uncertain and changing environment leading to development of intelligent autonomous systems. These systems form a broader class of newly-coined cyber-physical systems or CPS. In a CPS, the cyber resources representing computing, communication and control combine and coordinate with physical resources. For development of CPS systems, CI techniques are used as inspired by nature. These systems have the unique ability to learn and adapt to new situations utilizing the processes of generalization, abstraction and association with inspirations from nature[31-36]. There is a need to expose engineering students to the areas of Mechatronics, Robotics and Intelligent Systems for better understanding of the real-life complex systems and their future development[37-50]. It is also important to introduce these systems and their applications in the K-12 education through avenues of federal programs and initiatives for encouraging school students to join STEM disciplines. The development of "Mechatronics and Intelligent Systems" in the Mechanical Engineering Department at Georgia Southern University was motivated by the need to provide an integrated learner-centered environment and exciting opportunities for research at undergraduate and graduate levels.

The rest of the paper is organized as follows. In the first section, lab facilities that include the hardware and software platforms are discussed. Various experiments that are currently offered for different courses are briefly presented next. A few experiments are discussed as examples. It is followed with a discussion on the currently on-going research projects and topics. The survey results for the courses offered in the lab so far are presented next with concluding remarks in the final section.

Lab Facilities

The lab equipment are grouped in six broad areas: (i) basic instrumentation and measurement, (ii) digital logic and microcontroller programming, (iii) mechatronics sensors with integrated data acquisition interface, (iv) DC motor control with integrated interface, (v) advanced control of multi degree of freedom systems, and (vi) mobile robotics. Figures 1(a) and (b) give some overall views of the lab.

(a)

(b)

Figure 1. Overall views of the lab (a) from the front, (b) from the middle.

In addition to the devices for basic instrumentation and measurement, the lab is well equipped with a number of educational hardware platforms[51,52] including (i) mechatronics sensor modules, (ii) DC servomotors, (iii) multi-degree-of-freedom systems, both translational and rotational, along with inverted pendulum as accessories, and (iv) magnetic levitation module. The lab has PCs equipped with National Instruments (NI) data acquisition cards of different capabilities including multi-purpose I/O: 6010M, 6251M, and reconfigurable I/O 7831R[53]. The lab has NI ELVIS II platforms for interfacing the mechatronics and DC servomotor modules with PCs. All the computers have latest software such as MATLAB[54] (R2012a) with all toolboxes and LabVIEW 2012. For rapid control prototyping and hardware-in-the-loop investigations, the lab also has xPC real-time target platforms (both Educational and Performance kits) with accessories and I/O modules[55]. The lab has mobile robotic platforms of different shapes, sizes and capabilities: Boe-Bot from Parallax Inc.[56], NXT from LEGO Mindstorms[57], Create from iRobot[58], e-puck[59] from EPFL, Switzerland and Khepera III[60] from K-team, Switzerland. In addition to these fully operational mobile robots, the lab has open platforms with the mobile base and hardware for developing and implementing project based robots. In addition to the PCI based NI DAQ cards, there are a number of NI USB-6009 cards for mobile data acquisition applications.

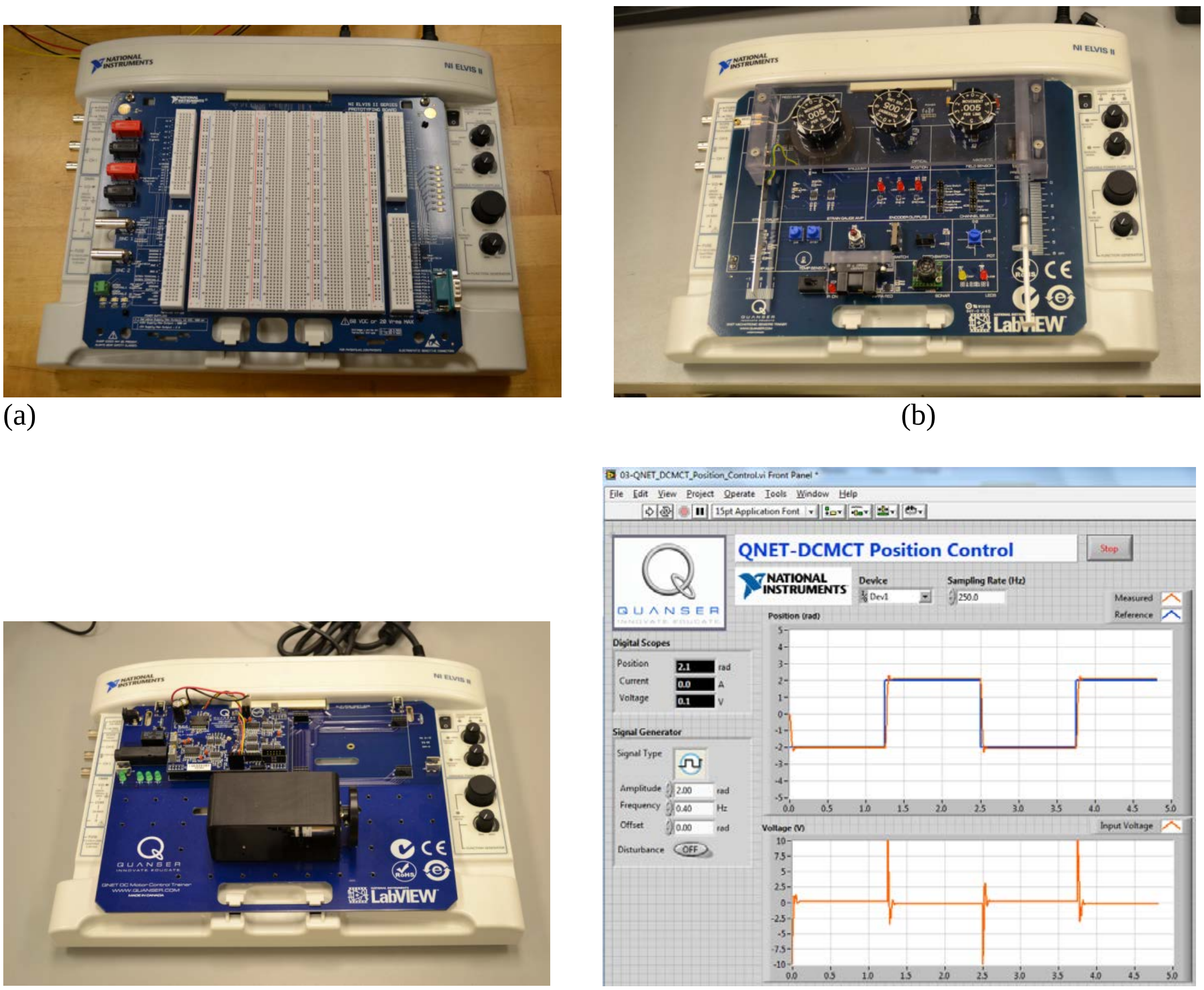
The equipment and facilities in each group are briefly discussed in the following subsections.

Basic Instrumentation and Measurement

The lab has 8 work stations for basic instrumentation and measurement, each equipped with a DC power supply, a digital multimeter, a function generator, a digital storage oscilloscope and a Pentium 4 HT PC. In each work station, students can perform experiments that include basic RC, RL circuit characteristics; analog signal manipulation using operational amplifiers; sensors like strain gages, thermocouples, load cells, encoders and their interfacing. Each PC is also equipped with National Instruments data acquisition (NI DAQ) hardware (NI PCI-6010) and LabVIEW for digital data acquisition and signal processing.

NI ELVIS II[53]

The ELVIS II is an educational design and prototyping platform (from National Instruments) which provides the functionality of a digital storage oscilloscope, function generator, digital multimeter, power supply and, breadboard all in one package. The ELVIS II communicates with a computer over a USB connection and has expandable functionality through applications available from National Instruments. The ELVIS II can also be used as a data acquisition system; it can monitor analog and digital IO lines at a sampling rate of up to 1 kHz. Figures 2(a)-(c) show NI ELVIS II platforms with prototyping board and QNET trainers. Figure 2(d) shows the screenshot of the DC motor position control results in one of the experiments conducted by the students in a course using ELVIS II.



(a) (b) (c) (d)

Figure 2. NI ELVIS II platform (a) Prototype board, (b) QNET Mechatronics Sensor Trainer, (c) QNET DC Motor Trainer, (d) DC Motor position control results.

Quanser QNET Mechatronics Sensor Trainer[51]

The QNET Mechatronics sensor trainer board is a platform for introducing various sensors and their calibration through data acquisition and analysis in the LabVIEW environment. Pre-designed experiments allow students to acquire data from transducers that include optical encoders, potentiometers, IR sensors, ultrasonic sensors, thermistors, and barometric pressure sensors. Strain and vibration can also be measured through a strain gage and piezo film vibrometer. All of the necessary data acquisition and computer interface are provided within the NI ELVIS II platform.

Quanser QNET DC Motor Control Trainer[51]

The Quanser QNET DC motor control trainer board is a platform intended to interface with the NI ELVIS II. The control trainer consists of a PWM amplifier, DC motor and optical encoder, and circuitry necessary to sense motor speed and position. The interface with the ELVIS II board provides the ability to send control signals to the motor from a computer and record the on-board sensor data using the integrated data acquisition system.

M Series NI DAQ cards PCI-6010 and PCI-6251[53]

The NI PCI-6010 is a low-cost 16-Bit, 200 kS/s, 16 analog input and 2 analog output multi-function DAQ. The NI PCI-6251 DAQ is available for high speed data acquisition. This card provides 16 analog inputs that can be sampled at 1 MS/s in multi-channel mode and up to 1.25 MS/s in single channel mode. The card also has 24 digital I/O lines and 2 analog output channels that can be controlled easily in the NI LabVIEW environment.

RIO FPGA DAQ PCI-7831R[53]

The NI PCI-7831R reconfigurable I/O (RIO) data acquisition card with integrated Virtex-II 1M logic gate FPGA (Field Programmable Gate Array) is available for high speed data acquisition and control. The card has 8 analog inputs with independent sampling rates up to 200 kHz, 16-bit resolution, ±10 V range, and 8 analog outputs with independent update rates up to 1 MHz, 16-bit resolution, ±10 V range. There are also 96 digital lines that can be configured as inputs, outputs, counters, or custom logic at rates up to 40 MHz.

ECP Experimental Modules[52]

A whole range of physical plants from ECP (Educational Control Products) are used for dynamics and control system laboratory experiments. Figures 3(a)-(c) show some of the ECP modules in the lab. Figure 3(d) shows the response of the torsional system bump test (with a step input of 2 V for 1.5 s and then step back to 0 V) for one of the system identification experiments. The rectilinear motion plant consists of interconnected cart masses, springs and dampers that are all driven by a servo motor on a rack and pinion. The torsional plant is comprised of rotating disks on a bearing shaft made of thin gage steel that provides torsional stiffness. Like the rectilinear plant, the torsional plant is driven by a servo motor but the power transmission is accomplished by a belt and pulley drive. Both the rectilinear and torsional plants use industrial grade quadrature encoders with 16,000 pulses per revolution resolution for obtaining cart and disk speed and position feedback data. Both the rectilinear and torsional plants also have an option of incorporating an inverted pendulum to investigate coupled non-linear dynamics. The third available plant is the one dealing with magnetic levitation. This plant provides two electromagnetic coils for controlling the levitating position of metallic disks between the two coils by way of adjusting coil current. Laser range finders are used to determine the disk position along the levitation path to provide feedback for control applications. All of the plants come with appropriate power amplifiers and termination blocks that allow easy acquisition of system sensor data and provide control signals to the actuators through NI DAQ/RIO cards.

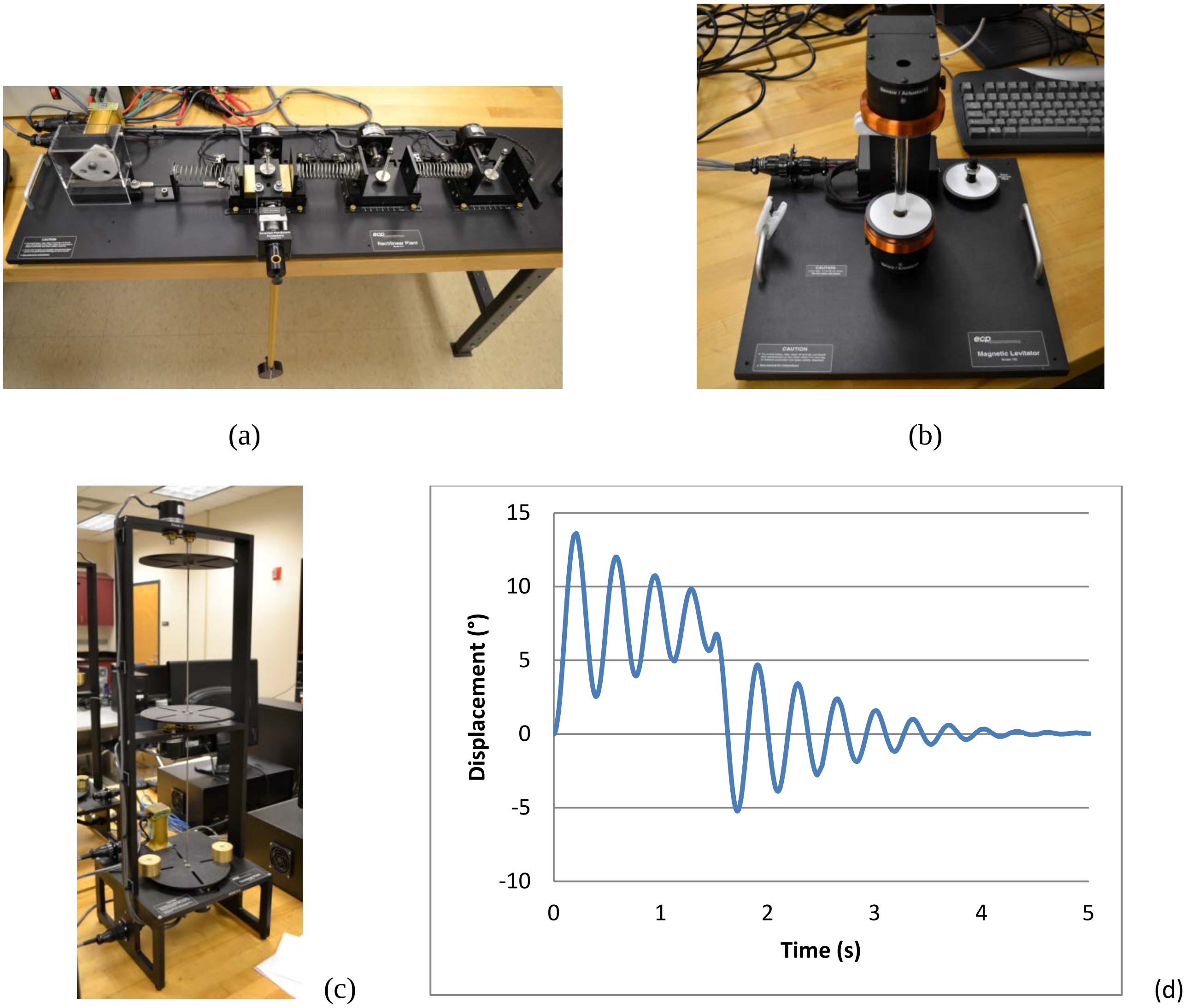


Figure 3. ECP experimental modules (a) Rectilinear System, (b) Magnetic levitation, (c) Torsional system, (d) response of the torsional system bump test for the system identification experiment.

xPC Target and Speedgoat Real Time Target Machine[54,55]

The laboratory computers have MATLAB software with xPC Target; Mathworks real time design and control software suitable for hardware-in-the-loop (HIL) design. Mathworks Simulink software can be used for simulation of systems and, when the simulation is completed, it can develop standalone applications for continuous real time operation through xPC Target on a x86 based industrial computer. The Speedgoat educational and performance real time target machines were chosen for interaction with xPC target in the HIL education and research. The real time target machines have two PCI data acquisition cards that provide 136 channels of analog and digital I/O.

Basic Stamp Discovery Kit[56]

The Basic Stamp Discovery kit is a microcontroller development platform from Parallax that is based on the Basic Stamp II. The Basic Stamp II operates at 20 MHz with 16 available digital IO lines. The Discovery kit covers basic embedded electronics and controller programming using the Basic Stamp's native programming language PBASIC. As the name suggests PBASIC is a specific command set of the Basic programming language suited for use with the microcontroller. The Basic Stamp Discovery kit includes a servo motor, a piezo-speaker, one seven-segment display, and a host of passive electronic components that coordinate with the included detailed sample experiments. The Basic Stamp development board (called the Board of Education) connects to a computer via a USB connection and Parallax provides a free integrated development environment called the Basic Stamp editor that is used for program design.

Parallax Boe-Bot Robot[56]

The Boe-Bot by Parallax is a mobile robotics platform based on the Basic Stamp II microcontroller. The Basic Stamp II is an 8-bit microcontroller operating at 20 MHz with 16 available digital IO lines. The robot uses the same Board of Education development board used in the Basic Stamp Discovery kit. Communication with a computer is performed over a USB connection, a free program development environment is available and the controller is programmed using the PBASIC language. The robot can interface with a variety of sensors to aid in navigation (such as touch, infra-red, ultrasonic, and color). Figures 4(a)-(c) show some of the mobile robotic platforms used for teaching and research in the lab.

LEGO Mindstorms NXT Education kit[57]

The Lego Mindstorms education kit is a microcontroller based development platform that is programmed through the device user interface, or through USB communication with NXT software that is based on LabVIEW. The programming is similar to creating a flowchart of the desired logic, and the resulting software can interface several sensors and actuators. The Lego Mindstorms NXT kit includes three servo motors, and sensors such as touch, sound, ultrasonic, and light. All of the basics of a measuring and actuating system are accompanied by a variety of Lego Mindstorms construction materials that are helpful in prototyping and robotics projects.

iRobot Create[58]

The iRobot Create is an educational mobile robot platform modeled after the iRobot Roomba. The robot uses an 8-bit, 18MHz Atmel ATMega microcontroller for interaction with the drive system and the 30 on-board navigational sensors, including optical encoders, touch and infra-red sensors. The Create platform is intended for stability and strength to provide the capability of user expansion. The robot can be programmed generally in the C and all communication is done over logic level serial connection. It can also be programmed in LabVIEW and MATLAB environments.

(a) (b) (c)

Figure 4. Mobile robotic platforms (a) Boe-Bot, (b) e-puck, (c) Khepera III.

GCtronic e-puck[59]

The GCtronic e-puck is a miniature mobile robot platform designed for education and research. At its core is a 60 MHz dsPIC microcontroller with digital signal processing capabilities. The little robot has 8 proximity sensors, a three dimensional accelerometer, 3 omni-directional microphones, a VGA camera, and an infra-red receiver; it also has plenty of measurement devices for data collection and navigational aid. The e-puck can be programmed in the C language over a bluetooth or serial connection. Another feature of the e-puck is its expandability. Through modules that can be added to the platform as needed, the robot can also have a high definition camera, a co-processor or the capability of wireless communication with other robots.

K-Team Khepera III[60]

The Khepera III is a robot platform produced by the K-Team. The robot is based around a dsPIC30F5011 microcontroller operating at 60 MHz. The platform incorporates brushed servo drive motors with 8 infra-red proximity and 5 ultrasonic sensors for navigation. Communication is done through logic level serial, USB or over Wi-Fi; any of which can be used for remote control from MATLAB or LabVIEW. Programming of the robot is done via a free integrated development environment with a C language compiler.

Courses and Experiments

The lab is to provide a learner-centered environment for the following courses in the Mechanical Engineering Department at Georgia Southern University.

a. Introduction to Mechatronics (TMET 2521)
b. Mechatronics Studio (MENG 3521)
c. Control (MENG 5536)
d. Mechatronics I (TMAE 7136)
e. Mechatronics II (TMAE 7137)

Of these courses, the first two are at the undergraduate level. The first course is offered in the Mechanical Engineering Technology program and the second course is introduced in the new Mechanical Engineering program. The third course is open to senior undergraduate and graduate students in the Department. The last two courses are offered to graduate students. Experiments are designed at appropriate levels for the courses. For example, for the first two courses, students conduct experiments in the areas of basic instrumentation and measurement, data acquisition and signal processing (using NI DAQ-6010 and LabVIEW), digital logic and microcontroller programming (mainly using Basic Stamp Discovery kits). The second course has a more analytical approach than the first to differentiate between the requirements of the two programs. For the Control course, students do experiments using the QNET DC motor modules with ELVIS II in the areas of system characteristics, system identification, closed loop control system analysis, design and implementation for motor speed and position. For Mechatronics I, experiments are offered using QNET Mechatronics sensor modules with ELVIS II to study the characteristics of different sensors and their interfacing, data acquisition and signal processing, digital logic and microcontroller programming. For Mechatronics II, the experiments include system identification, control system analysis, design and implementation using the ECP modules and LabVIEW with appropriate NI interface (DAQ-6251 or PCI-7831R, depending on the ECP module).

In each course, students are required to do experiments related to the topics covered in the classes in the first 10 weeks. In the remaining weeks of the semester, students work on the projects integrating the topics covered in the course and making use of the hardware and software support available in the lab. The data acquisition and analysis are mainly conducted in NI LabVIEW environment. The modeling, analysis and simulation studies are done using the MATLAB/SIMULINK environment. The rapid control prototyping and hardware-in-the-loop investigations are done using LabVIEW and MATLAB xPC Target environments.

Figure 5 shows the experimental setup for position control of a rectilinear system. Figure 6 shows the block diagram (VI) in the host PC that gets the encoder data from the FPGA card, calculates the control voltage using PID control algorithm, and gives the control voltage to the FPGA card output channel. The FPGA VI reads the encoder data, calculates the cart position from the encoder data and passes the host VI calculated output control voltage to the motor. The front panel for the host block diagram is used as the user interface for setting up different controls like Start/Stop, sample time, sample size and graphical outputs.

Figure 7 shows the results of a PID controller implemented on the cart-pole system. The motor response follows closely the desired command signal.

Projects and Research

In addition to the above-mentioned regular courses, the lab is also utilized for conducting undergraduate and graduate research on mechatronics and intelligent systems. Students also use the lab facilities for their Independent Studies. Some of the undergraduate projects include convoy formation using Boe-Bot, and swarm robotics using NXT. Graduate students use the lab facilities for their independent study courses, projects and theses. Current graduate students' thesis topics include intelligent control of nonlinear dynamic systems, magnetic levitation and co-operative control of heterogeneous robot swarms in dynamic environments. Students work on traditional control algorithms like PID, phase lag-lead controllers as well as artificial intelligence based techniques like artificial neural networks (ANN), fuzzy logic and Adaptive Dynamic Programming (ADP).

Figure 5. Experimental setup for position control of a cart-pole system.

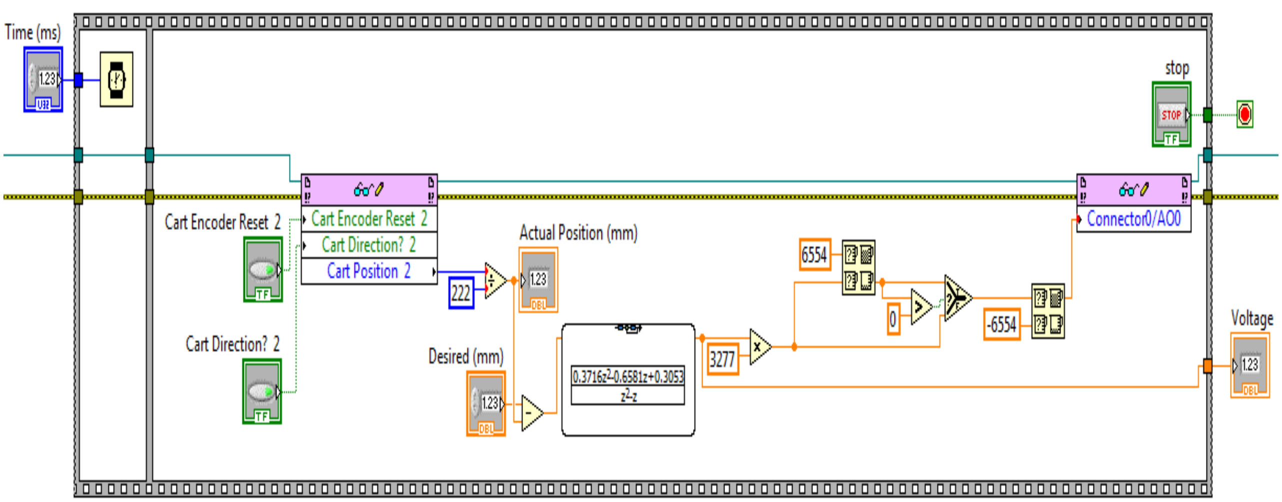


Figure 6. Block diagram VI in the host PC for control calculation and interfacing the FPGA card.

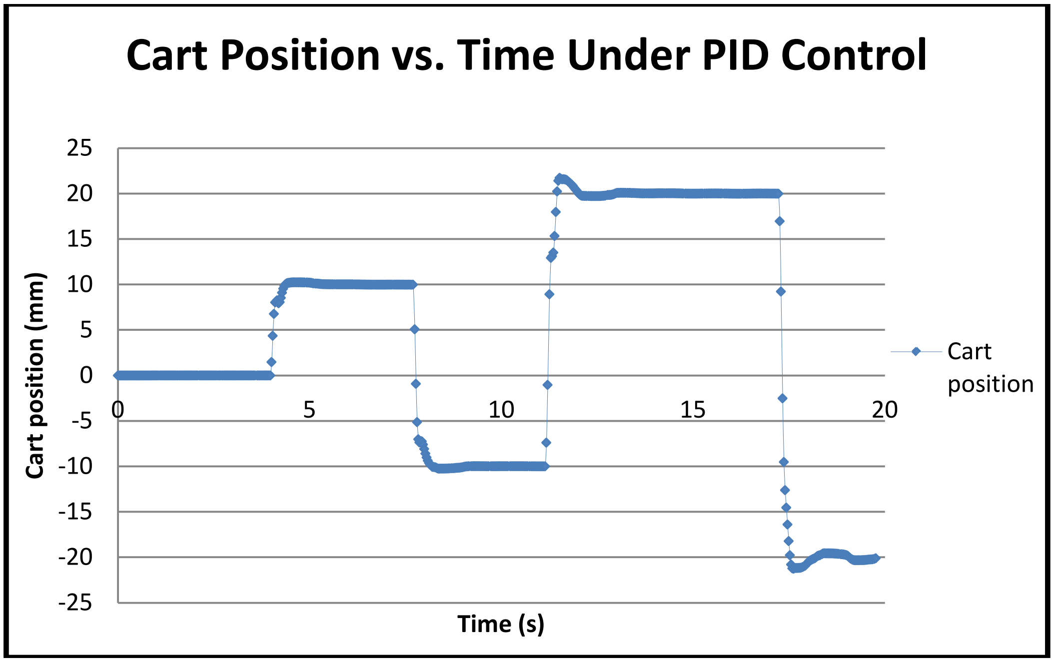


Figure 7. Results of position control of a cart-pole system.

Survey Results

The lab facilities were available to the students taking Introduction to Mechatronics (TMET2521) and Mechatronics II (TMAE7137) in Fall 2011, with the class size of 9 and 7 respectively. The students were given end of course surveys to assess the effectiveness of the lab facilities. In the present paper, only the overall effectiveness of the lab facilities was assessed through surveys. The assessment of individual experiments in terms of learning outcomes and specific skills will be reported in future papers. For the current work, the students were asked to give their rating on the usefulness of the lab facilities in learning and understanding the course materials and their applications in the course projects, in the scale of 1-5, (5 being the highest). The students were asked to rate each topic of the course. For this paper, we are only concentrating on the overall rating of the lab.

For the undergraduate course survey, one student gave 3, three students gave 4 and the rest gave 5 with an average of 4.44 (out of 5). For the graduate course, two students gave 4 and the rest gave 5 with an average of 4.71. In Spring 2012, the lab is being used for Mechatronics I (TMAE7136) with 11 graduate students. These students were given a mid-semester survey on the usefulness of the lab facilities, similar to the ones given in the previous semester. Among these 11 students, 3 gave a score of 4 and the rest gave 5 with an average of 4.74.

In addition to the quantitative response, the students were also asked to give their comments for qualitative analysis. Many of the students provided positive feedback in their comments that include "*The lab experiments were great in learning the course material*", "*The robot project was enjoyable and helped me learn a lot of things in an integrated manner*", "*The lab experiments provided valuable control implementation experience*", "*The NI ELVIS II board is a very handy trainer board for learning mechatronics*", "*The ELVIS II and LabVIEW are very useful in understanding the mechatronic sensors and devices*", " *I enjoy that the class applies all of the information to real world ideas*", "*Progression of labs was appropriate with each becoming slightly more difficult than the last. NXT robot project is exciting*", "*LabVIEW is awesome and should be integrated into other courses in the Department. I learned a lot from build-*

ing a VI for thermocouple and also working with ELVIS II. I like using LabVIEW to program the robots instead of C or MATLAB".

The scores, though based on very small class sizes, indicate high level of students' positive view on the usefulness of the lab facilities. In addition, the students' engagement and interest in conducting laboratory activities, completing their course projects and independent studies, even in hours beyond their normal schedules show the encouraging and engaging learning environment the lab facilities offer. It is also worth mentioning that out of 7 graduate students in Mechatronics specialization in Spring 2012, 4 are working on their MS Theses in the lab. All these, along with the positive feedback, indicate the usefulness and effectiveness of the lab facilities in teaching and research at both undergraduate and graduate levels.

Conclusions

The "Mechatronics and Intelligent Systems" lab in the Mechanical Engineering Department at Georgia Southern University provides an integrated hardware and software environment for multidisciplinary education and research at undergraduate and graduate levels. The lab equipment and facilities cover a wide range of areas from basic instrumentation and measurement to rapid control prototyping, hardware-in-the-loop investigations, and intelligent robotic systems. The usefulness and effectiveness of the lab facilities were assessed using anonymous surveys of the students taking the courses related to the lab and the responses were very positive and encouraging, although the class sizes were initially relatively small. The interest from students, both undergraduate and graduate, to do research in the lab towards their senior level independent study courses and graduate theses confirm the positive impact the lab is having on the students. The class size and the number of students working in the lab for their independent study courses and graduate theses are expected to rise considerably in the coming semesters with the newly introduced Mechanical Engineering program at the University. The assessment of the lab effectiveness is being worked out as a part of the program-wide assessment and continuous improvement process for ABET accreditation. Currently, the lab is being utilized as a education and research facility for Mechanical Engineering students at sophomore or higher levels. In the future, it will be open to multidisciplinary teaching and research with other disciplines within the newly formed College of Engineering and Information Technology at Georgia Southern University. It is also being planned to extend the lab facilities, with additional support and in collaboration with other colleagues in the College, as a potential REU (Research Experiences for Undergraduates) site.

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