7-29-2013

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Citation/Publisher Attribution

Jouaneh, Musa, and William J. Palm. "Control systems take-home experiments." *IEEE Control Systems* 33, 4 (2013): 44-53. doi: 10.1109/MCS.2013.2258764.

M. Jouaneh, and W. Palm, "Control Systems Take-Home Experiments", IEEE Control Systems Magazine, Vol. 33, No. 4, pp. 44-53, 2013.

Control Systems Take-Home Experiments

Musa K. Jouaneh and William J. Palm, III

June 3, 2012

Most Mechanical Engineering curricula include courses in system dynamics, controls, mechatronics, and vibrations. The laboratory component for these courses is often limited and involves using a limited number of experimental setups. At many institutions, the laboratories associated with these courses are not taken in the same semester preventing students from practicing the concepts learned in the lecture in a timely manner. Even in lab courses that are offered in the same semester as the lecture courses, in many cases, it is not possible to synchronize the concepts covered in the lecture with the laboratory exercises since there are usually only a few lab setups for each experiment.

While increased lab time is needed, many students work at outside jobs and live far from campus in many schools. Most laboratories are only open during normal business hours, severely limiting the times at which students can access equipment. This makes it harder for these students to have enough time to come to school to perform an experiment in the university laboratory. In addition, almost all students have home PC's (either desktops or laptops) that are suitable for take-home experiments. This makes it possible for students to perform an experiment or obtain measurements outside the lab at their own convenient time, just as they would with a homework assignment.

Providing engaging laboratory experience is one of several challenges to effective undergraduate education in STEM disciplines as reported by The National Research Council

(NRC) [1]. Control systems concepts are often perceived by the students as a "large collection of abstract mathematics" [2]. An experiential approach, such as that offered by take-home experiments, offers a means to show the role of the course material in engineering devices and systems. Furthermore, providing personalized learning is one of the 14 Grand Challenges for Engineering in the 21st century as determined by a committee of the National Academy of Engineering [3]. Take-home kits allow every student to perform experimentation at his or her own pace tailored to the student's individual learning needs.

This article addresses the development and implementation of take-home hardware kits and software that can be used to perform laboratory experiments and measurements at home to improve the understanding of system dynamics concepts in an undergraduate student population. Rather than having students perform an experiment in the university laboratory, the students are given a compact, low cost kit with which they can perform an experiment at home using their own PC/laptop. The kits are designed so that the experiments can be conducted on a provided experimental setup or can be used to perform dynamic measurements on engineering systems that are available at home such as motor powered devices and heating/cooling systems.

A survey of the literature showed that there is an increasing interest in performing measurements and experimentation in engineering programs outside of the traditional university laboratory. Reference [4] reported on take-home experiments in fluid mechanics to illustrate basic concepts such as hydrostatics and the Bernoulli equation. Reference [5] reported on a pump flow take-home experiment in an introductory fluid flow lecture class. Reference [6] reported on the use of commercially available attaché cases or electronic trainers that cost in the $200 to $350 range for conducting experiments at home in lower division electronic laboratory courses. In [7], the authors reported on a project to develop take home experimental setups. They developed two setups, a linear mass spring-damper-system for frequency response and system identification, and an analog filtering system that uses music and synthetic sound as an input. Reference [8] discuss the use of the LEGO programmable brick as a portable data acquisition system to conduct personal engineering experiments at home. In [9], the authors reported on the use of take-home kits in an introductory digital design course. In [10], the authors reported on the use of a home experimentation kit for digital and analog electronics in a first-year undergraduate electronics course.

Many educators have also reported work on remote control of experiments; see for example [11-23], where students perform an experiment at a distance location using the Internet as the control interface. This approach allows the same experimental setup to be used by many students, while also giving the students the opportunity to conduct an experiment at a convenient time and location. However, it does not give the same experience as performing the experiment in person, and there could be issues in equipment availability, especially in large classes.

A challenge in performing experiments at home is developing low-cost experimental setups that are rugged, easy to set up and use by the students, and also at the same time produce meaningful results and opportunities for testing of theory. The NI LabVIEW software, which is available at many institutions, is a powerful package for laboratory data acquisition, but it has a steep learning curve, is expensive for home use, and requires additional hardware. The authors believe that the approach developed by them offer a robust, scalable, and economical approach for take-home kits development and use.

Portions of this article were previously presented in [24] and [25]. The remainder of this article is organized as follows. The next section discusses the components of the take-home kit.

This is followed by a discussion of the two control experiments: motor control, and temperature control. The article also discusses how the take-home kits were administered, and how the effectiveness of the kits were measured. The article concludes by discussing the lessons learned from performing this project.

Take-Home Laboratory Kit

The take-home kit consists of three components. The first component is a hardware interface board that interfaces with the student's PC and with the experiment's hardware. The second component is the User-Interface (UI) Program that is loaded on the student's PC and is used to run the experiment and collect data. The third component is the actual experimental setup or the sensor system to perform the measurement. In this project, we have developed five experiments that were used in various courses in the mechanical engineering curriculum at the University of Rhode Island. In this article, we will discuss the two control experiments that were developed: a DC motor with tachometer, and a plate with heater. In the following sections, we will discuss the components of the kits along with the details of these experiments.

Hardware Interface Board

The hardware interface board houses all the components that perform measurement, actuation, control, and communication. The hardware interface board was custom-designed and was built around a PIC18F4550 microcontroller from Microchip Technology, Inc. A photo of the developed board is shown in Figure 1. The board is mounted inside a plastic enclosure with openings at both ends. The openings are designed to allow cables and connectors to be easily attached to the board. We decided to design a custom board because there is no commercially-available board that has all the components that we need to perform all the experiments. In addition to the microcontroller, the hardware interface board includes the following:

- 32K bytes of additional RAM since the PIC18F4550 has only 2K of RAM
- A 20 MHz crystal with associated capacitors
- Status LEDs, and several resistors and capacitors
- A 5-amp H-bridge driver chip
- A MAX232 chip for serial communication with the PC
- Connectors for: a 12-volt power supply; programming cable, USB and serial interfaces, and the various experimental setups

To use the hardware-interface board, the student connects the output of the provided 12-volt power supply adapter to the board. The student needs also to connect the serial/USB interface cable from the PC to the board, and the cable for the specific experiment to be performed. With these connections, the experimental hardware is ready. Powering the board causes the loaded program inside the microcontroller to run. The program waits for user input from the UI Program

User Interface Program

A screen shot of the developed Windows-based UI Program is shown in Figure 2. The UI Program was developed in Visual Basic Express 2008, and it communicates with the embedded program on the microcontroller through either a serial or USB connection. The embedded program was developed in C using the PICC compiler from CCS, Inc. of Waukesha, WI. The UI Program transfers the experiment's settings to the PIC microcontroller, provides monitoring and control of the experiment's progress, retrieves the data collected after the experiment is completed, and performs saving of the collected data to a file. The UI Program does not perform any measurement or feedback control activities. These are done on the PIC microcontroller. On each processor, the software is implemented as a state-transition machine [26]. The UI Program acts as the master which initiates all communication between the two devices. Since the UI and the PIC programs are running independently, a handshaking mechanism is employed in the transfer of data between the two programs to insure that the data is transmitted properly. No new data is sent from the UI Program to the PIC unless the UI Program receives an acknowledgement from the PIC on the previous data transfer.

The Motor Control Experiment

The experimental hardware consists of a small DC motor (Transicoil 1121-110 DC Servo Motor Tachometer) with a built in tachometer (see Figure 3). The control input to the motor is supplied from the PWM output of the micro controller through the H-Bridge driver. The speed of the motor is measured from the tachometer using the 10-bit A/D converter on the microcontroller.

In this experiment, the students first performed a calibration test to relate the steady state speed of the motor to the input voltage. This test will reveal any nonlinearities in the response such as those caused by friction. The students then performed an open-loop step response of the motor-tachometer system. From the data, the students obtained the parameters of a first order model of the system. The model was then used to compute the PI gains K_P and K_I necessary to achieve a desired time constant and damping ratio for the closed loop system. Finally they ran the experiment with the computed gain values and compared the data with simulation results.

The motor can be modeled as a first order system with a time constant τ and a zero-frequency gain b. An RC filter was connected the motor output terminals to reduce noise. Its time constant is $RC = 0.01$ s. Thus the open-loop model form is

$$\frac{V_o(s)}{V_i(s)} = \frac{b}{(\tau s + 1)(0.01s + 1)}$$

where $Vi(s)$ and $Vo(s)$ are the transforms of the input and output voltages. The students obtained open-loop speed data by selecting a 4 V input. Noting that if V_i is a constant, the steady-state output voltage is bV_i. Using this fact with $V_i = 4$ V, the students used the open-loop step response plot to estimate b. They then estimated τ from the time it takes for the output to reach 63% of its steady-state value. Using the MATLAB *tf* and *step* functions with a step input magnitude of 4, they refined their estimates of τ and b by comparing the model response with the data. Table I shows the time constants measured by each of the eight students who performed the experiment in the spring 2009 semester. A different motor was used by each student. The data is close to the time constant measured by the authors (0.041 s).

The motor model was then used to compute the PI gains K_P and K_I necessary to achieve a) a desired steady-state output of 4, b) a dominant time constant no greater than 0.1 s, and c) a damping ratio greater than 0.707. The students did this by using the root locus method applied to the following root-locus equation.

$$1 + K\frac{s + 1/T_I}{s(s + 1/\tau)(s + 100)} = 0$$

where the root-locus gain is $K = 100bKP/\tau$. Using the MATLAB utility *rltool*, they selected a suitable value for T_I and then adjusted the gain K to meet the specifications, using the method illustrated in [27]. The proportional and integral gains were then found from $K_P = \tau K/100b$ and $K_I = K_P/T_I$. Finally they ran the experiment with the computed gain values and compared the data with simulation results. Figure 4 shows a plot of the simulation and the experimental data for a particular motor. The command input was 4 V, and the PI gains were 0.61 and 20, respectively. For the open-loop plant model given in the figure, a 4 V input would result in a steady-state output of 4(0.4888) = 1.95V. However, the figure shows that the closed-loop system produces a steady-state output of 4 V, so the steady-state error is zero. The closed-loop time constant is less than 0.1, and the damping ratio is greater than 0.707, as required.

The Temperature Control Experiment

The experimental hardware (see Figure 5) consists of a small rectangular (50.8 mm x 38.1 mm x 12.7 mm) copper plate heated by a 10-W flexible silicone-rubber heat strip that is glued to the bottom of the plate. The plate is mounted horizontally on a 76 mm x 102 mm polycarbonate base that acts an insulator. A small hole is drilled into one side of the plate, and a thermo-transistor temperature sensor (LM35C plastic package from National Semiconductor) is inserted into the plate to read to read the temperature of the plate. The temperature sensor has a sensitivity of 10 mV/°C, and a measurement range of -40 to 110 °C. A small brushless DC fan is attached to the base to provide optional cooling or disturbance input. The control input to the heater is supplied from the PWM output of the micro controller through the H-Bridge driver. The temperature is measured using the 10-bit A/D converter on the micro controller. With a voltage reference of 2.5 volts for the A/D, the temperature measurement resolution is 0.244 °C. The heat output rate q from the heater is directly proportional to the heater voltage v: $q = Kv$, where K = 10/12 W/V.

In this experiment, the students collected the open loop temperature response of the plate over 1 hour when subjected to two different input voltage levels such as 6 volts and 9 volts. This was done to check the linearity of the system. Then they used the open loop data to obtain a dynamic model of the heated plate. Based on that model, they selected appropriate control gains to control the temperature of the plate. Finally they tested the selected gains by running a closed loop control test for about one hour with a desired temperature of 50 °C. Figure 6 shows the results for an open loop test in which the heater output was 7.5 W (9 V input).

A basic model of the copper plate excluding radiation effects is:

$$RC\frac{dT}{dt} = T_a - T + Rq$$

where T = plate temperature, T_a = ambient temperature, q = heater output (W), C = thermal capacitance, and R = convective resistance. The solution is (assuming that $T(0) = T_a$):

$$T(t) = T_a + Rq(1 - e^{-t/RC})$$

The parameter R and C can be determined experimentally from analyzing the open-loop temperature response of the plate to a given heat input. For example, using the data in Figure 6, R is 8.66 °C/W and the time constant τ is 1100 s. The figure also shows the solution of the model. The model agrees well enough with the data to be useful for designing the control algorithm. Table II shows the range of time constants for this system as determined by each student using a different setup in a group of 23 students who did the experiment in the Fall 2010 semester. The variability comes from how the students estimated the time constant from the experimental data.

The model was used to design a PI controller. The PI gains were selected to give a closed loop system with a damping ratio of ζ =1 and a desired closed-loop time constant τ_d close to 550 s.

Since the heater voltage is limited to 12 V, if τ_d is selected too small, the heater will saturate. A Simulink model was constructed to investigate how small τ_d could be made without causing saturation. It was found that τ_d close to 550 s was the smallest possible value. Figure 7 shows the experimental results using the calculated gains (Kp = 0.40 and Ki = 4.8 x 10-4) for ζ = 1 and τ_d =566 s. The agreement between the data and the model is obvious.

Kit Administration

The speed control experiment was administered three times so far (Spring 2009, Spring 2011, and Spring 2012 semesters), but evaluation data is available for only the first two offerings. The experiment was used in the senior-level technical elective Computer Control of Mechanical Systems course (MCE431) which had an enrollment of 9 and 20 students, respectively in these semesters. The heated plate experiment was administered three times so far (Fall 2009, Fall 2010, and Fall 2011 semesters), but evaluation data is available for only the first two offerings. The experiment was used in the senior-level technical elective Mechatronics course (MCE433) which had an enrollment of 10 and 23 students, respectively in these semesters. We gave each student one complete kit that consists of the hardware interface board, power supply, interface cable, and the experimental system used to perform the take-home experiment. The students were asked to download and install the UI Program on their PC. The students were given about a week to do the take-home experiment, after which they were required to submit a report on the experiment. The students returned the kit to the instructor after the completion of the experiment. The theory of each experiment was covered in class before the experiment is conducted. The dynamic model of the respective system was derived in class, and the relationship between the control gains and the performance parameters such as damping ratio and time constant were also discussed. A web-site with You-Tube videos, that shows how to set-up and run each experiment, was developed and made available to the students. The instructors were also available in and out of class to answer any student's questions about the take-home experiments.

Kit Effectiveness

To evaluate the kit effectiveness in increasing student understanding of system dynamics and control concepts, the students were given a survey after they completed the experiment. In addition to the report that the students needed to write on the take-home experiment, the students were also tested on the relevant topics in course exams or quizzes, given before and after the experiment.

Tables III and IV show the response of the students to two questions on the survey that determine their perceptions on performing unsupervised experiments at home. The results for Question 1 ("How convenient is a take-home experiment than doing an experiment in the school lab?") are shown in Table III

The data shows that the majority of the students had reported that the take-home kits were convenient compared to doing an experiment in the school lab (53.8% of the entire sample reported it is Very Convenient and 36.6% of the entire sample reported that is Somewhat Convenient). A similar response was obtained for Question 2 ("How comfortable are you in performing an unsupervised experiment at home?") where more than 96% of the students said that they were Very comfortable or Somewhat Comfortable in performing unsupervised experiment at home. Note that the Very Convenient and Very Comfortable rating has improved on the second usage of the kits in both courses.

When students were asked to rate the extent to which the kits contributed to their learning of basic control concepts in these two courses (Question #3 on the Student Survey), the majority indicated that the take home kits contributed either To Some Extent or To a Great Extent, across all of the conceptual topics with the exception of one topic in MCE433- Fall 2009. The data is illustrated in Tables V and VI. For MCE431 class, close to 70% of the students have said that the kit had contributed To Great Extent in understanding three of the five concepts (Concepts 3a, 3c, and 3d) covered by the take-home experiment with the other two concepts not far behind. For MCE433, more than 90% of the students have said that the kits had contributed either To a Great Extent or to Some Extent in understanding the concept of the "Response of closed-loop control system" (Concept 3e) in both offerings of the course. The two concepts that the students ranked the least in Fall 2009 semester were "First order system response" and "Model development from data" (Concepts 3a and 3b). Note that the 2010 offering data showed that more students have rated the kits as having To Some Extent or a To a Great Extent impacted their learning compared to the first offering with the kits in Fall 2009. This is attributed to refinements in the kits software that were made in the second offering.

Students were also asked to further elaborate by ranking the extent of contribution of the Kits, Lectures, Text(s) and Homework to their understanding of the main concepts (Question #4 on the Survey). The results are shown in Figure 8. In the MCE431 course (Computer Control of Mechanical Systems), the kit was ranked the highest for one concept (4b) but behind class lecture in the other concepts. In both offering of the MCE433 course (Mechatronics), the students ranked the kit first just ahead of class lectures and the text, and significantly ahead of the homework. From this data, we can say that the students had perceived the take-home kits to have a contribution to understanding of system dynamics concepts comparable at least to class lectures and more effective than traditional homework and textbook examples. Note that Questions #3 and #4 in the student survey were not used in the Spring 2009 semester, so data for the MCE431 offering in the Spring 2009 semester is not shown.

Table VII presents a compilation of the quiz and lab grades for the two affected courses. The quizzes were given before and after administering the take-home kit in each course. The pre and post quizzes contained similar conceptual problems but were worded and presented differently. A review of this table indicates that for the three sections where quiz data was available, the students quiz averages increased from pre to post testing. There is no definitive way to credit the kits with this increase in student grades. The evaluation design did not include a control group so that a simultaneous comparison of both quiz grades and final grades to students in other classes where the kits were not implemented can be performed. Nevertheless, the data indicated that the kits had a positive effect on student quiz grades. An examination of the Take-Home Lab reports scores indicates that for the corresponding sections, the average grades were high, and were substantially higher than the quiz grades. One explanation for the higher lab reports grades is that they were done at home with no limitation on time or additional resources to use.

The majority of the students also noted that both the software and the hardware of the take-home kits were easy to set up and use. We also noticed a substantial increase (>100%) in undergraduate mechanical engineering student interest in experimental system dynamics courses as evidenced by an increase in the student enrollment in the technical elective courses in this area in the semesters after the kits were placed in service. It is to noted that, given that the only opportunity–prior to the kits–students might have to perform such experiments would have been if such activities occurred during a class or through a separate lab session, these kits made it convenient and easy to perform at a time more convenient to them. Consequently, one can surmise that this was an improvement to the experiential learning of URI Engineering students.

Lessons Learned

Designing and developing a custom interface board as was done in this project was an involved and lengthy process that took about two months of effort. This investment is worthwhile since it resulted in a cleaner (no need for multiple circuit boards) and error-proof method of connecting the different components to the board (prevents student from making a wrong connection) through the use of connectors that only fit one way. We also find that providing instructions on the use and setup of the kits through YouTube videos is an effective way to distribute information and appeals very well to students.

While the development and use of the take-home kits was accomplished, there were some difficulties that were encountered during the project implementation. One difficulty was the reliability of data transmission from the PIC microcontroller to the PC using a USB interface across different Windows operating systems. This problem was resolved by utilizing a USB-to-serial converter interface instead of pure USB interface. One interesting thing we have noted is that few students (less than 5%) did not attempt to do the take-home experiment at all. This is no different from regular homework assignments where some students do not attempt to do the homework.

The major benefit of the take-home experiments is that they give the students an opportunity to conduct a control experiment on their own. Students were able to better understand the concept of the response of a closed-loop control system and the effects of the control gains on changing the response of the system. The take-home kits have also allowed URI students to perform experimentation in courses that normally have had no experimentation (such as MCE431). Students feedback has shown that, over conventional instruction alone, the kits provided supplemental instruction that was realized, noted and appreciated by the students, and were perceived as more effective than traditional homework and textbook examples Also, the majority of students reported that they were comfortable working on and with the take-home kits independent of a lab or instructor.

An advantage of the developed take-home kit is its low-cost (total components less than $150), ruggedness, reliability, and the use of the same User Interface Program for all experiments. Noteworthy is that after administering the kits in many courses over a three year period, the kits were almost in perfect condition. This is a combination of the high degree of responsibility on the part of the students and the rugged design of the kits. The kits are also scalable and were also used in other courses with much larger enrollment (about 60). Work is underway to pursue the development of additional experimental setups and the implementation of the kits at other institutions.

Acknowledgment

The authors would like to thank James Byrnes for his help with the detail design of the hardware interface board. This work was supported in part by the National Science Foundation under Award # DUE-0736603.

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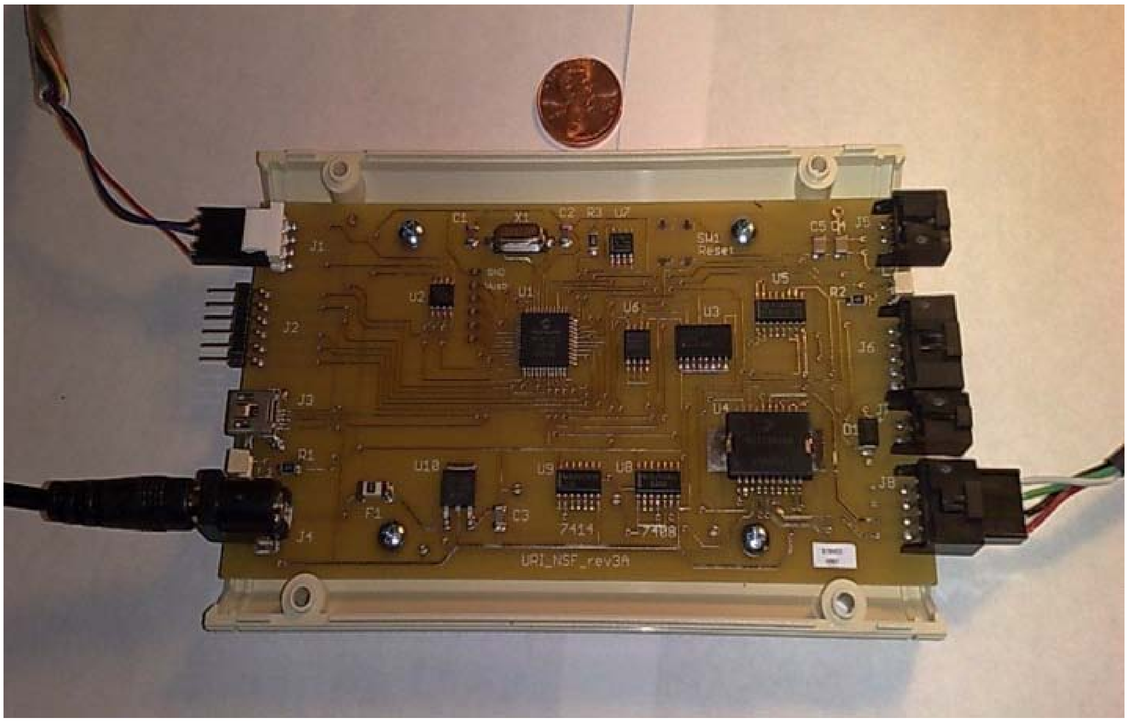


Fig. 1. Hardware interface board with the plastic cover removed. The board uses Microchip PIC18F4550 microcontroller as the processor. The right-hand side of the figure shows the connectors for the different experiments, while the left-side of the board shows the connectors for serial, programming, USB, and power. This board was custom made. After the board was designed, the Eagle design files were sent to a company which made the board and also robotically assembled the board components. At URI, we assembled the board into the plastic enclosure (pre-selected at the design stage).

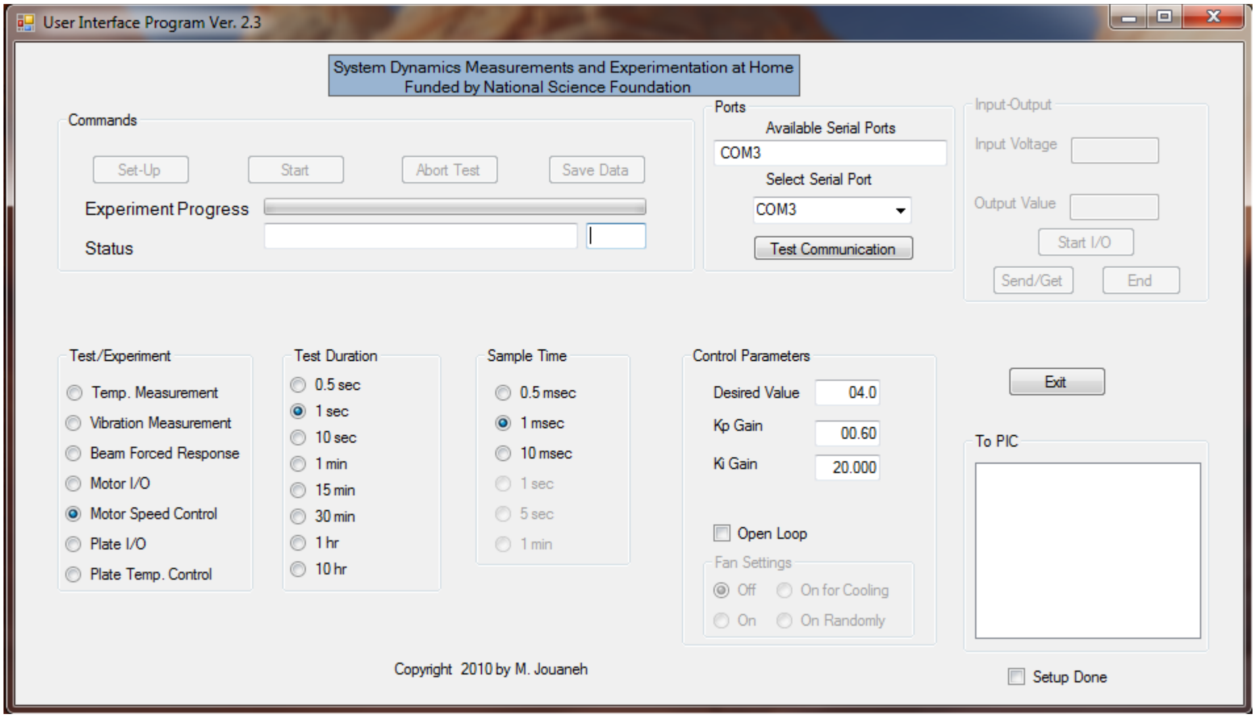


Fig. 2. A screen-shot of the User-Interface (UI) Program. The UI Program was developed in Visual Basic Express 2008, and it communicates with the embedded program on the microcontroller through either a serial or USB connection. The embedded program was developed in C using the PICC compiler from CCS, Inc. of Waukesha, WI. The UI Program transfers the experiment's settings to the PIC microcontroller, provides monitoring and control of the experiment's progress, retrieves the data collected after the experiment is completed, and performs saving of the collected data to a file. The UI Program does not perform any measurement or feedback control activities. These are done on the PIC microcontroller. The UI program allows the student to select the type of experiment to perform, the test duration, and the sample time. Depending on the experiment performed, the UI allows also the entry of the desired and control gains values as well as the ability to perform open or closed-loop control tests.

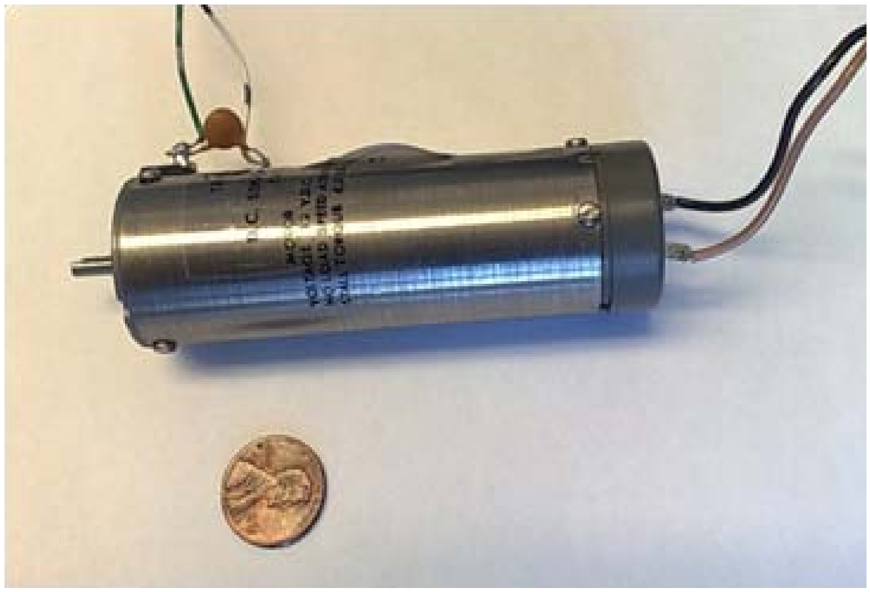


Fig. 3. Motor-Tachometer Setup**.** The setup consists of a small DC motor (Transicoil 1121-110 DC Servo Motor Tachometer) with a built in tachometer. The DC-motor tachometer was fitted with a low-pass filter with an RC value of 0.01 s (resistor and capacitor shown in the upper part of the figure) to reduce the ripple from the tachometer. The control input to the motor is supplied from the PWM output of the micro controller through the H-Bridge driver. The speed of the motor is measured from the tachometer using the 10-bit A/D converter on the microcontroller.

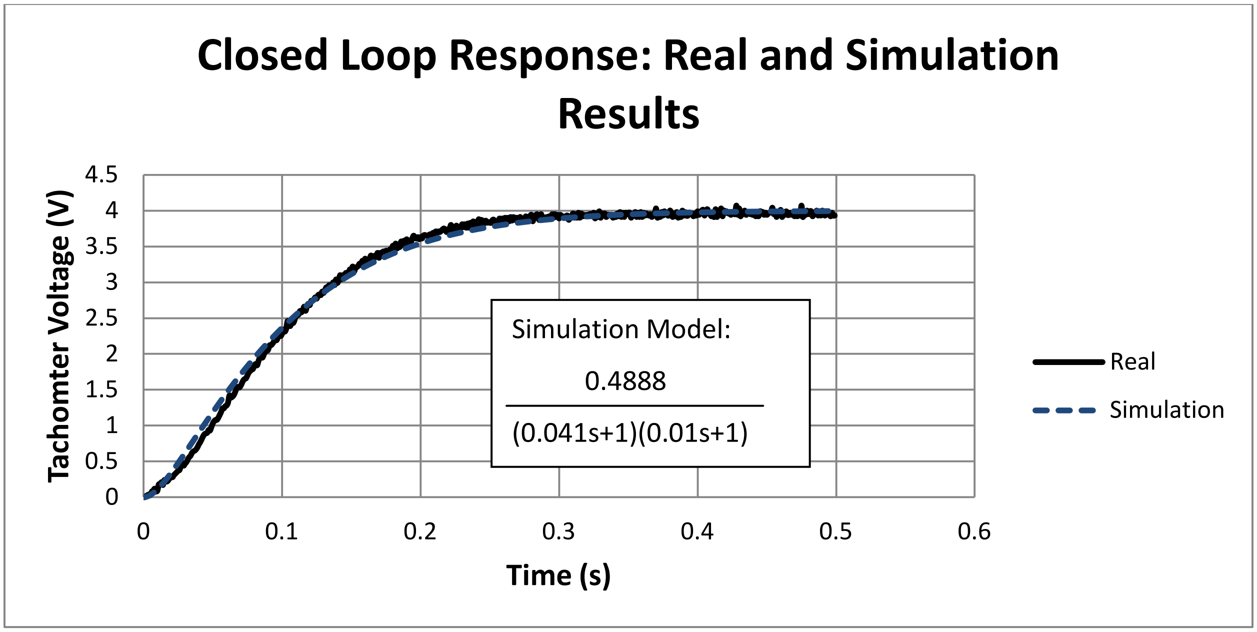


Fig. 4. Experimental and simulation results for closed-loop speed control using a PI controller. In this test, a desired speed of 4 volts (same units as the tachometer output) was specified, the test duration was 1 second, and the sampling interval was 1 ms. After the experiment is completed, the UI program writes the data into a text file using a two-column format. The data file is then read by MATLAB or Excel for plotting.

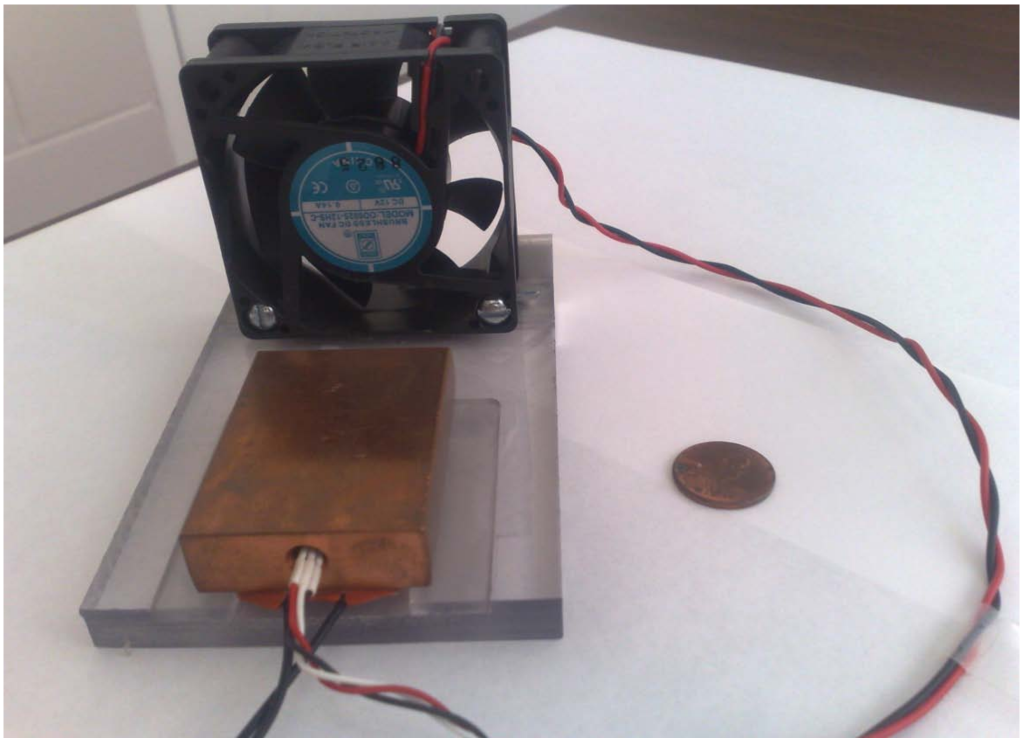


Fig. 5. Experimental Hardware for Temperature Control Experiment. The hardware consists of a small rectangular (50.8 mm x 38.1 mm x 12.7 mm) copper plate heated by a 10-W flexible silicone-rubber heat strip that is glued to the bottom of the plate. The plate is mounted horizontally on a 76 mm x 102 mm polycarbonate base that acts an insulator. A small hole is drilled into one side of the plate, and a thermo-transistor temperature sensor (LM35C plastic package from National Semiconductor) is inserted into the plate to read to read the temperature of the plate. The temperature sensor has a sensitivity of 10 mV/°C, and a measurement range of -40 to 110 °C. A small brushless DC fan is attached to the base to provide optional cooling or disturbance input.

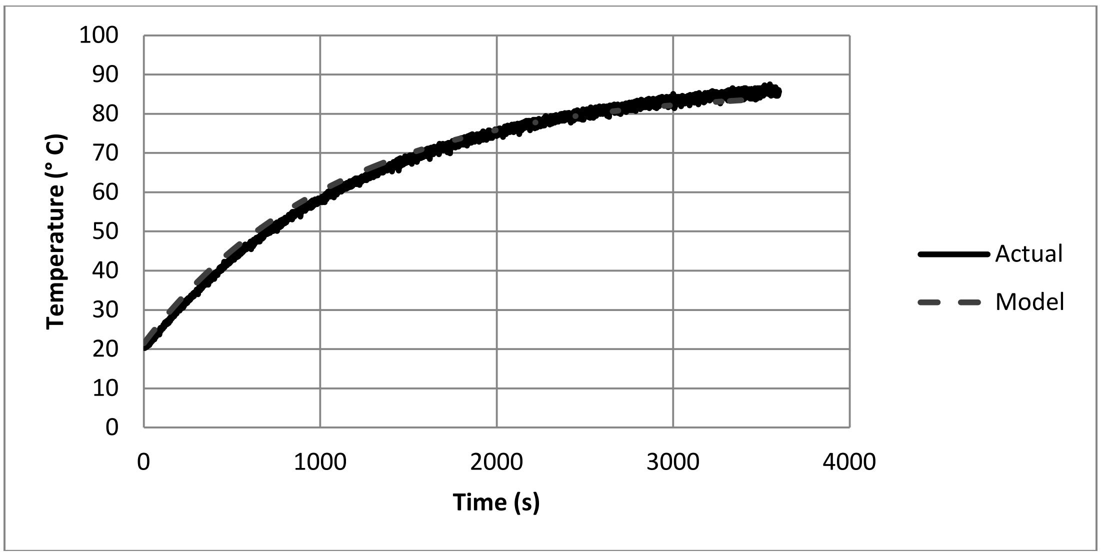


Fig. 6. Open loop response of the plate/heater system with q = 7.5 W. The test duration is 1 hour, and the sampling interval is 1 s.

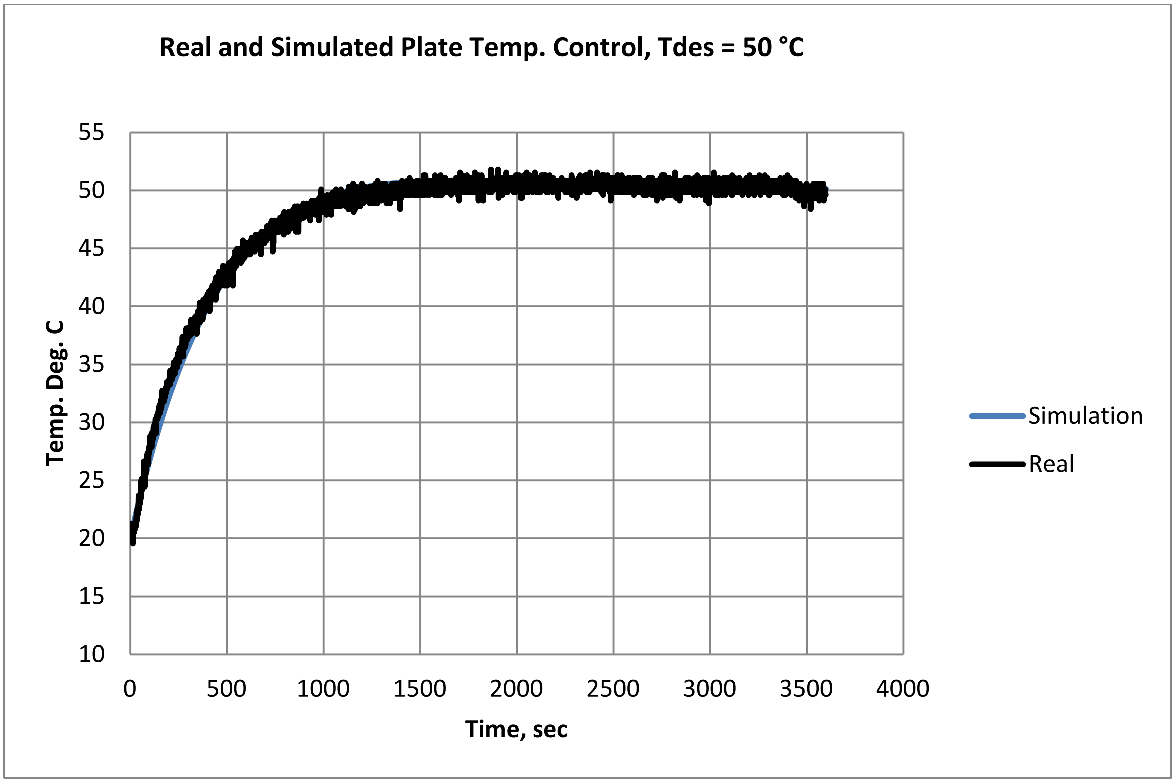
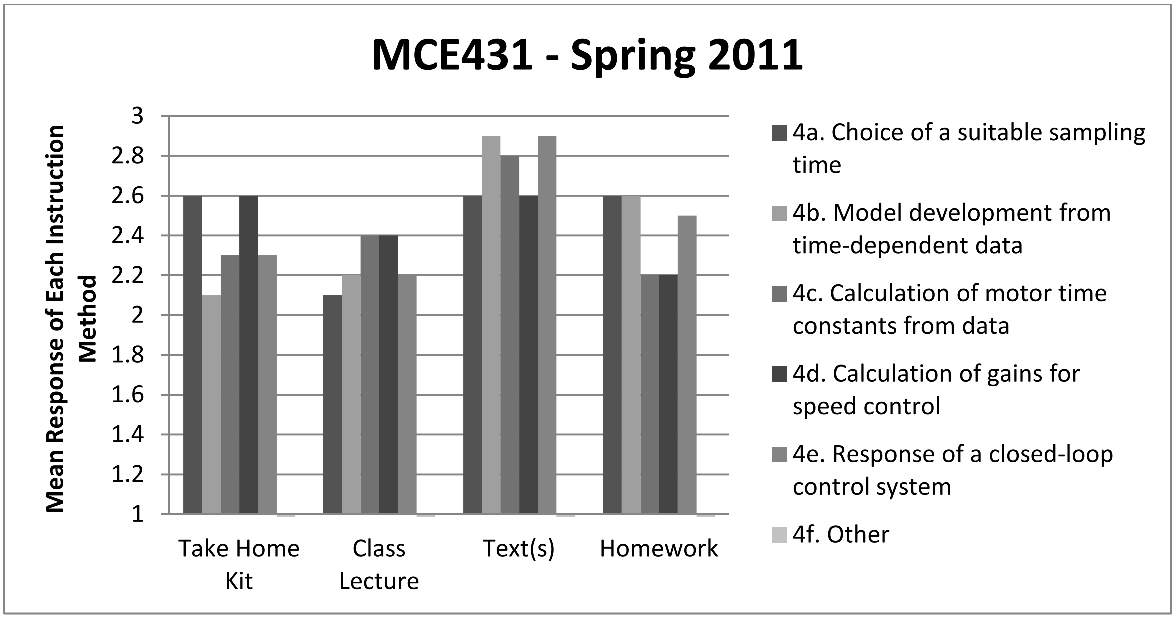


Fig. 7. Experimental and simulated closed-loop PI control for the plate setup. The desired temperature is 50 C, and the sampling time is 1 second. The PI gains were selected to give a closed loop system with a damping ratio of ζ =1 and a desired closed-loop time constant τ_d close to 550 s.



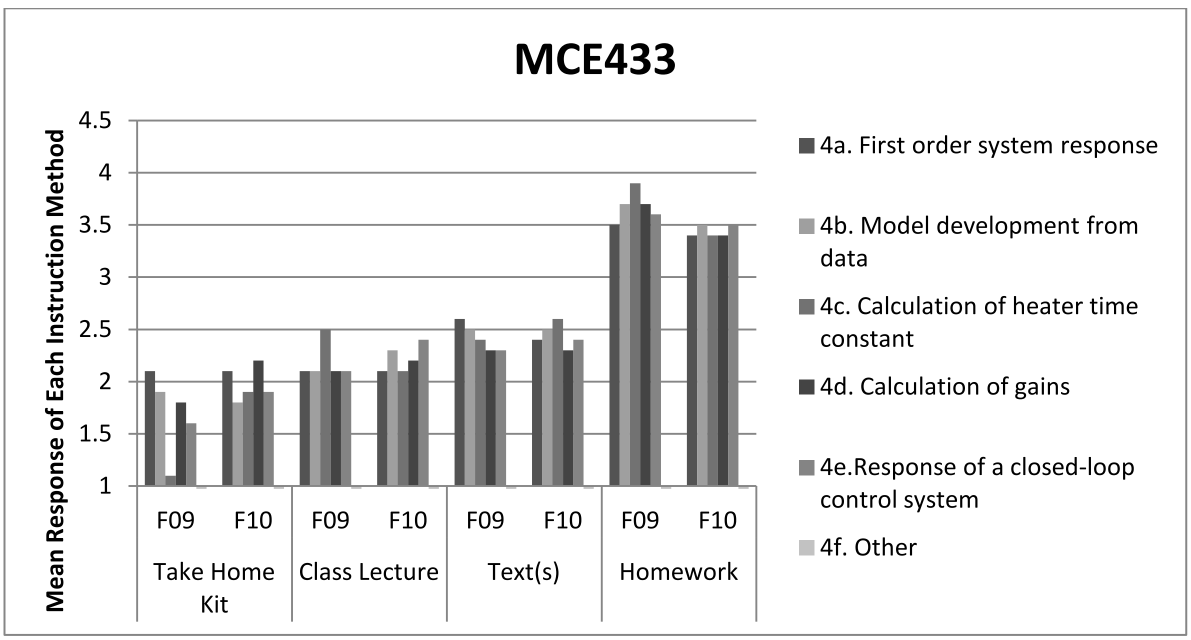


Fig. 8. Response of students to the question that ranks the effectiveness of the different instructional methods (1: the most effective, 4: the least effective). The data is shown for two offering of the course, Fall 2009 and Fall 2010. The mean response for each instructional method is shown.

TABLE I

Time constants (s) determined by eight students who performed the speed control experiment in Fall 2009.

Data	0.034, 0.03, 0.04, 0.03, 0.031, 0.04, 0.027, 0.03
Average	0.033

TABLE II

Time constants (s) for the heated plate experiment determined by twenty three students who performed the experiment in Fall 2010 semester.

Minimum	960
Maximum	1325
Average	1160
Standard Deviation	93

Table III

Response of students (percentage) to Question 1 on the student survey - "How convenient is a take-home experiment than doing an experiment in the school lab?". The survey is given to the students after they have performed the experiment.

Semester	Course	Class Size	Sample Size (N)	Very Inconvenient	Somewhat Inconvenient	Cannot Decide	Somewhat Convenient	Very Convenient
Spring 2009	**MCE431**: Computer Control of Mech. Systems	9	8	0.0	12.5	0.0	50.0	37.5
Fall 2009	**MCE433**: Mechatronics	10	8	0.0	0.0	0.0	62.5	37.5
Fall 2010	**MCE433**: Mechatronics	23	20	0.0	0.0	15.0	35.0	50.0
Spring 2011	**MCE431**: Computer Control of Mech. Systems	20	16	0.0	6.3	0.0	18.7	75.0
	Results for Entire Sample (N = 52)			0.0	3.8	5.8	36.6	53.8

Table IV

Response of students (percentage) to Question 2 on the student survey - "How comfortable are you in performing an unsupervised experiment at home?". The survey is given to the students after they have performed the experiment.

Semester	**Course**	**Class Size**	**Sample Size (N)**	Very Uncomfortable	Somewhat Uncomfortable	Cannot Decide	Somewhat Comfortable	Very Comfortable
Spring 2009	**MCE431**: Computer Control of Mech. Systems	9	8	0.0	0.0	0.0	62.5	37.5
Fall 2009	**MCE433**: Mechatronics	10	8	0.0	0	0	50.0	50.0
Fall 2010	**MCE433**: Mechatronics	23	20	0.0	5.0	0.0	30.0	65.0
Spring 2011	**MCE431**: Computer Control of Mech. Systems	20	16	0.0	6.3	0.0	37.5	56.2
	Results for Entire Sample (N= 52)			0.0	3.8	0.0	40.4	55.8

Table V

Compiled response (%) for question 3 on student survey in MCE431 course in spring 2011 (n= 16). The question asks the students to rate the extent to which the kits has contributed to their learning of several concepts. The survey is given to the students after they have performed the experiment.

3. **To what extent has the Take Home Kit contributed to your learning the concept of:**	**Not At All**	**Little**	**To Some Extent**	**To a Great Extent**
3a. choice of a suitable sampling time.	-	6.2	25.0	68.8
3b. model development from time-dependent data.	-	13.6	27.3	59.1
3c. calculation of motor time constants from data	-	-	31.2	68.8
3d. calculations of gains for speed control.	-	-	31.2	68.8
3e. response of a closed-loop control system.	-	-	43.7	56.3
3 f. Other	-	-	-	6.2

TABLE VI

Compiled response (%) for Question 3 on student survey in MCE433 course in Fall 2009 (n= 8) and Fall 2010 (n = 20). The question asks the students to rate the extent to which the kits has contributed to their learning of several concepts. The survey is given to the students after they have performed the experiment.

3. To what extent has the Take Home Kit contributed to your learning the concept of:	Not At All		Little		To Some Extent		To a Great Extent		Blank	
	09	10	09	10	09	10	09	10	09	10
3a. first order system response.	0	0	37	0	38	65	25	35	0	0
3b. model development from time-dependent data.	0	0	50	0	38	35	12	65	0	0
3c. calculation of heater time constant from data.	0	0	12	15	63	30	25	50	0	0
3d. calculation of gains for temperature control.	0	0	25	15	37	40	38	40	0	5
3e. response of a closed-loop control system.	0	0	0	5	12	60	88	35	0	0
3 e. Other	0	5	0	0	0	0	0	0	0	95

TABLE VII

MC431 and MCE433 pre/post quiz results. The quizzes were given before and after administering the take-home kit in each course. The pre and post quizzes contained similar conceptual problems but were worded and presented differently.

Sem.	**Enrollment**	**Pre-Lab Quiz Average**	**Take-Home Lab Average**	**Post-Lab Quiz Average**
Fall 2009	10	48%	91%	61%
Fall 2010	23	44%	90%	60%
Spring 2011	20	77%	91%	84%