Development of Mobile Interfaces to Interact with Automatic Control Experiments

JARED ALAN FRANK and VIKRAM KAPILA

Mobile devices have been widely adopted in recent years. Market researchers and futurists forecast that personal computers (PCs) will become a relic of the past, being gradually overshadowed by low-cost portable devices like tablet computers and mobile phones [1]. Today's mobile devices have wireless network connectivity, granting users increased accessibility and mobility. In industry, engineers have already begun to leverage these benefits of mobile devices to perform their jobs more conveniently and collaboratively [2]. Companies that design applications (a.k.a. apps) for engineering say "people need tools equivalent with what they have on their desktop but that they can take with them wherever they go" [2]. In a similar vein, mobile applications that free users from being tethered to a PC to monitor, command, or control laboratory equipment can allow hands-on experiential learning to be accessible from virtually anywhere and at any time, including at unexpected moments. For instance, if an engineering student is reminded of a laboratory experiment while going about her daily life, a mobile app can enable her to connect with the experiment to examine her hypotheses immediately instead of waiting to access the laboratory on campus and possibly forgetting valuable ideas. That is, since new ideas often arise spontaneously, mobile devices may support the creative learning process [3].

As people increasingly connect with each other by using their mobile devices, students can use their mobile devices to not only interact with laboratory test beds but also with each other by posting and sharing their findings in a quick and seamless manner. Thus, both on- and off-campus mobile learning has the potential to promote collaboration between students by allowing them to schedule their time to perform laboratory experiments together and provide each other with instant feedback. Such an approach also enables collaboration between team members, even in situations when some students are physically present in the laboratory and other students are participating remotely.

Today's mobile devices are equipped with sensors and features that can be used to interact with the laboratory equipment in novel ways as opposed to traditional mouse-and-keyboard interfaces. These mobile devices may even facilitate new forms of interaction with equipment that improve students' mental models and enhance their sense of telepresence, both of which have been acknowledged as having a significant impact on distance learning with remote laboratories [4]. Mobile devices may also be useful for students with situational impairments or special needs. Mobile applications can serve as interactive learning aids that provide supplemental content while guiding students through experimental steps. Learning may be facilitated by using mobile apps that have the same look and feel as the apps that students already use to play games, check the weather, and connect with friends and family.

As mobile devices begin to dominate the market and as laboratory equipment is increasingly connected to the Internet, there is an opportunity for laboratory instructors to recognize and respond to these changes by developing mobile apps for interacting with the equipment. Most reported incorporation of mobile devices thus far have been in virtual laboratories [5], [6] that use software to simulate experiments [7]. Although such laboratories have the benefit of allowing students to learn from mistakes without damaging remote equipment, student learning can be limited by denying them access to real data from real equipment [8]. The primary contribution of this article is to outline the development of several mobile apps for interacting with real physical test beds in an automatic control laboratory, both in the laboratory and remotely. Results are provided from a preliminary investigation of the usability and user experience associated with the applications, using students who would ultimately be the users of the applications when they are integrated into the curriculum. Implementation considerations such as the application development, wireless communication, hardware interfaces, and control are discussed. A microcontroller-based interface to the laboratory hardware provides a low-cost solution that can monitor, command, and control experiments via mobile devices.

EXPERIMENTAL SETUPS

This section introduces various approaches that can be used to control remote laboratory equipment and make the equipment accessible from mobile devices. Different setups use different hardware and software to handle the feedback control of the experiment and the wireless communication with the mobile devices. When designing a remote laboratory, these selections depend on a number of factors, including the available budget, the nature and the number of the test beds to be controlled, and the average number of students that are expected to *simultaneously* interact with the test beds.

Digital Object Identifier 10.1109/MCS.2014.2333312
Date of publication: 16 September 2014

 1066-033X/14©2014IEEE

PC-Based Data Acquisition and Control Approach: iPad and 3-DOF Helicopter Experiment

Figure 1 shows a hardware setup to wirelessly interface an iPad with a three degree-of-freedom (DOF) underactuated helicopter experiment using commercial hardware and software. The details of various components and operation of the helicopter test bed are provided in [9]. Both an iPad 2 and a laboratory PC are on a wireless local area network (WLAN), hosted by a wireless router located in the laboratory, and communicate over a Transmission Control Protocol/Internet Protocol (TCP/IP) connection. A mobile app allows a student to interact with the helicopter. A commercial data-acquisition-and-control board (DACB) interfaces the laboratory PC to the helicopter's sensors and actuators. A Simulink model running on the laboratory PC implements a linear quadratic regulator (LQR) that uses commands received from the iPad to control the helicopter. Live video of the helicopter is captured by a Web camera and streamed over the network from the laboratory PC. If the wireless router in this setup is connected to the Internet, the student may remotely interact with the test bed from anywhere with Internet access.

Hybrid PC/Microcontroller-Based Approach: iPhone and Magnetic Levitation Experiment

Figure 2 shows a hardware setup to wirelessly command and monitor a magnetic levitation experiment with an iPhone. This setup uses a microcontroller and Wi-Fi module to wirelessly interface the iPhone to the test bed and a commercial DACB to interface the test bed to a laboratory PC. The details of various components and operation of the magnetic levitation test bed are available in [10] and [11]. The use of the microcontroller and Wi-Fi module provides a low-cost solution that replaces a wireless router while allowing a separate ad hoc network to be hosted for each experiment. Although this setup supports groups of students who wish to work collaboratively with an experiment by connecting their mobile devices to the ad hoc network, connecting experiments that use this setup to the Internet requires a separate connection for each ad hoc network. An Arduino UNO microcontroller establishes a serial communication link with the laboratory PC and a serial peripheral interface (SPI) connection with a WiFly shield, which is an expansion board that provides the microcontroller with Wi-Fi capability. Using an iPhone interface, the student can issue commands for the height of a levitating steel ball and receive sensor feedback from the test bed, as well as perform all steps of the experiment from calibrating sensors to changing control parameters and obtaining the resulting response of the test bed. A Simulink model running on the laboratory PC is used to implement the control algorithm. A variation of this setup, where the microcontroller also replaces the DACB, can be implemented to collect sensor data and transmit control signals to the experiment. However, for the magnetic levitation experiment, feedback control necessitates sampling rates beyond the capabilities of the microcontroller. In general, when selecting a data acquisition and control solution, it is important to be aware of the requirements imposed by the nature of the signals involved, such as the frequency content of sensor signals and protocols used by digital sensors.

Microcontroller-Based Wi-Fi Approach: iPod and Two-Tank Experiment

Figure 3 shows a low-cost setup used to wirelessly command and monitor a two-tank experiment with an iPod Touch. This setup uses the microcontroller and WiFly shield not only for the wireless communication but also for implementing a control algorithm for regulating the water level in the lower tank to the level set by the student from her iPod. The details of various components and operation of the two-tank test bed are available in [10]–[12]. Data acquisition and control are facilitated by using SPI connections to interface the microcontroller with a low-cost analog-to-digital convertor (LTC1296) and a digital-to-analog converter (MAX537). Similar to the setup used to control the magnetic levitation experiment, if the WiFly shield is configured to connect to the Internet, students can access the experiments from outside the laboratory.

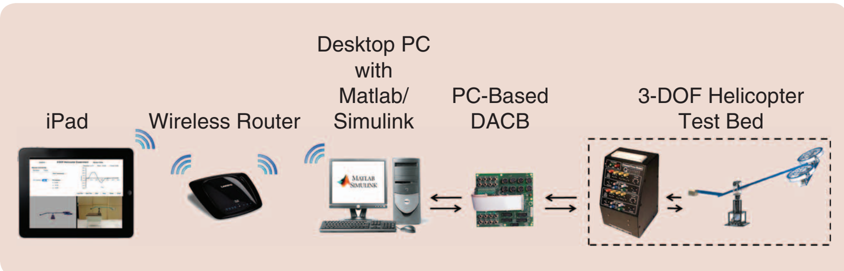


FIGURE 1 The setup for interfacing an iPad with the 3-DOF helicopter experiment.

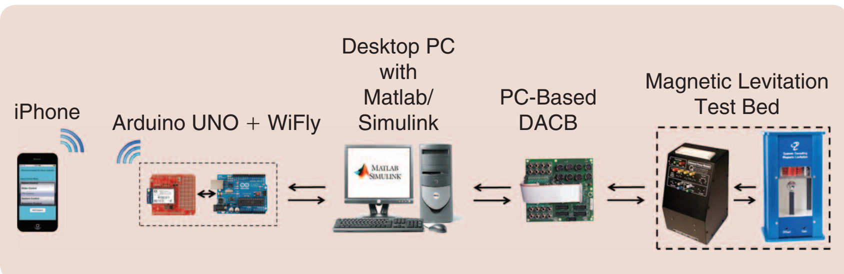


FIGURE 2 The setup for interfacing an iPhone with the magnetic levitation experiment.

Microcontroller-Based Ethernet Approach: iPhone 5 and dc Motor Experiment

Figure 4 shows a hardware setup used to support wireless interaction with a dc motor experiment test bed over the Internet using an iPhone. Like the setup used to control the two-tank experiment, this setup also uses the Arduino microcontroller to implement a control algorithm; however, no WLAN or ad hoc network is being hosted for connecting to the in-lab test bed. Instead, an Ethernet shield is used to directly connect the microcontroller to the Internet. Therefore, students must have Internet access either via a cellular network, such as 3G or 4G LTE, or via some other wireless network, such as used in the home or the laboratory. The details of various components and operation of the dc motor test bed are available in [10] and [11]. The microcontroller implements a control algorithm to regulate the angular position of the motor arm to the position set by the student from her iPhone. As in the two-tank experiment, LTC1296 and MAX537 electronics are used to convert between analog and digital signals.

CONTROL AND COMMUNICATION IMPLEMENTATIONS

Feedback control and network communication for each experiment are implemented either on a laboratory PC using a graphical model in the Matlab/Simulink environment or on a microcontroller using a C-based language. This section describes these implementations in detail. The network communication implementation for each experiment test bed is considered to be the server for the experiment, while the mobile devices that connect to the experiment are clients. The networks use the standard TCP/IP communication protocol. Since the control algorithm for each experiment is implemented locally on the server side, any network delays between the server and mobile devices will not affect the closed-loop performance of the experiment. Thus, the closed-loop response of the experiment remains unchanged by in-lab or remote access to the experiment. Unwarranted network delays can cause a lag in the communication of 1) user commands to the server or 2) sensor data from the server to a mobile client. As discussed below, these issues can be alleviated to some extent by using buffers.

Helicopter Controller

For the helicopter experiment, an LQR controller is used to stabilize two of the helicopter's 3-DOF. The Simulink model for the helicopter experiment is composed of two main subsystem blocks [see Figure 5(a)]. The "helicopter tracking control" subsystem collects sensor measurements from the helicopter's optical encoders; implements the LQR control law, with integral control for setpoint tracking, to control the travel and elevation of the helicopter; and transmits the control signals to the DACB. The "iPhone communication" subsystem block [see Figure 5(b)] acts as a server communicating with the iPad client over a TCP/IP connection. The iPhone communication subsystem is responsible for both sending the sensor data from the helicopter experiment to the iPad and receiving the student's commands from the iPad. The Wi-Fi messages are formatted as strings by using a prefix-value-terminator (PVT) protocol [13], which consists of capital letter headers delimited with the standard carriage return-line feed combination (CR+LF, '\r\n'). The PVT protocol makes it easy to interpret messages by their capital letter header. For example, messages sent to the iPad with the travel, elevation, and pitch angles begin with the characters "T," "E," and "P," respectively, which helps each device agree on the meaning of the information in each message. Live video is captured from a Web camera, and a media stream segmenter and Windows Apache MySQL PHP (WAMP) server are used for splitting

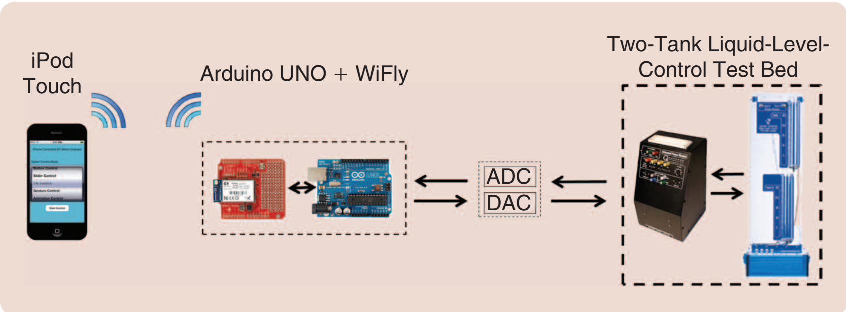


FIGURE 3 The setup for interfacing an iPod Touch with the two-tank experiment.

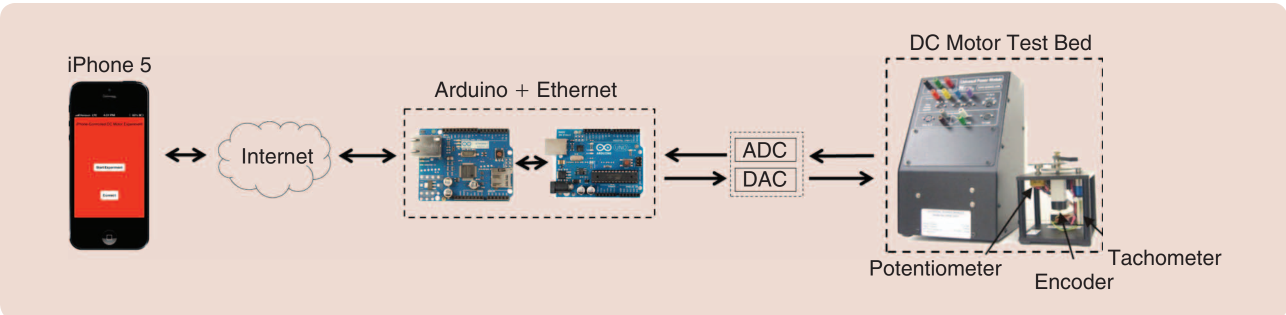


FIGURE 4 The setup for interfacing an iPhone 5 with the dc motor experiment over the Internet.

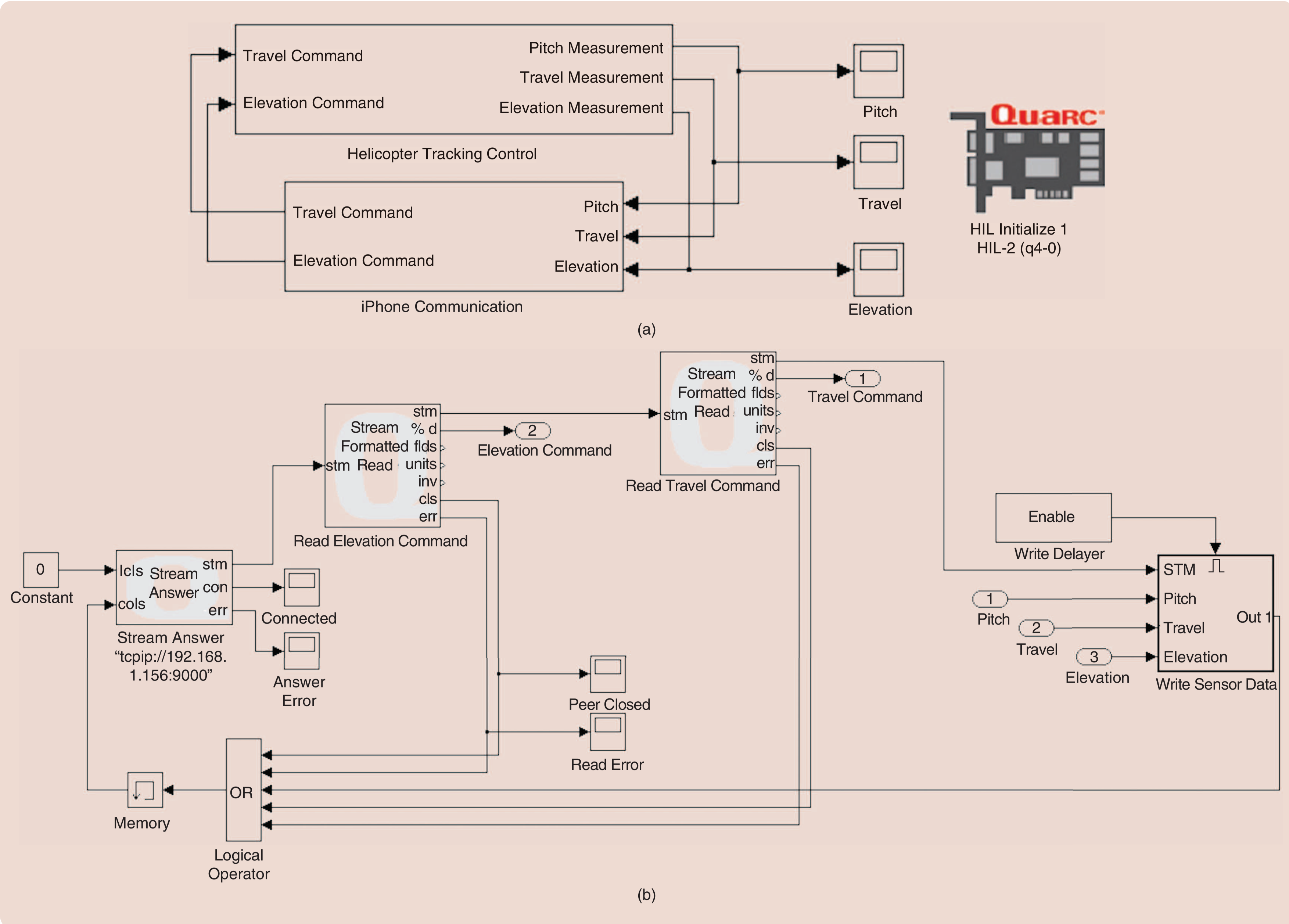


FIGURE 5 (a) A Simulink model for controlling the 3-DOF helicopter test bed with an iDevice and (b) an iPhone communication subsystem block for the 3-DOF helicopter experiment.

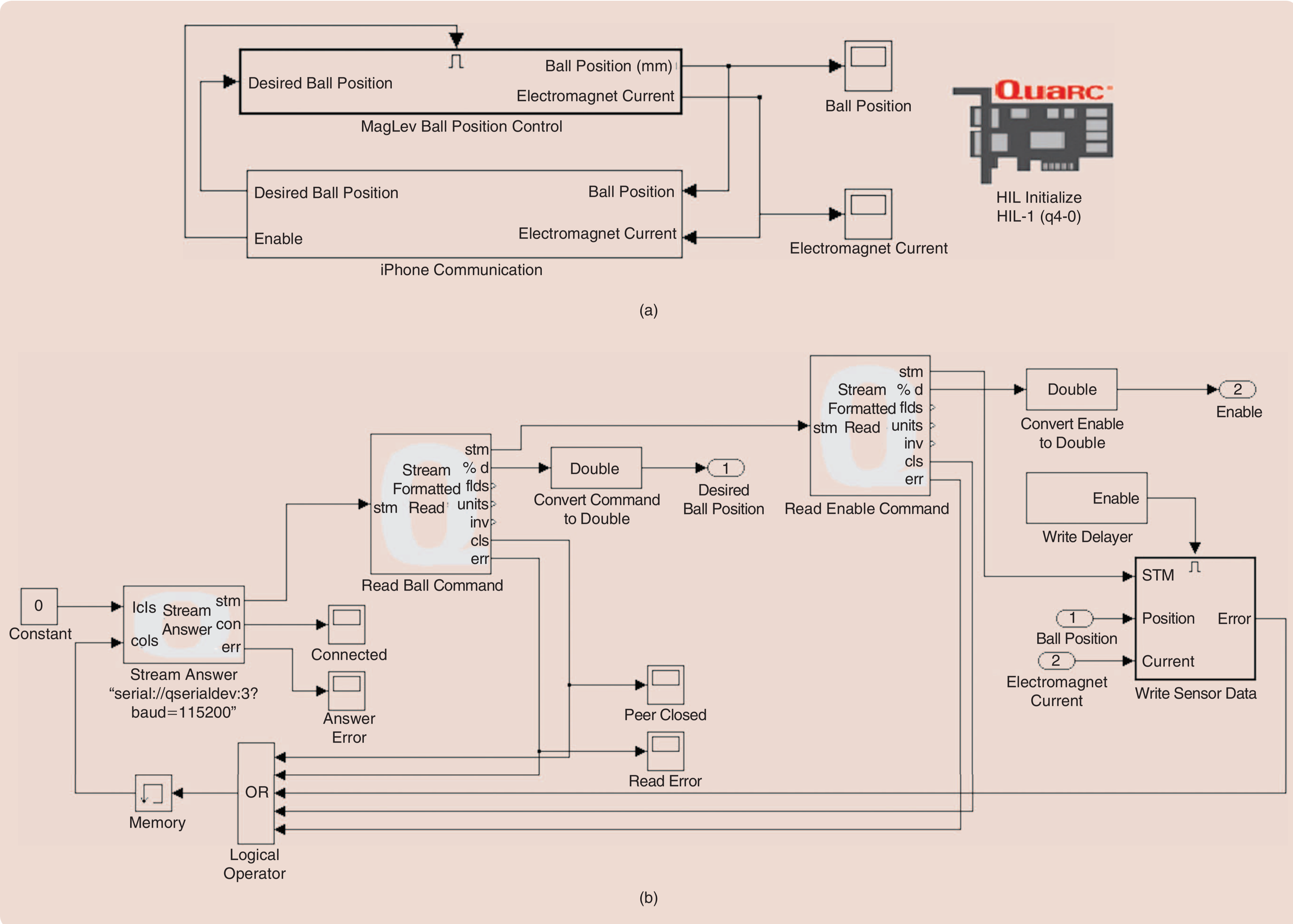


FIGURE 6 (a) A Simulink model for controlling the magnetic levitation system with an iDevice and (b) an iPhone communication subsystem block for the magnetic levitation system.

the video into 1-s-long segments and streaming the segments over the network. The server, implemented in the Simulink environment, can simultaneously handle multiple clients through the use of multiple iPhone communication subsystem blocks, with each connecting to a different network port.

Magnetic Levitation Controller

For the magnetic levitation experiment, a proportional-integral (PI) and a PI-derivative (PID) controller are designed to track the current through the electromagnetic coil and the position of the levitating ball, respectively [10], [14]. Analogous to the helicopter experiment, the Simulink model for the magnetic levitation experiment is composed of two main subsystem blocks [see Figure 6(a)]. The "maglev ball position control" subsystem collects the sensor data from the experiment, implements the PI and PID controllers, and transmits the control signals to the DACB. The "iPhone communication" subsystem block [see Figure 6(b)] establishes serial communication with an Arduino microcontroller over a communication port of the laboratory PC at a baud rate of 115,200 bit/s. A message format similar to the helicopter experiment is used for interpreting sensor data and commands. The program running on the microcontroller acts as a server, relaying messages containing sensor data and reference commands between the iPhone client and the laboratory PC. An advantage of using an ad hoc network and implementing the server on the microcontroller is that multiple clients can be set up more readily.

Two-Tank Controller

For the two-tank experiment, an attached WiFly shield is used to implement the server, which accepts connections from the iPod client. The microcontroller program performs three tasks: 1) collects the sensor data from the two-tank experiment, 2) computes and sends control voltage signals to the experiment's power module, and 3) sends and receives sensor data and reference commands, respectively, using the WiFly shield to communicate with the iPod client. The control algorithms running on the microcontroller implement PI controllers [10], [12].

DC Motor Controller

For the dc motor experiment, a microcontroller with an attached Ethernet shield is used to connect the experiment to the Internet, and a Webserver is implemented to accept connections from up to four clients simultaneously. The microcontroller program performs the same three tasks as the microcontroller program for the two-tank experiment: 1) collects sensor data, 2) computes and sends control voltage signals to experiment's power module, and 3) sends and receives sensor data and reference commands, respectively, using the Ethernet shield to communicate with the iPhone client. The control algorithm running on the microcontroller implements a PID controller [10].

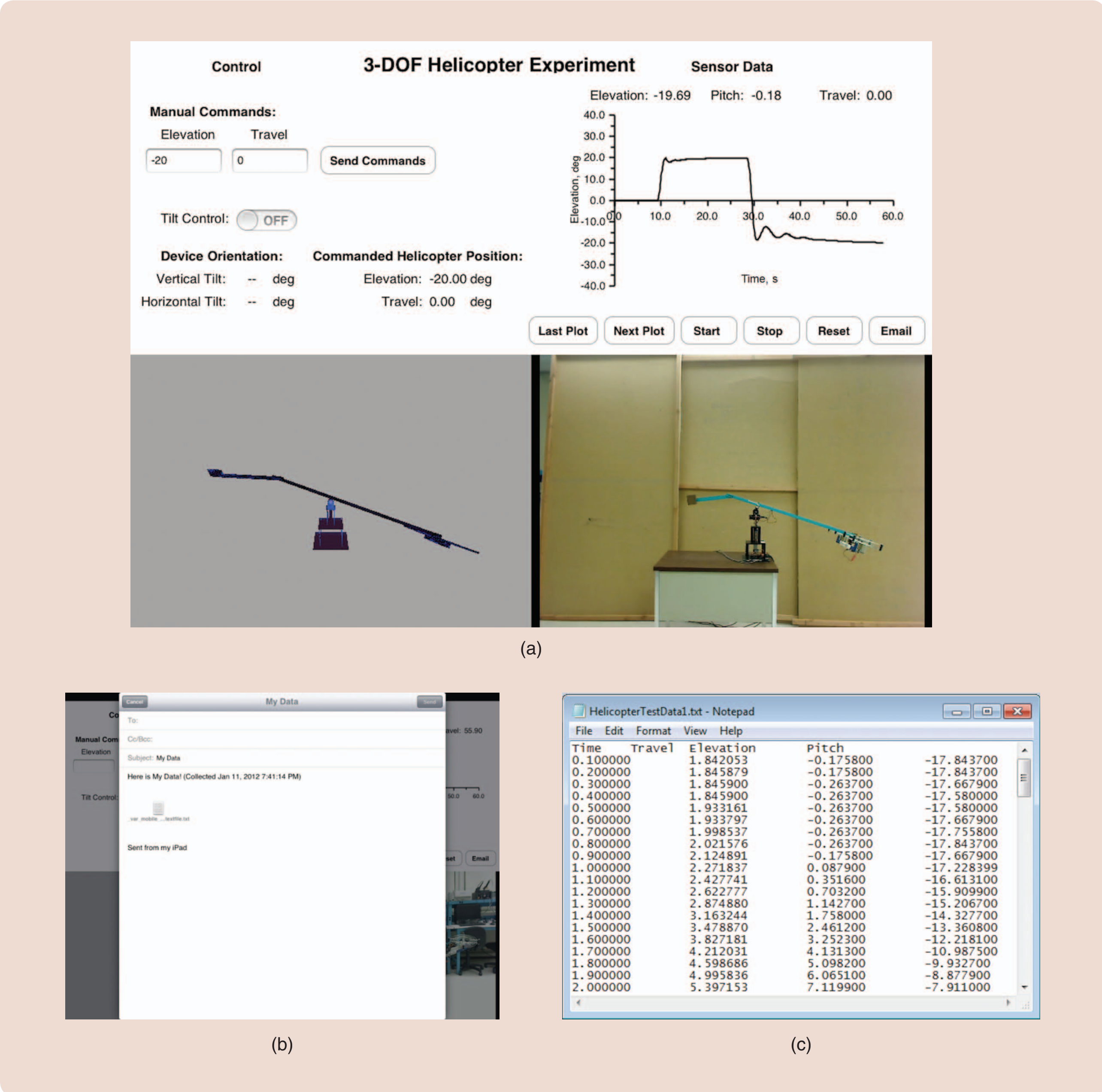
USER INTERFACES

Mobile applications have been developed for interacting with each of the experimental setups and have been tested on the iPod, iPhone, and iPad platforms. These iDevices are chosen because of their market penetration and their computational capabilities. Since the standard TCP/IP protocol is used for the network communication, applications for performing the experiments can be developed for alternative Internet-enabled devices, such as those that run the Google Android operating system. However, as seen below, the computational capabilities of Apple's iDevices make them a particularly suitable platform for applications to interact with laboratory experiments.

There are several factors to consider when developing applications for effective learning. It has been widely acknowledged that interactivity plays a crucial role in knowledge acquisition and the development of cognitive skills and that educational tools with higher levels of interactivity enhance learning potential [15]. The results of a study conducted with 111 students from multiple countries indicate that students prefer interactive content and animations when performing experiments online [16]. Thus, highly interactive applications may not only result in improved learning outcomes but also engage and stimulate student interest [17]. In this spirit, approaches that leverage the interactivity of mobile applications are being developed to support the teaching of science concepts [18].

Responsiveness is another essential factor in any user interface. Since 100 ms is the maximum delay time at which users feel the system is responding instantaneously [19], it is important that applications refresh at a frequency of 10 Hz, or faster, to exhibit acceptable responsiveness. An application that does not meet this specification can potentially interrupt a student's flow of thought and inhibit learning. Moreover, an application that takes several seconds to respond to user commands will not keep the attention of the student and will be regarded as unsatisfactory.

There are two major alternative strategies for developing user interfaces on mobile platforms: one that uses native technologies and one that uses Web technologies. Applications that use native technologies, called native apps, are developed for a specific platform and can take full advantage of the resources and features offered by that platform, for example, the device's graphics, camera, accelerometers, and other motion sensors; Bluetooth and Wi-Fi functionality; complex app-defined touch-screen gestures; and even the user's personal information (such as contact and calendar information) stored on the device. Alternatively, applications that use Web technologies, called Web apps, are actually Web sites that have the look and feel of native applications but are accessed from a remote server by a Web browser on the device. Since Web apps rely on an Internet connection to deliver information to the client device, they cannot be used offline. However, an advantage of Web apps is that they are universally accessible across all



Time	Travel	Elevation	Pitch
0.100000	1.842053	-0.175800	-17.843700
0.200000	1.845879	-0.175800	-17.843700
0.300000	1.845900	-0.263700	-17.667900
0.400000	1.845900	-0.263700	-17.580000
0.500000	1.933161	-0.263700	-17.580000
0.600000	1.933797	-0.263700	-17.667900
0.700000	1.998537	-0.263700	-17.755800
0.800000	2.021576	-0.263700	-17.843700
0.900000	2.124891	-0.175800	-17.667900
1.000000	2.271837	0.087900	-17.228399
1.100000	2.427741	0.351600	-16.613100
1.200000	2.622777	0.703200	-15.909900
1.300000	2.874880	1.142700	-15.206700
1.400000	3.163244	1.758000	-14.327700
1.500000	3.478870	2.461200	-13.360800
1.600000	3.827181	3.252300	-12.218100
1.700000	4.212031	4.131300	-10.987500
1.800000	4.598686	5.098200	-9.932700
1.900000	4.995836	6.065100	-8.877900
2.000000	5.397153	7.119900	-7.911000

FIGURE 7 (a) An iPad application for monitoring and controlling the 3-DOF helicopter, (b) an e-mail composition screen for sending data, and (c) a tab-delimited text file containing data.

mobile platforms so an application needs only be designed once [20]. Native apps can work offline and are typically faster, and thus more responsive, than Web apps. To meet the needs of interactivity and responsiveness, the benefits of native apps outweigh those of Web apps for interfacing students with remote laboratory experiments.

Another important consideration is the specific mobile device that will be used for interacting with a particular experiment. Different types of mobile devices have distinct physical characteristics, features, sensors, and available services. It is prudent to consider both the device characteristics and interface elements that will provide students with the best ability to issue commands to and receive information from the laboratory experiment. The size of the device's screen is a significant factor to consider. For example, an iPad application was chosen to interact with the 3-DOF helicopter experiment because the interface was expected to provide students with a larger three-dimensional (3-D) interactive animation of the helicopter, live video from the laboratory, dynamic plots, and a variety of controls on one screen. Alternatively, if an on-site student is expected to physically interact with the experiment, such as to calibrate a sensor, while holding a mobile device, then the smaller-sized iPhone or iPod, which can be held in only one hand, should be chosen

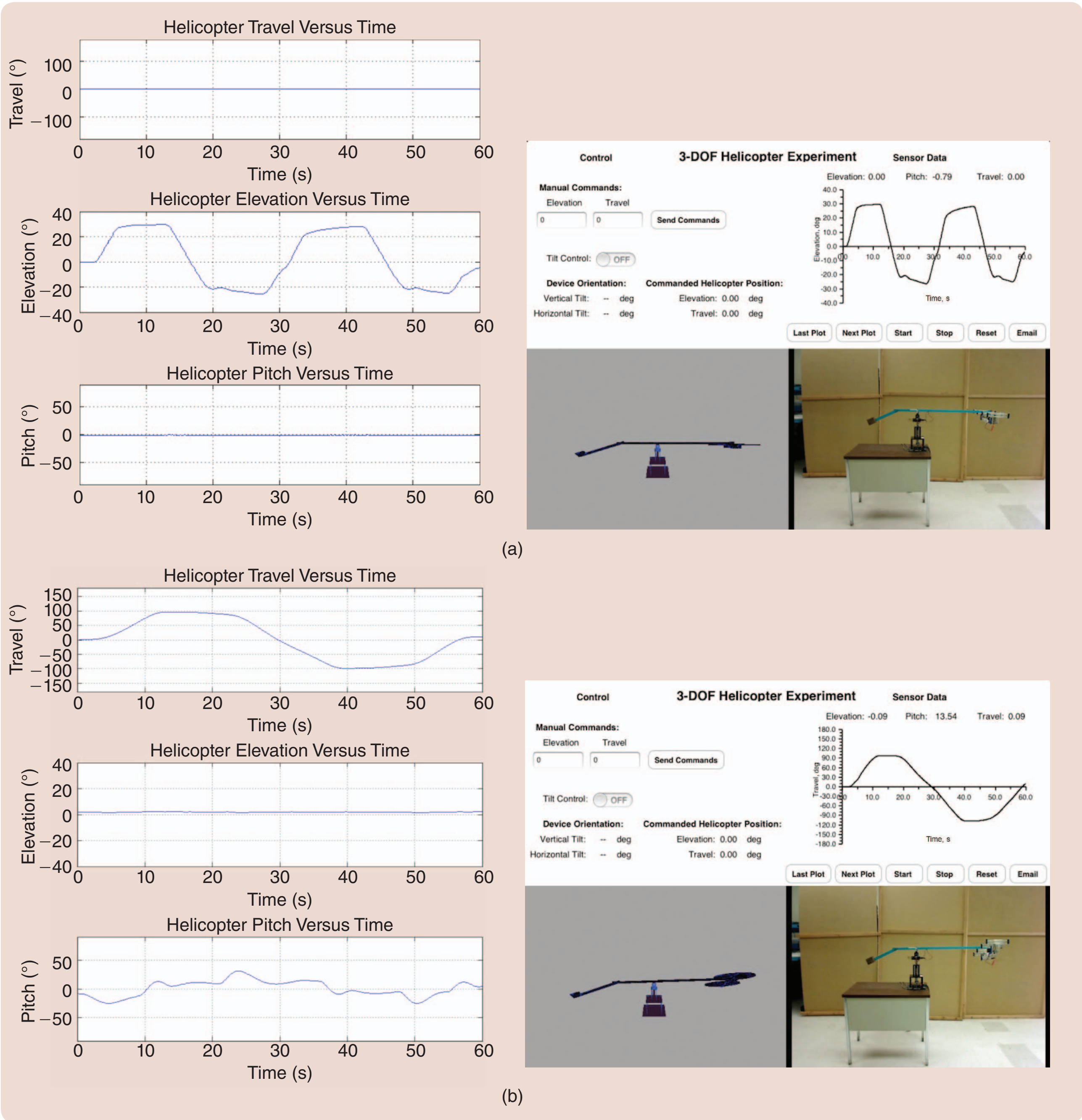


FIGURE 8 Plots of the sensor data shown as both imported into Matlab and displayed by the iPad application while controlling only the (a) elevation and (b) travel of the helicopter.

so as to free the other hand for physical interaction with the experiment. There are many similarities and shared features between most smartphones and other handheld smart devices, such as the iPod Touch, and the distinctions are lessening with time. However, an important difference is that phones allow for complete mobility by using the cellular network to provide Internet access, whereas handhelds without a cellular data connection require a Wi-Fi network to access a remote experiment. The Apple software development environment allows for the development of universal applications that can be run on the iPad, iPhone, or iPod and can adjust the features and the layout of the interface.

Each of the interfaces presented in this article is a native app containing a graphically rich animation of the experiment, which can be used to interact by using touch-screen gestures or the motion sensors of the device. These two- or 3-D animations create an immersive environment for the student by providing visual feedback that automatically updates in real time to reflect the current state of the experiment. It is no surprise that video games, the most interactive and responsive

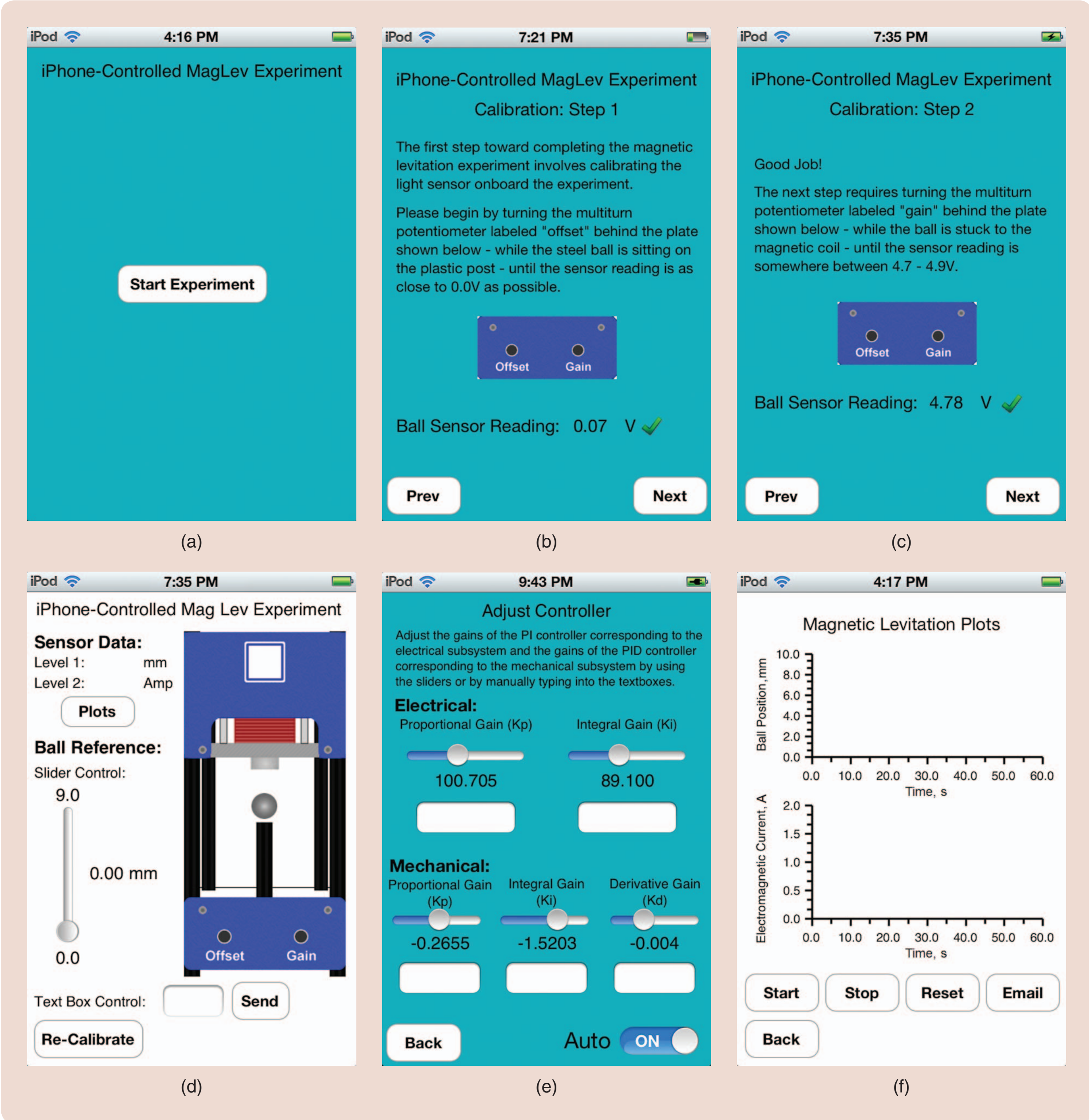


FIGURE 9 The views contained in the iPhone application for interacting with the magnetic levitation experiment. The application contains the following screens: (a) introduction, (b) first calibration, (c) second calibration, (d) main experiment, (e) controller adjustment, and (f) plotting.

mobile applications available, are also undoubtedly the most popular applications among mobile device owners [21]. Thus, for both on-site and remote students, the graphics and touch-screen interface permit interactions with the experiments that have the look and feel of playing a video game to increase the engagement of students.

Each mobile interface performs bidirectional TCP/IP communication with either a laboratory PC or a microcontroller to send commands and receive sensor data from an experiment. An open-source library that makes use of Apple's networking framework is used to accomplish this communication. Students also have the ability to generate plots of the sensor data as it is wirelessly collected from the experiment. An open-source plotting library has been modified to produce these plots and Apple's MessageUI framework used to allow students to e-mail themselves tab-delimited text files containing the sensor data. This implementation makes it easy for students to import experimental data into software for post-processing or presentation. Programming for iOS apps is done in C, C++, and the Objective-C language [22] using Apple's Xcode Suite as the development environment. For additional details concerning the development of iOS apps, including the use of Apple's various libraries, frameworks, and user interface objects, see [23].

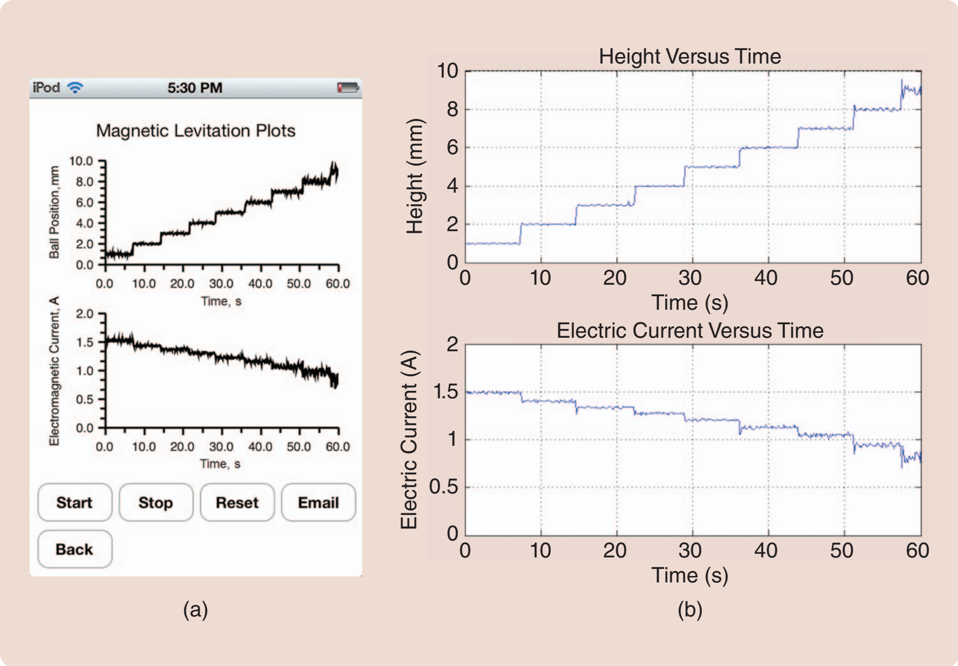


FIGURE 10 The sample plot after commanding the ball height in steps of 1 mm starting from 1 mm and ending at 9 mm: (a) generated by the iOS application and (b) generated by Matlab after importing the tab-delimited text file.

iPad Application for the 3-DOF Helicopter Experiment

The application developed for the iPad [see Figure 7(a)] offers a multifeatured interface to: 1) command the travel and elevation of the helicopter using text input boxes, the touch screen, or the onboard accelerometer; 2) view sensor data plots; 3) view a real-time sensor-driven 3-D animation of the helicopter; and 4) watch a live video feed of the experiment captured by a Web camera. By activating a switch in the interface, a student can select to use the iPad as a joystick, where tilting the iPad commands the helicopter to move. Tilting the iPad, forward or backward, controls the elevation of the helicopter through Simulink. Similarly, tilting the iPad left or right alters the travel command. The animation of the experiment updates at a specified frame rate and changes based on the sensor data received from the experiment. The top-right quadrant of the interface provides the student with an area to generate plots of the sensor data as it is received over the network. By pressing different buttons in the interface, the student is able to navigate between plots of the helicopter's travel, pitch, and elevation as well as start, stop, and reset the plots at any time. When the "e-mail" button is pressed, an e-mail composition screen is displayed [see Figure 7(b)]. The e-mail composition screen provides the student with a prepopulated e-mail containing a date, timestamp, and a tab-delimited text-file attachment containing the data from the experiment. Figure 7(c) shows a screenshot of a tab-delimited file generated by the application. Figure 8 shows plots produced using Matlab after importing the text files and creating vectors from the data. In the bottom-right quadrant of the interface, Apple's Media Player framework is used to retrieve and play the live video on the iPad screen.

iPhone Application for the Magnetic Levitation Experiment

Unlike the helicopter application, the application developed for interacting with the magnetic levitation apparatus allows a student to perform the entire procedure of an undergraduate laboratory experiment, starting with the calibration of the sensors. Figure 9 shows screenshots of the different views contained in the application. During each of the two required calibration steps (ball sensor offset and span), a view in the application supplies the student with instructions to perform the calibration, while providing readings collected by the sensor onboard the experiment [see Figure 9(b) and 9(c)]. Next to the sensor readings, a green checkmark (✓) or a red cross (×) indicate whether the equipment has been calibrated to within an acceptable tolerance. In the main experiment view, labels provide the student with the sensor information received from the experiment and the current reference command being sent to the experiment. A two-dimensional animation of the experiment updates at a specified frame rate to provide the student with visual feedback based on the actual sensor data being received from the experiment [see Figure 9(d)]. The student may choose to command the height of the steel ball by manually typing the height command into a text box, by dragging a vertical slider to the desired height, or by touching the animation at the height where the ball should be placed. When the button labeled "re-calibrate" is pressed, the student is taken back to perform the calibration steps again. Pressing the button labeled "adjust controller" loads a view where the student may adjust the values of the five control parameters associated with the PI and PID controllers [see Figure 9(e)]. When the "set" button is pressed, the values of the parameters chosen by the student are sent to the experiment where they are used to control the steel ball. If the "restore" button is pressed, however, the values of the parameters are restored to nominal values coded in the Simulink model.

The height of the magnetically levitated ball and the current in the electromagnet are also displayed graphically in real-time plots. While the experiment is running, the student can press the "plots" button to view plots of the sensor data [see Figure 9(f)]. As in the iPad application for the helicopter experiment, the same "start," "stop," "reset," and "e-mail" buttons can be used in the plotting interface. Figure 10 shows an example of plots generated by the application and after importing the data into Matlab. In this example, the student commanded the ball height in steps of 1 mm, starting from 1 mm and ending at a height of 9 mm. Figure 11 shows screenshots of what the application looks like when the ball is commanded to 2, 5, and 8 mm.

iPod Application for the Two-Tank Experiment

The application developed for the iPod allows a student to perform the two-tank water-level control experiment, starting with calibration of the pressure sensors. Figure 12 shows screenshots of the application's different views, which function analogously to the views contained in the iPhone application for the magnetic levitation experiment (Figure 9). Specifically, Figure 12(b)–(f) illustrates the views for the calibration step, the main experiment, adjustment of the controller, and real-time plots, respectively. Figures 13–15 show an example where the student commanded the water level in the lower tank to 5, 10, 15, and 20 cm. While Figure 13 shows screenshots of the main experiment view as the water level is increased, Figure 14 shows the plots of the sensor data after it has been imported into Matlab, and Figure 15 shows the plots generated by the application.

iPhone Application for the DC-Motor Experiment

The application developed for the iPhone allows a student to remotely control a dc motor test bed and to adjust the control parameters. Figure 16 shows screenshots of the different views contained in the application. Specifically, Figure 16(a)–(c) illustrates the views to connect to the test bed over the Internet, interact with the experiment, and adjust the control parameters, respectively. Figure 17 shows screenshots after the student has commanded the motor to move back and forth between $-60°$ and $+60°$ with different values for the control parameters. Specifically, in Figure 17(a)–(d), the proportional and derivative gains are held fixed as the integral gain is increased. Figure 17(e) shows the effect on the response after the derivative gain is increased. Figure 18 shows plots of the motor response after the data has been imported into Matlab. These dc motor responses were collected approximately 9 mi away from the laboratory. When interacting with the experiment from this distance, no discernibly larger delays in the response were observed, as evidenced from the jitter-free plots. However, as the distance between a student and the test bed increases to dramatically larger distances, Internet delays may become an issue. In such a scenario, sensor data may no longer arrive in time to be available when the mobile application updates, and animations and plots may appear distorted. This problem can be addressed to some extent by having the server store and send small batches of sensor data. Using this approach, while the app awaits a new batch of data, it can update plots and

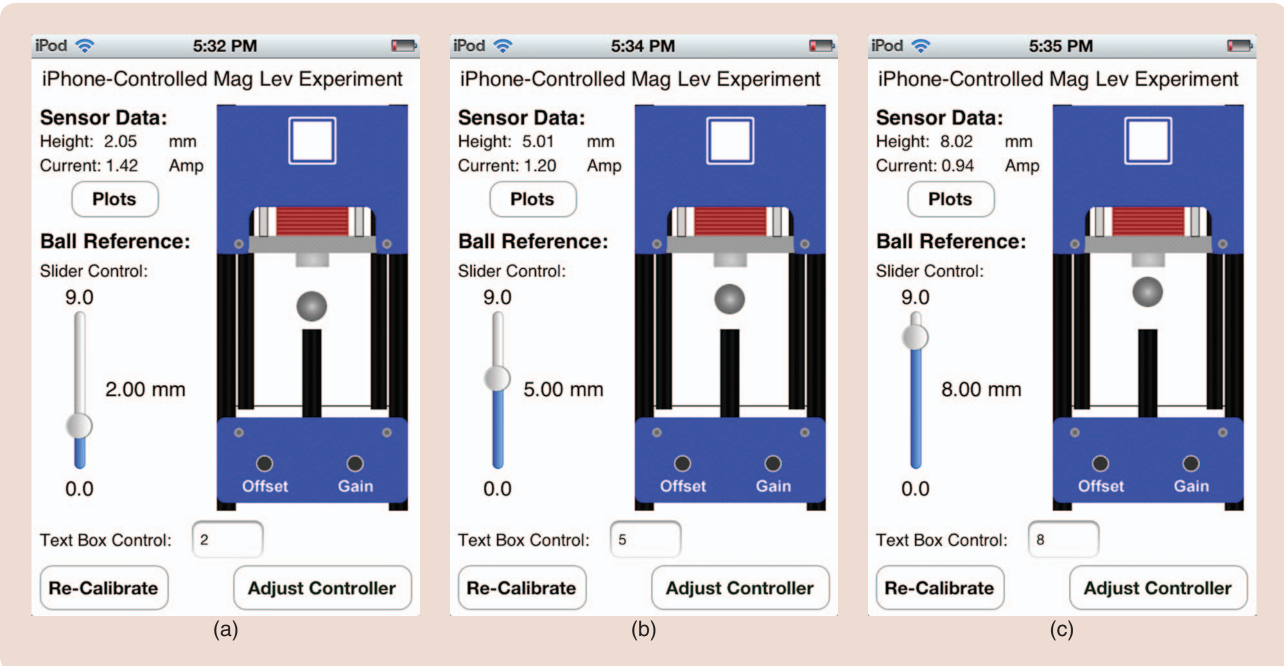


FIGURE 11 Screenshots of the iPhone application while the steel ball is commanded to a height of (a) 2, (b) 5, and (c) 8 mm.

animation with the buffered data. An advantage of using mobile applications with remote laboratory experiments is the ease with which distant students can collaboratively work with equipment. Figure 19 shows two students who each have a mobile device simultaneously connected to the experiment to share data and exchange ideas about the experiment. Such collaboration is investigated further in the next section. Finally, the aforementioned capability of allowing multiple clients to simultaneously connect to the experiment can afford deeper engagement and learning for even onsite students. Specifically, all members of a laboratory team can use their own mobile devices to obtain and observe the system response, instead of having to gather around one desktop computer and looking over each other's shoulders.

USER EXPERIENCE EVALUATION

The integration of the mobile applications, as discussed in this article, into the automatic control laboratory curriculum

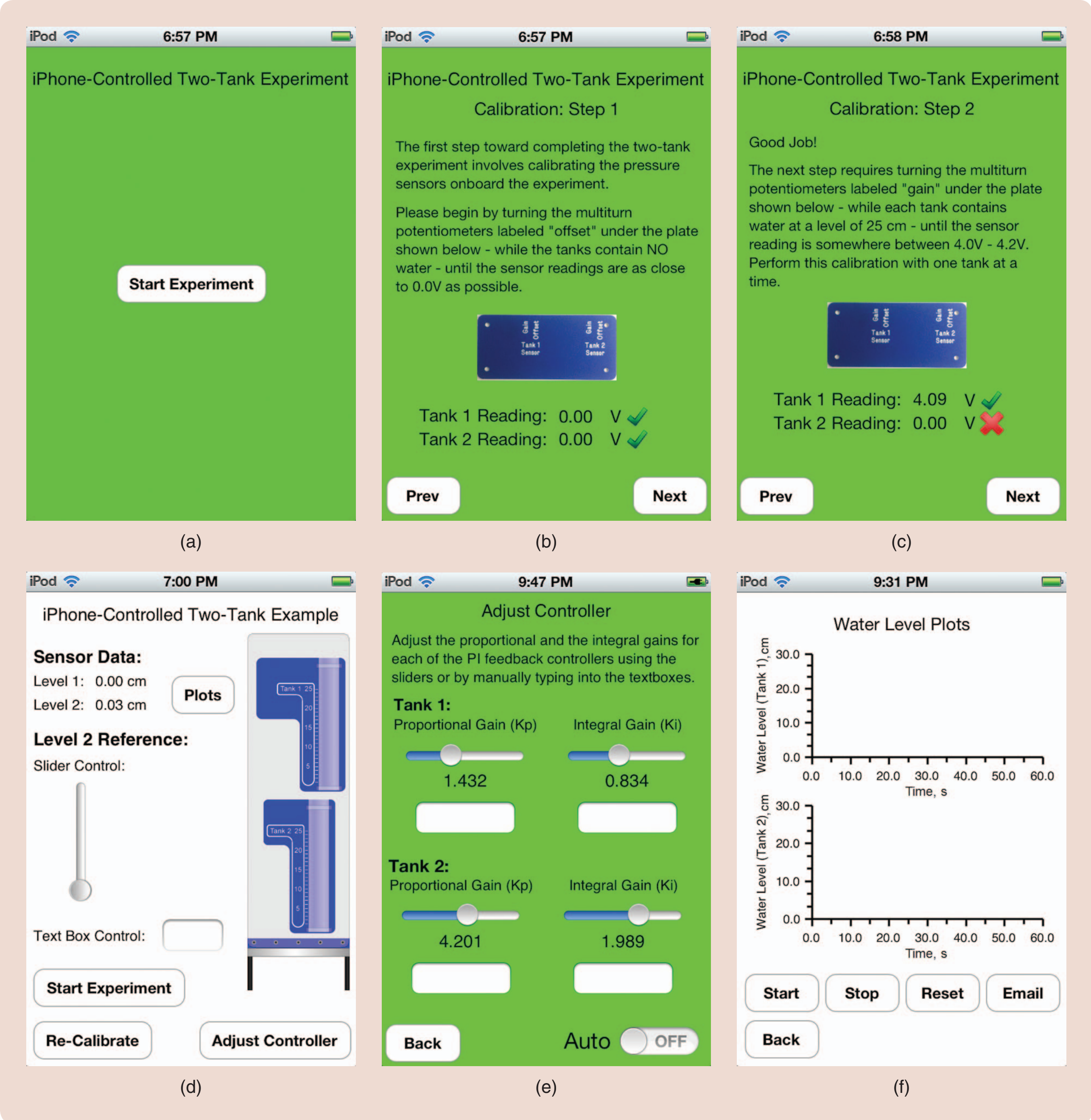


FIGURE 12 The views contained in the iPod application for interacting with the two-tank control experiment. The application contains the following screens: (a) introduction, (b) first calibration, (c) second calibration, (d) main experiment, (e) controller adjustment, and (f) plotting.

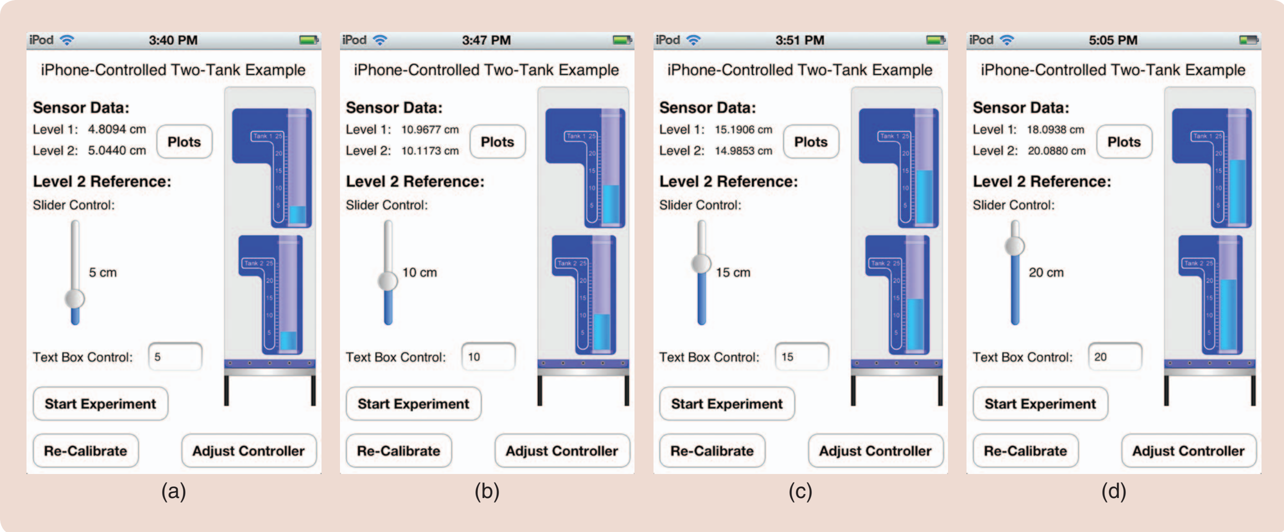


FIGURE 13 Screenshots of the iPod application after the level of the lower tank has been commanded to a height of (a) 5, (b) 10, (c) 15, and (d) 20 cm.

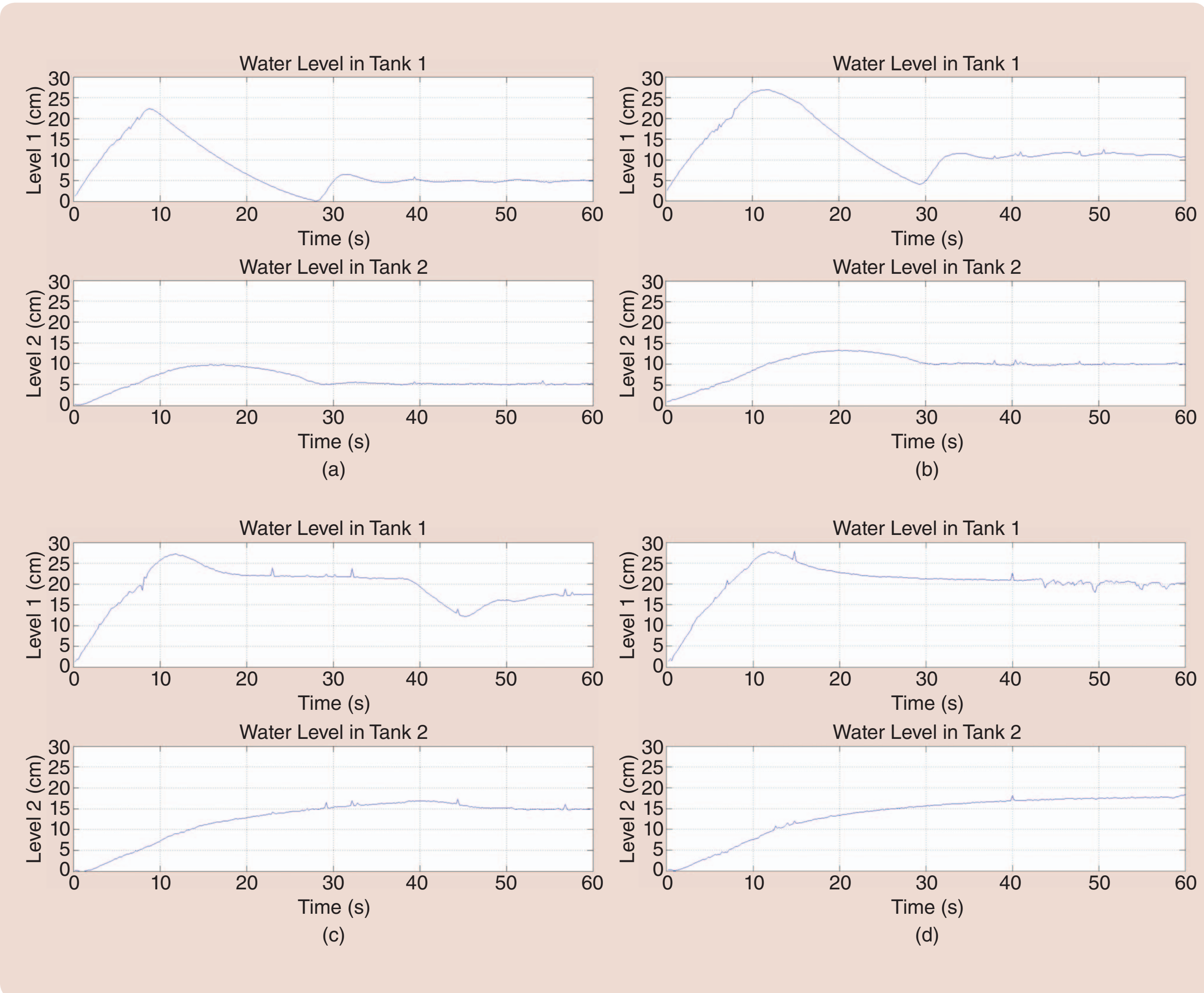


FIGURE 14 Plots of the water levels in each tank generated by Matlab after importing the iOS-produced tab-delimited text files when the level in the lower tank is commanded to (a) 5, (b) 10, (c) 15, and (d) 20 cm.

necessitates a consideration of the expected learning outcomes for the students, as well as the associated assessment methods and criteria for success. This process demands a careful review of the ways that the applications influence the students' interaction with the laboratory test beds.

Traditional laboratory experiments are expected to yield understanding of the practical applications of theoretical concepts and to promote collaborative learning. Yet it has been widely acknowledged that a large amount of time in traditional laboratories is dedicated to understanding the experimental procedure and to preparing the equipment [4]. Using mobile applications to conduct laboratory experiments can redirect students' time and effort to readily collect and save experimental data as they repeat experiments several times, varying control parameters and reference values to observe their effects on system response. The ability to perform laboratory experiments by using mobile apps allows students to gain a greater understanding of the role that the control parameters play in the dynamic response of feedback-controlled systems. Moreover, such an approach is expected to permit student-directed learning and collaborative learning, both desirable learning outcomes.

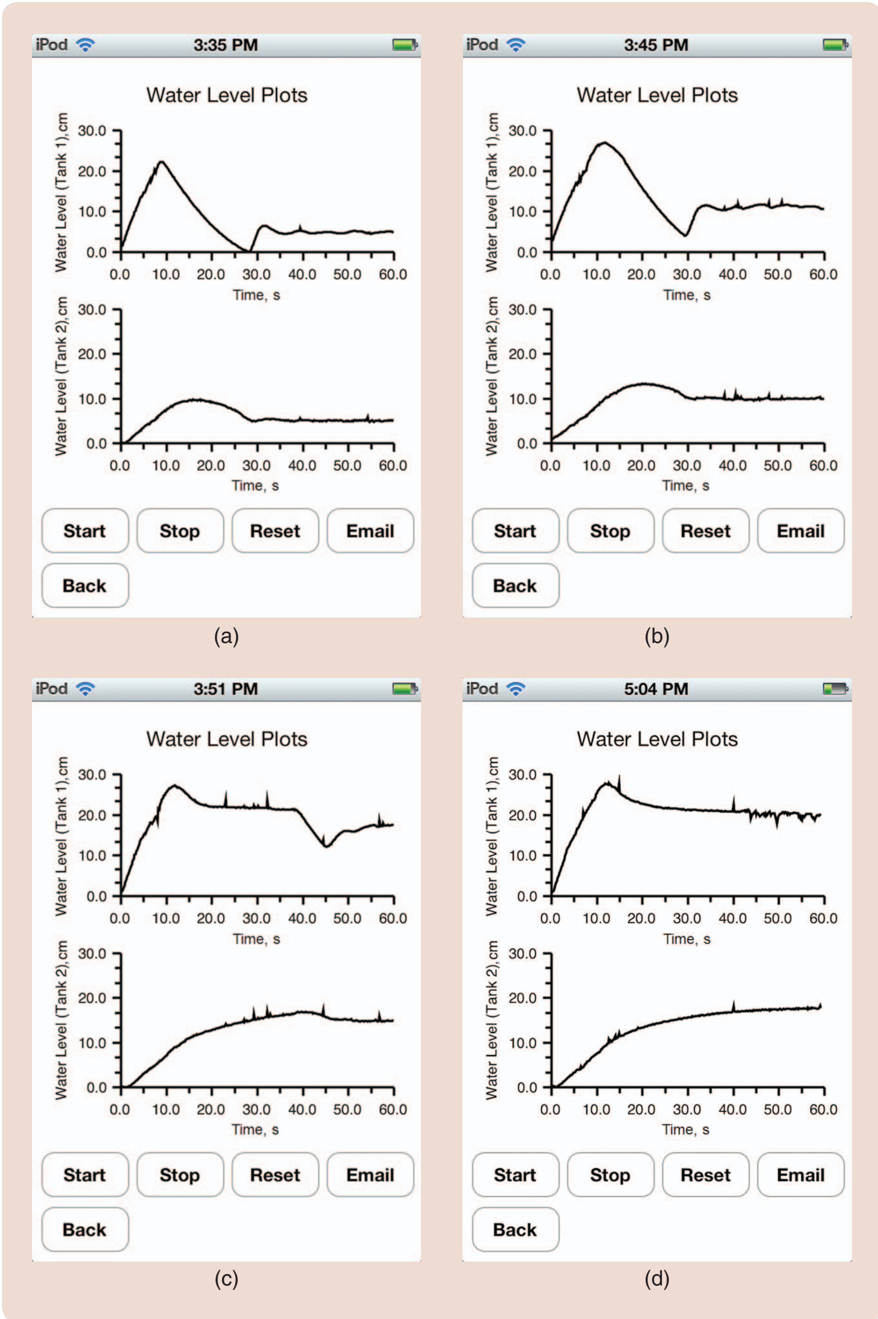


FIGURE 15 Plots of the water levels in each tank generated by the iPod application after the level in the lower tank is commanded to (a) 5, (b) 10, (c) 15, and (d) 20 cm.

In the Laboratory

To assess aspects of the user experience with the developed interfaces and the feasibility of integrating the iDevice applications into the undergraduate control laboratory, an evaluation has been conducted with 29 undergraduate students. These students attended a formal offering of the regular Automatic Control Laboratory course at NYU Polytechnic School of Engineering (NYU-Poly) in the spring 2012 semester. During the semester, students were instructed in mathematical modeling of physical systems and used feedback control theory to design and select values for control parameters that would cause the closed-loop system to be regulated to a specified state while achieving a specified dynamic response. The students then entered their designed control parameters and specified reference values into a premade Simulink-based controller running on a laboratory PC. Given the time needed to review the mathematical modeling of the system, design the control parameters, set up the equipment, and calibrate the sensor measurements, students typically only have enough time to enter their calculated control parameters once and collect the data that results from these values.

After spending the semester working with the experiments following the established laboratory procedure

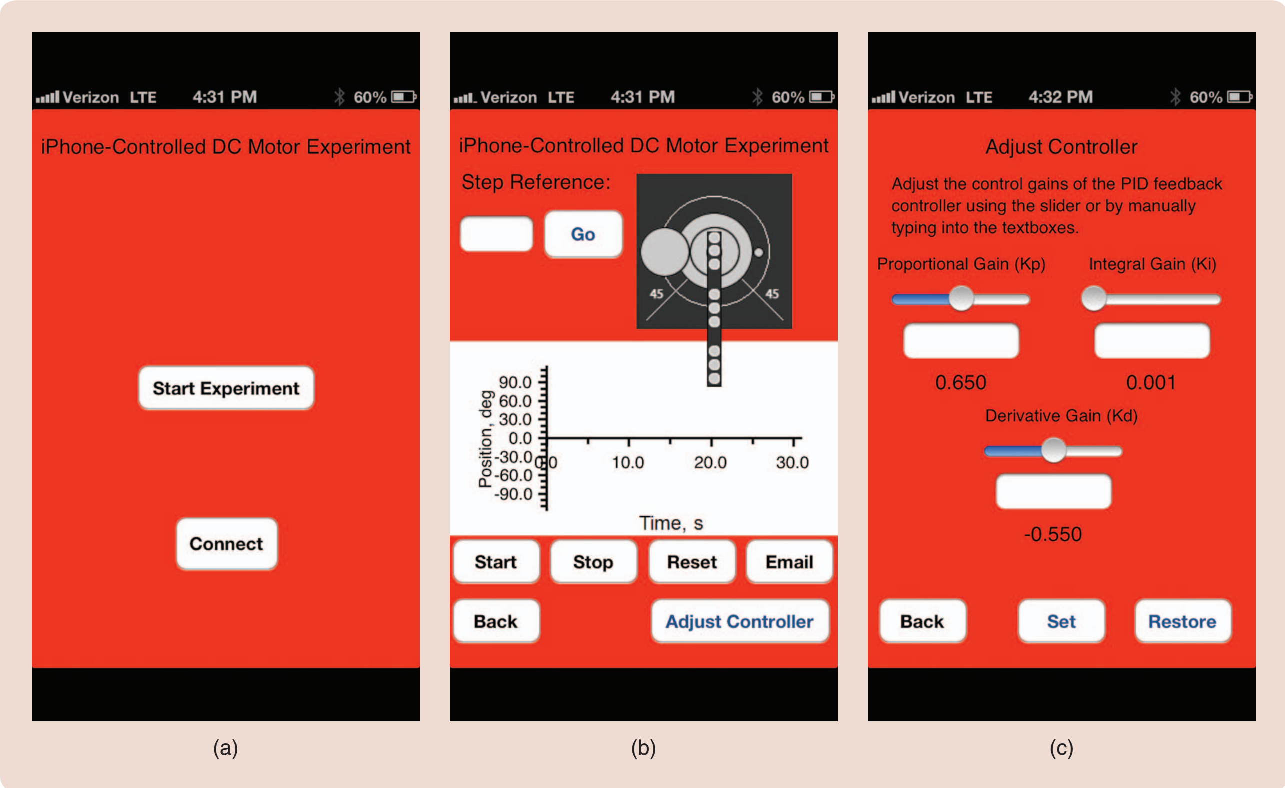


FIGURE 16 The views contained in the iPhone application for interacting with the dc motor control experiment. The application contains the following screens: (a) introduction, (b) main experiment, and (c) controller adjustment.

with desktop computers [10], [11], the students were given iPhones, iPods, and iPads and asked to conduct the same experiments again using the iDevice applications. With the mobile devices, students had an easier time adjusting the controller parameters and reference values and observing how these changes influence the response of the experiment. Next, the students were administered a survey to rate certain aspects of their experience with the applications on a five-point scale, which used the traditional laboratory experience as a reference for the neutral, or average, rating. A copy of the survey administered to the students is shown in Figure 20. The responses to each question in the survey are given in the histogram in Figure 21(a).

The aspects of the user experience that received the highest ratings were concerned with the interactivity and the portability provided by the interface. The results of the evaluation indicate that the students are attracted to the interactive nature of the applications, specifically, the interactive plots and the interactive animations of the test beds. These results were expected since the aim was to design the interface between student and test bed to look and feel like games. Insightful comments were provided by the students. Thirteen students reported that the applications were fun, easy to use, and suitable to be integrated into the curriculum. Five students commented that the applications could replace the laboratory manuals altogether since they could be used to provide the instructional content while guiding students through the entire experimental procedure, which would reduce the time and effort required to perform the experiments since all aspects of the learning would be provided in one interface.

Usually tasks such as sensor calibration, observing the effect of control parameter changes, and collecting experimental response data for applied disturbances can be inconvenient for one person, who must go back and forth between the test bed and the desktop computer. The portability of the mobile devices enables one person to perform these tasks conveniently and immerses them in the interaction with the experiment. The tally of all the responses given by the students in the evaluation is provided in Figure 21(b), which shows that 88.9% of all responses assigned a rating of at least "above average." Most of the students reported an overall positive and beneficial laboratory experience using the mobile applications with respect to the original laboratory experience. The results also suggest that the user experience may be enhanced by incorporating additional animation and live video that students can directly interact with as opposed to methods like tilting the device, pressing buttons, and dragging sliders.

Students also provided critical feedback for improvements, including that the helicopter motion control was not as easy to accomplish by tilting the iPad compared to using a traditional joystick. The feedback suggests that the large size of the tablet device presents a challenge when

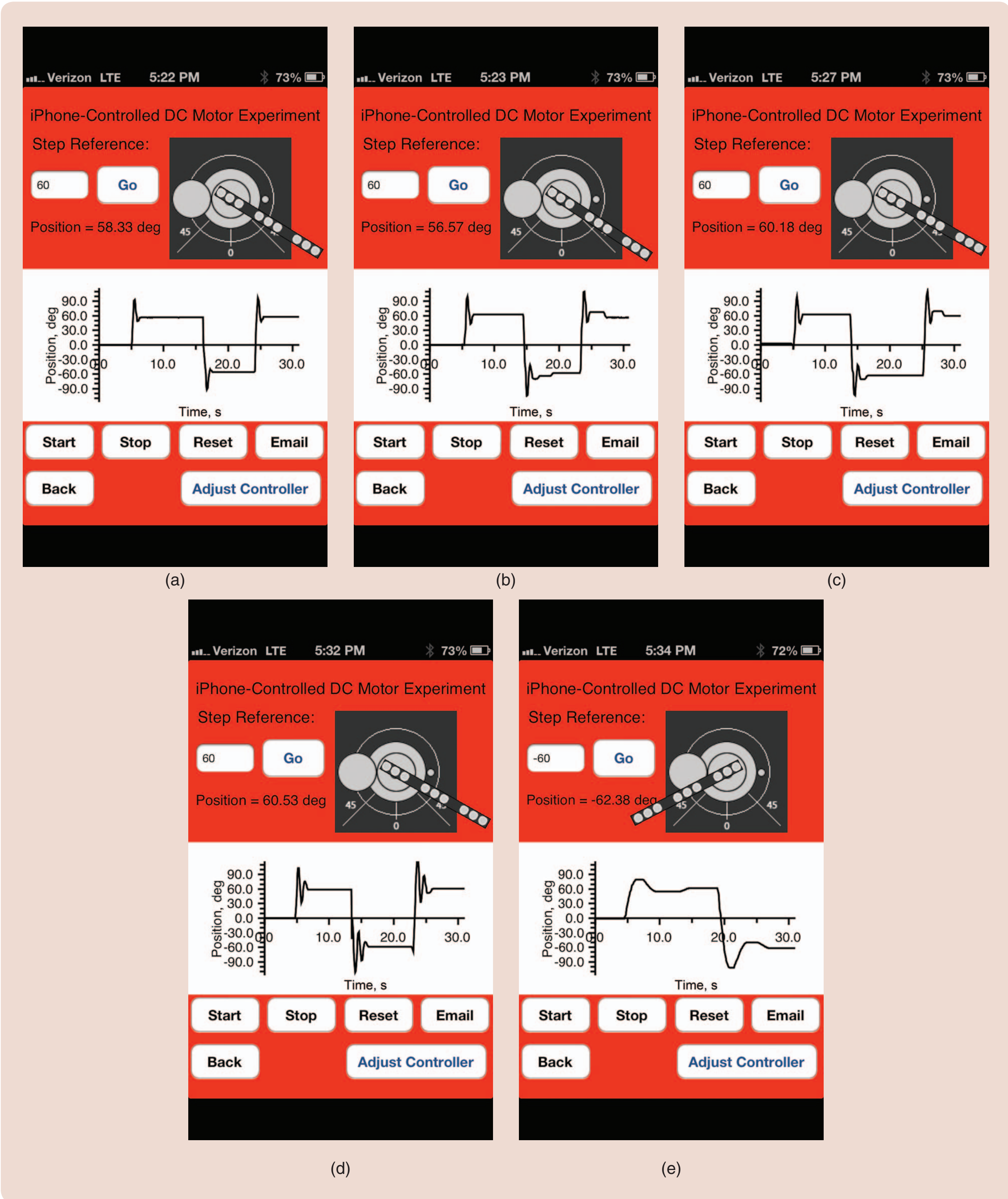


FIGURE 17 Screenshots of the iPhone application after the PID control parameters have been commanded to (a) $k_p = 0.65$, $k_i = 0.00$, $k_d = -0.55$; (b) $k_p = 0.65$, $k_i = 0.10$, $k_d = -0.55$; (c) $k_p = 0.65$, $k_i = 0.50$, $k_d = -0.55$; (d) $k_p = 0.65$, $k_i = 1.00$, $k_d = -0.55$; and (e) $k_p = 0.65$, $k_i = 1.00$, $k_d = 0.25$.

implementing a motion-based interface. Students preferred interacting with the helicopter manually through the less interactive text boxes and interacting with the animation through the touch screen. Some students reported that they preferred the traditional interface provided by the Matlab/Simulink environment because they wanted to be able to

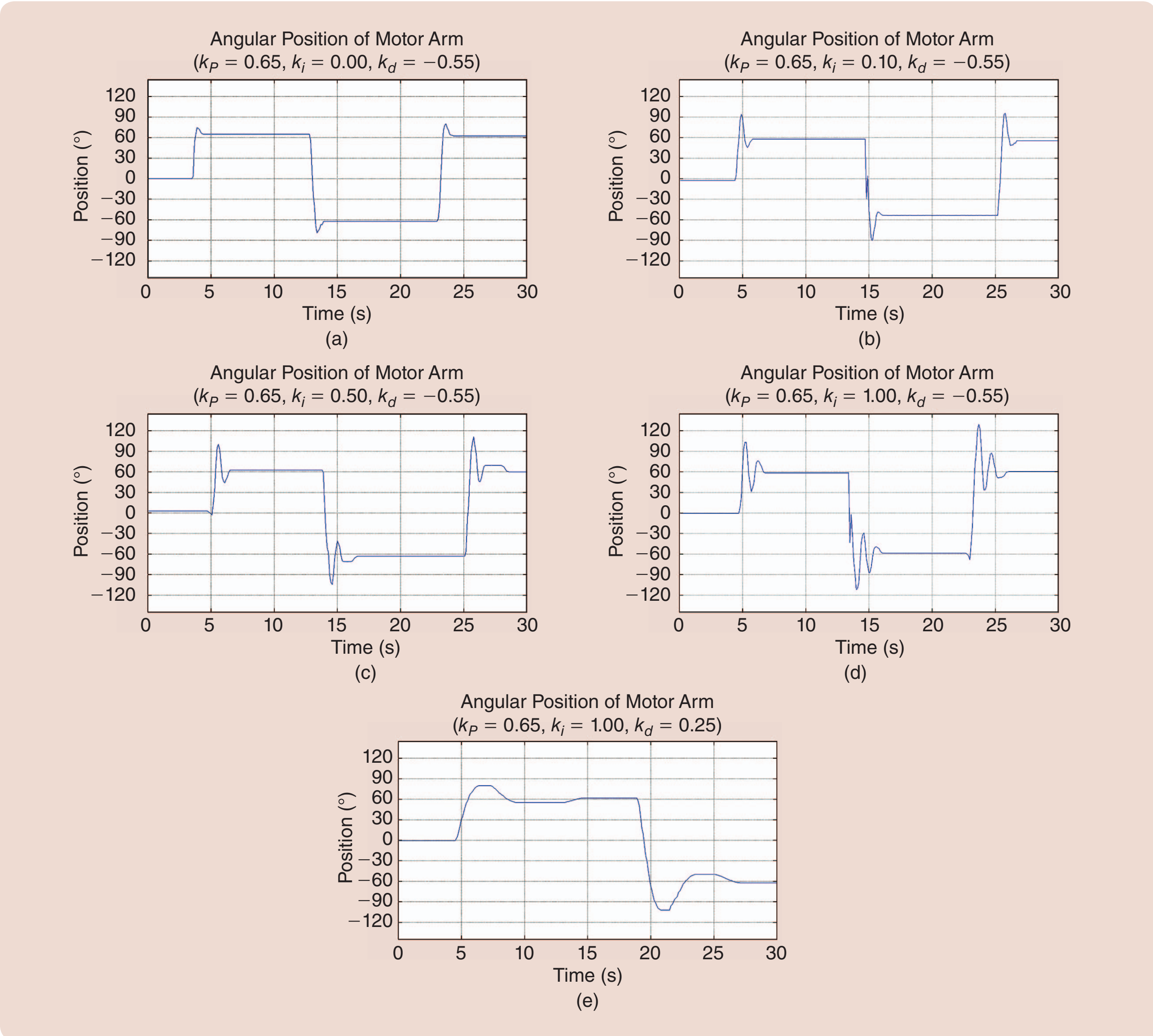


FIGURE 18 Plots of the angular position of the motor arm generated by Matlab after importing the iOS-produced tab-delimited text files when the PID control parameters are commanded to (a) $k_p = 0.65$, $k_i = 0.00$, $k_d = -0.55$, (b) $k_p = 0.65$, $k_i = 0.10$, $k_d = -0.55$, (c) $k_p = 0.65$, $k_i = 0.50$, $k_d = -0.55$, (d) $k_p = 0.65$, $k_i = 1.00$, $k_d = -0.55$, and (e) $k_p = 0.65$, $k_i = 1.00$, $k_d = 0.25$.

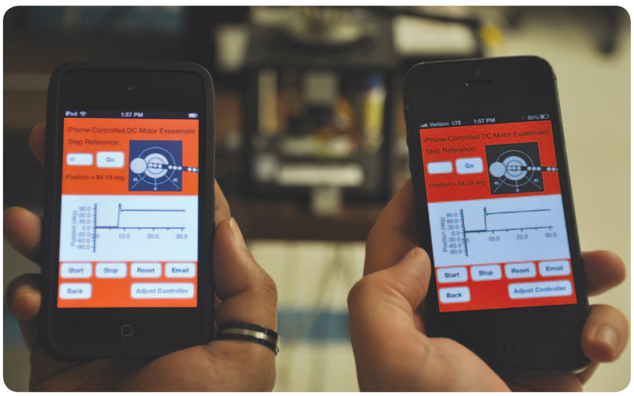


FIGURE 19 A photograph of two students collaboratively learning about proportional-integral-derivative control using the iOS application for interacting with the dc motor control experiment.

see and modify the structure of the controller implementation. Although it is important that the students see the controller implementation and are given the ability to modify its structure, or even create their own controller structure from scratch, the current 3 h/week laboratory is not amenable to accommodate such experimentation.

Remote Learning

To investigate how the mobile applications could support remote and collaborative learning, the dc motor application was used to conduct a preliminary study with 48 engineering students. The participants included 16 underclassmen who had never heard of PID control (Group 1), 16 upperclassmen who were currently taking a class that discussed PID control (Group 2), and 16 graduate students who reported

The purpose of this evaluation is to get feedback from you on the suitability of using iOS-based mobile applications for controlling lab experiments in contrast to the conventional PC-based approach used in the laboratory. We wish to determine whether the iOS applications developed for interacting with the experiments can support learning of a remote student who does not have access to an on-site laboratory. We also wish to determine whether on-site students can benefit from having access to iOS-based applications for interacting with the experiments. You are requested to answer the following questions. The following coding scheme is to be used to fill in the table:

Unacceptable: 1 Below Average: 2 Average: 3 Above Average: 4 Superior: 5

iPod/iPhone-Controlled Magnetic Levitation and Two-Tank Experiments

	1	2	3	4	5
1. Ability to Use the Mobile Applications for Quicker, More Portable Completion of the Laboratory Experiments.					
2. Ability to More Effectively Calibrate Sensors and Identify Unknown System Parameters of the Experiments Using the Mobile Applications Versus On-Site PC-Based Lab.					
3. Ability to Tune Your Control Design On-the-Fly by Adjusting Controller Gains Using the Mobile Applications Versus On-Site PC-Based Tuning of the Controllers.					
4. Ability to Receive Visual Feedback in the Mobile Applicaions Regarding the State of the Experiment via Two-Dimensional Graphical Animations.					
5. Ability to Analyze the Performance of Controllers Using Mobile Applications Versus On-Site Lab.					

iPad-Controlled Helicopter Experiment

6. Ability to Control the Motion of the Helicopter Using the Methods Provided by the Mobile Interface Versus the Traditional Joystick and PC-Based Methods.					
7. Quality of Visual Feedback via Three-Dimensional Animations.					
8. Quality of Visual Feedback via Live Video Stream.					

General

9. Ability to Collect and Plot Data in Real Time for Remote Monitoring of the Behavior of the Experiments Using the Mobile Applications Versus On-Site Lab.					
10. Ability to E-mail Collected Data for Importation into Post-Processing Software and Reports.					
11. Overall ease of Navigating and Using the Mobile Applications Graphical User Interfaces (GUIs).					
12. Overall Suitability of the iOS Applications as Remote Interfaces for Off-Site Students.					
13. Overall Suitability of the iOS Applications as Portable Interfces for On-Site Students.					
14. Overall Concept of Interacting with the Experiments via Mobile Devices.					

Below, Kindly Provide Comments on Your Overall Experience Using the iOS Applications with the Lab Experiments Versus Performing the On-Site Labs (What Did You Like, What Did You Not Like, Suggestions, etc).

FIGURE 20 An iOS-based mobile-controlled laboratory experiments evaluation form. The traditional laboratory experience served as a reference for the average rating.

having used PID control and knew it well (Group 3). All students owned a mobile phone and were thus already familiar with how to use one. The students were separated into teams of two each and were brought, one team at a time, to a room away from the laboratory where they were given two mobile devices and briefly introduced to the dc motor experiment and mobile application. The students were then asked to sit at desks on opposite sides of the room. One member in the team was assigned the task of commanding the motor arm to different positions while the other team member was responsible for adjusting the values of the PID control parameters. Then, the students were asked to use the mobile devices

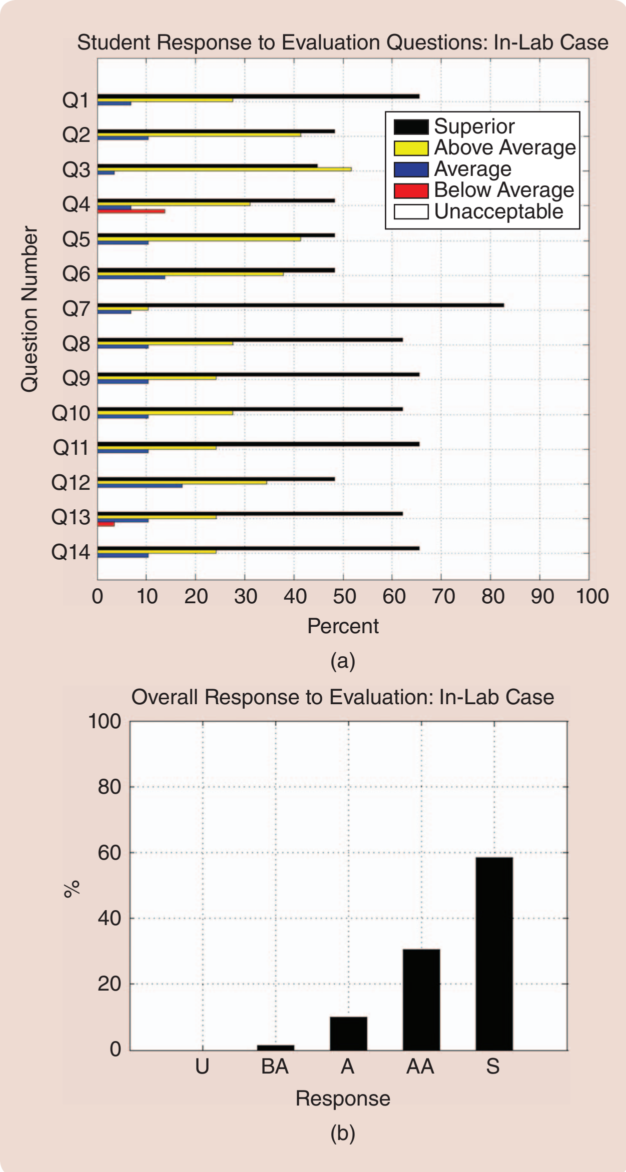


FIGURE 21 A relative histogram showing responses from students of the in-lab experiment for (a) each question and (b) overall.

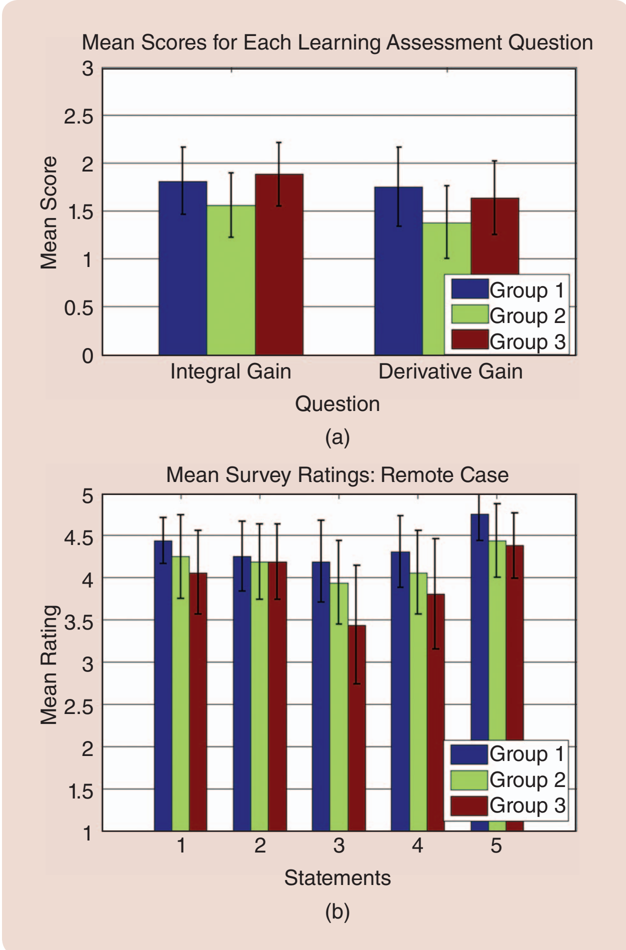


FIGURE 22 The results of the remote experiment: (a) the mean scores obtained by the students for the learning assessment questions, out of a maximum score of three and (b) the mean survey ratings reported by the students for each of the user experience statements, out of a maximum score of five. Error bars represent 95% confidence intervals.

to collaboratively perform the following procedure: 1) command the motor to different positions, while incrementing only the value of the integral gain in four steps, and observe the dynamic response of the motor using the interactive plots, and then 2) command the motor to different positions after incrementing only the derivative gain once and again observe the dynamic response of the motor.

After performing the remote experiment, the students were given a questionnaire to assess their learning from and experience in using the application. The learning assessment consisted of two questions asking the students to describe, in terms of steady-state error, overshoot, and speed of response, the effects they observed on the dynamic response of the motor arm due to: 1) the increase in the value of the integral gain and 2) the increase in the value of the derivative gain. These questions were graded by tallying how many of the three effects the student correctly commented on. Students received scores from zero to three. Figure 22(a) shows the mean scores obtained by the students for each of the learning assessment questions, with error bars representing the 95% confidence intervals. Figure 22(a) shows that the mobile application not only allowed students to effectively monitor and control the remote test bed but enabled them, even if they had no prior knowledge of PID control, to gain a conceptual understanding of the effects that tuning certain control parameters had on the dynamic response of the test bed. In fact, conducting single-factor analysis-of-variance (ANOVA) tests [24] on the students' scores resulted in p-values of 0.346 and 0.351 for the first and second questions, respectively, showing that there was no significant difference between the mean scores of the three groups. This result is supported by the observation of the overlap of the confidence intervals in Figure 22(a).

Following the learning assessment, the students were given survey questions that sought to assess the user experience associated with the application. The students were asked to rate, on a five-point Likert scale [25], their level of agreement with five statements: 1) it was easy to navigate the application; 2) it was easy to collect, plot, and e-mail data from the remote experiment; 3) the application made it easy and fun to collaborate with a team member; 4) I believe that using the application helped me gain a conceptual understanding of the PID controller; and 5) I would like to see more mobile applications like the dc motor app introduced into engineering laboratories. Figure 22(b) shows the mean survey ratings reported by the students for each of the statements, with error bars representing the 95% confidence intervals. The results provide evidence that the majority of the students were sufficiently satisfied with their experience during the remote experiment with the mobile application.

CONCLUSIONS

Mobile devices can enhance interaction with physical hardware and increase the accessibility of remote laboratory equipment. These benefits make mobile devices a novel technology with potential to enrich experiential learning in engineering education. In this article, the development of several mobile applications for interacting with laboratory equipment either remotely or from within the laboratory was discussed. To demonstrate the usefulness of these applications, PC- and microcontroller-based experimental setups were used to control the laboratory test beds and to make them accessible to students via mobile devices. The touch screen and the graphics of the mobile devices were found to be the most crucial elements for giving the mobile applications the look and feel that students prefer and are most familiar with. These features, along with the computational capabilities and state-of-the-art sensors of iDevices, contribute to the interactivity of the applications, which is directly responsible for immersing the student in the laboratory experience. A preliminary evaluation, conducted with 29 students in the laboratory and 48 students outside of the laboratory, was used to assess the usability and user experience and assess the learning outcomes associated with using mobile interfaces with laboratory experiments. After interacting with a remote test bed using a mobile application, students with no prior knowledge of PID control demonstrated an understanding of the roles played by control parameters on the dynamic response of the test bed that was not significantly different from the understanding demonstrated by the students currently learning, and who have already learned, PID control.

ACKNOWLEDGMENTS

This article is based upon work supported in part by the National Science Foundation (NSF) under the Research Experience for Teachers (RET) Site grants EEC-0807286 and EEC-1132482, an NSF GK-12 Fellows grant DGE-0741714, and NASA/NY Space Grant Consortium under grant 48240-7887. The authors are thankful to several coworkers for contributions in the development and testing of the work reported in this article. Specifically, the authors thank RET project participant Hilary Mallar and graduate students David Lopez, Ryan Caeti, and Daniel Kimani.

AUTHOR INFORMATION

Jared Alan Frank received the B.S. and M.S. in mechanical engineering from the NYU Polytechnic School of Engineering in 2010 and 2012, respectively. He has been conducting mechatronics and robotics research in the Mechatronics and Controls Laboratory at NYU Polytechnic School of Engineering since his first undergraduate summer research experience in 2007 as a freshman. During his M.S. study, he served as a teaching assistant for the Automatic Control Laboratory course in fall 2011 and spring 2012 semesters. His M.S. research focused on mobile applications that wirelessly interface with physical systems in an effort to investigate the use of smart devices, such as smartphones and tablet computers, for intuitive, multimodal, human-machine interaction. He started his doctoral studies in mechanical engineering in 2012 with a research focus on human-robot interaction. He is an author or coauthor of several conference and journal publications.

Vikram Kapila (vkapila@nyu.edu) is a professor of mechanical engineering at the NYU Polytechnic School of Engineering where he directs a National Science Foundation (NSF) funded Mechatronics and Control Laboratory, an NSF-funded Research Experience for Teachers site, and an NSF-funded GK–12 Fellows project. His research interests are in control system technology, mechatronics, and K–12 STEM education. He received Polytechnic's 2002, 2008, 2011, and 2014 Jacobs Excellence in Education Award, 2002 Jacobs Innovation Grant, 2003 Distinguished Teacher Award, and 2012 Inaugural Distinguished Award for Excellence in the category Inspiration Through Leadership. His scholarly activities have included three edited books, seven chapters in edited books, one book review, 53 journal articles, and 106 conference papers.

REFERENCES

[1] International Data Corp. (2014, Jan.). Tablet shipments forecast to top total PC shipments in the fourth quarter of 2013 and annually by 2015. [Online]. Available: http://www.idc.com/getdoc.jsp?containerId=prUS24314413

[2] J. Thilmany, "Working away: Mobile apps gain traction with engineers," *Mech. Eng. Mag.*, vol. 136, no. 1, pp. 40–43, 2014.

[3] D. May, T. Claudius, T. Haertel, and C. Pleul, "Bringing remote labs and mobile learning together," *Int. J. Interact. Mobile Technol.*, vol. 7, no. 3, pp. 54–62, 2013.

[4] C. Bright, E. Lindsay, D. Lowe, S. Murray, and D. Liu, "Factors that impact learning outcomes in both simulation and remote laboratories," in *Proc. World Conf. Educational Multimedia, Hypermedia Telecommunications*, 2008, pp. 6251–6258.

[5] J. Liu, A. Spanias, M. K. Banavar, J. J. Thiagarajan, K. N. Ramamurthy, S. Hu, and X. Zhang, "Work in progress—Interactive signal-processing labs and simulations on iOS devices," in *Proc. IEEE Frontiers Education Conf.*, 2011, pp. F2G-1–F2G-2.

[6] A. Alkouz, A. Y. Al-Zoubi, and M. Otair, "J2ME-based mobile virtual laboratory for engineering education," *Int. J. Interact. Mobile Technol.*, vol. 2, no. 2, pp. 5–10, 2008.

[7] L. Gomes and S. Bogosyan, "Current trends in remote laboratories," *IEEE Trans. Ind. Electron.*, vol. 56, no. 12, pp. 4744–4756, 2009.
[8] L. Cui, F. P. Tso, D. Yao, and W. Jia, "WeFiLab: A web-based WiFi laboratory platform for wireless networking education," *IEEE Trans. Learn. Technol.*, vol. 5, no. 4, pp. 291–303, 2012.
[9] J. Apkarian and A. Dawes, "Interactive control education with virtual presence on the Web," in *Proc. American Control Conf.*, Chicago, IL, 2000, pp. 3985–3990.
[10] V. Kapila. (1999). Laboratory experiment manual for control laboratory. Polytech. Univ., Brooklyn, NY. [Online]. Available: http://mechatronics.poly.edu/Control_Lab/manual.pdf
[11] V. Kapila, M. S. de Queiroz, and A. Tzes, "A multidisciplinary undergraduate real-time experimental control laboratory," in *Proc. American Control Conf.*, Chicago, IL, 2000, pp. 3980–3984.
[12] C. Dubey, H. Wong, V. Kapila, and P. Kumar, "Web-enabled remote control laboratory using an embedded Ethernet microcontroller," in *Internet Accessible Remote Laboratories: Scalable E-learning Tools for Engineering and Science Disciplines*, A. K. M. Azad, M. E. Auer, and V. J. Harward, Eds. Hershey, PA: IGI Global, 2011, pp. 338–361.
[13] T. Igoe, *Making Things Talk*. Sebastopol, CA: O'Reilly, 2007.
[14] B. Kuo, *Automatic Control Systems*, 7th ed. Englewood Cliffs, NJ: Prentice-Hall, 1995, pp. 188–189.
[15] R. Sims, "Interactivity: A forgotten art?" *Comput. Human Behav.*, vol. 13, no. 2, pp. 157–180, 1997.
[16] N. E. Cagiltay, E. Aydin, C. C. Aydin, A. Kara, and M. Alexandru, "Seven principles of instructional content design for a remote laboratory: A case study on ERRL," *IEEE Trans. Educ.*, vol. 54, no. 2, pp. 320–327, 2011.
[17] J. Liu, S. Hu, J. J. Thiagarajan, X. Zhang, S. Ranganath, M. K. Banavar, and A. Spanias, "Interactive DSP laboratories on mobile phones and tablets," in *Proc. IEEE Int. Conf. Acoustics, Speech Signal Processing*, 2012, pp. 2761–2764.
[18] G.-J. Hwang, P.-H. Wu, and H.-R. Ke, "An interactive concept map approach to supporting mobile learning activities for natural science courses," *Comput. Educ.*, vol. 57, no. 4, pp. 2272–2280, 2011.
[19] J. Nielsen, *Usability Engineering*, 1st ed. Boston, MA: Academic Press, 1993.
[20] P. Orduña, J. García-Zubia, J. Irurzun, D. López-de-Ipiña, and L. Rodriguez-Gil, "Enabling mobile access to remote laboratories," in *Proc. IEEE Global Engineering Education Conf.*, 2011, pp. 312–318.
[21] (2014, Jan.). The state of mobile apps. Nielsen Co. New York. [Online]. Available: http://www.nielsen.com/content/dam/corporate/us/en/reports-downloads/2010-Reports/Nielsen-State-of-Mobile-Apps-Whitepaper.pdf
[22] D. Mark and J. LaMarche, *Beginning iPhone Development: Exploring the iPhone SDK*. Berkeley, CA: Apress, 2009.
[23] J. A. Frank, "Multimodal mobile apps for intuitive human-machine interaction," M.S. thesis, Dept. Mechanical Aerospace Eng., Polytech. Inst. NYU, Brooklyn, NY, 2013.
[24] J. Sauro and J. R. Lewis, *Quantifying the User Experience: Practical Statistics for User Research*. Waltham, MA: Morgan Kaufmann, 2012.
[25] W. Albert and T. Tullis, *Measuring the User Experience: Collecting, Analyzing, and Presenting Usability Metrics*, 2nd ed. Waltham, MA: Morgan Kaufmann, 2013.

» PRESIDENT'S MESSAGE (continued from p. 13)

NEWS

A related information item is that the IEEE Control Systems Society (CSS) Board of Governors approved a new Technical Committee on Smart Cities at its June 2014 meeting. Raja Sengupta is the founding chair.

TRIVIA

Conversations with fellow members of the CSS Executive Committee (ExComm) provided me with the answers to the following two trivia questions.

- Who has hoboed their way, via train, across the United States?
- Who had an early career as a professional magician?

These two individuals are both current members of ExComm. If you think you know the answers, I will be happy to confirm or deny.

CLOSING

Ideally, enhanced sensing, actuation, communication, and computational capabilities enable increasing utilization of control theory research results, improving performance and reliability, giving rise to new realms of control applications, and motivating new directions of control research. The potential applications keep the value and impact of control theory research in the minds of funding agencies.

I hope to see you at the IEEE Multiconference on Systems and Control (MSC) in Antibes this month. I can be reached in person at the MSC or by e-mail anytime at farrell@ee.ucr.edu.

REFERENCES

[1] T. Ray, "Finally, sensors get personal," *Barron's Technol. Week*, p. 31, Mar. 15, 2014.
[2] P. Saffo. (1997). Sensors: The next wave of infotech innovation. [Online]. Available: http://www.saffo.com/essays/sensors-the-next-wave-of-infotech-innovation/
[3] T. Samad and A. M. Annaswamy, Eds. (2014). "The impact of control technology," 2nd ed. IEEE Control Systems Society. [Online]. Available: http://www.ieeecss.org
[4] Kiva Systems LLC. North Reading, MA. [Online]. Available: http://www.kivasystems.com/

Jay A. Farrell