# Undergraduate Controls Laboratory Experience

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## Abstract

The purpose of this paper is to share the educational experience offered to the students through a controls laboratory course in the electrical engineering program at the University of North Florida. The laboratory experience included the design and prototyping of proportional, proportional-integral, proportional-derivative, and PID controllers as operational amplifier circuits and also as stand-alone C programs that ran on Motorola's M68HC912B32 microcontrollers. Both types of controllers (analog and digital) were applied to a single shaft mechanical plant driven by a dc motor. Through these controllers, the students attained precise position and speed control of the motor. They also observed the difference in the performances of the analog and digital controllers and identified the advantages and disadvantages of each type. This paper describes the labs developed for the students, the lab results, and the students' learning experience. Student evaluations for this lab course were very favorable. Through this lab course and two control theory courses, the students gained good understanding of the fundamentals of feedback control systems.

## I. Introduction

This section gives a brief discussion on the motivation of developing the controls laboratory course and the enhancement of the controls area in the electrical engineering curriculum at the University of North Florida.

It was the wish of the electrical engineering faculty at the University of North Florida to create a controls laboratory in the Department of Electrical Engineering. One of the purposes was to strengthen the controls area of the curriculum.

For many years there was only one controls course (Linear Control Systems EEL4657, 3 credit hours) in the electrical engineering curriculum. The controls course covered the design and analysis of feedback control systems modeled by transfer functions. The course was a theory course. The topics included Routh stability test, Nyquist stability criterion, frequency response design methods, and root locus design methods. There was no coverage of computer-aided control system design (CACSD) techniques.

In 1996, CACSD techniques were added to the controls course. The software package used was Program CC[16,17]. A set of computer simulation experiments was developed to guide the students through the CACSD process. The simulation experiments covered mostly the design of a range of compensators for improving control system performance. The simulation experiments were described in [18]. Later, the funding allowed Matlab to be used in place of Program CC. The simulation experiments were rewritten for Matlab in 1999. The list of the simulation experiments is shown below.

Experiment 1: Laplace transforms
Experiment 2: Step responses of first, second, and higher order systems
Experiment 3: Computation of poles and zeros and determination of stability
Experiment 4: Transfer function and state-space representations
Experiment 5: Root locus and delay
Experiment 6: Root locus design: proportional integral compensation
Experiment 7: Root locus design: cascade lag compensation
Experiment 8: Root locus design: cascade lead compensation
Experiment 9: Root locus design: cascade lag-lead compensation
Experiment 10: Root locus design: velocity feedback and proportional derivative compensation
Experiment 11: Root locus design: PID compensation
Experiment 12: Bode plots, Nyquist plots, gain and phase margins
Experiment 13: Frequency response design: proportional integral compensation
Experiment 14: Frequency response design: cascade lag compensation
Experiment 15: Frequency response design: cascade lead compensation
Experiment 16: Frequency response design: cascade lag-lead compensation
Experiment 17: Frequency response design: velocity feedback compensation
Experiment 18: Frequency response design: PID compensation

To widen the coverage of the controls area in the curriculum, a new three credit-hour controls course (Modern Control Systems EEL4610) was added to the curriculum in 1997-1998. This course covered the design and analysis of control systems modeled by state-space equations. The course was a theory course with intensive coverage of CACSD techniques.

Topics of the course included state-space representation, transformations, and diagonalization; time-domain responses of state space equations; asymptotic stability; BIBO stability; pole-zero cancellation; controllability and observability; state feedback and pole placement; observer design; reduced-order observer design; linear-quadratic regulator problem; Kalman filtering; linear-quadratic Gaussian problem; and numerical solution of algebraic Riccati equations.

Linear algebra was also extensively covered in this course. The ABET 2000 advanced math requirement for electrical engineering includes, typically, linear algebra and other topics. The modern controls course is the only course in our electrical engineering program that covers linear algebra.

Matlab was used extensively in the course. Eight Matlab simulation experiments were developed covering most of the topics in the syllabus. The simulation experiments helped the students to gain good understanding of the course materials. The Matlab experiments were described in [19]. The list of the simulation experiments are shown below:

Experiment 1: Conversion between state-space representation and transfer function representation
Experiment 2: Similarity transformation, diagonalization, and time response of a state-space system
Experiment 3: Controllability, observability, and pole placement using full state feedback
Experiment 4: Full-order observer design
Experiment 5: Linear quadratic regulator problem
Experiment 6: Kalman filter design
Experiment 7: Linear quadratic Gaussian problem
Experiment 8: Numerical solution of algebraic Riccati equations

The electrical engineering faculty at the University of North Florida also desired to provide hands-on controls laboratory experience to the students. A one credit-hour controls laboratory course (EEL4657L) was added into the curriculum as an elective in fall 2000. The prerequisite for the controls laboratory course was the first controls course. The controls laboratory course covered the applications of proportional, PD, PI, and PID controllers in position and speed control of dc motors. The theory of designing these controllers can be found in many controls textbooks [6, 7, 8, 9, 12, 13, 15].

A controls laboratory was developed to support the controls laboratory course. There were eight stations of equipment in the laboratory when it was first used in fall 2000. The controls laboratory was moved to a new and larger place in spring 2004. There are now thirteen stations of equipment.

The enrollments for the controls laboratory course in 2000-2001 and 2001-2002 were only a few students. There were several reasons for the low enrollment. First, a significant number of students took the first controls course in their last semester. When they finished the course, they graduated and did not need the controls laboratory course. Second, many students took the first controls course in their second last semester. By the time they finished the course, many of them had already taken enough electives that they would not need the controls laboratory course. Third, the students preferred to take electives of three or four credit hours. The one credit-hour controls laboratory course did not match their preferences. Some changes to the controls laboratory course were made to increase the enrollment.

First, the controls laboratory course has been changed from an elective to a required course since fall 2001. Second, the course was revamped. One of the additions was the applications of microcontrollers. The microcontrollers selected were Motorola M68HC912B32 [3, 4]. The applications of the Motorola microcontrollers can be found in many microcontrollers textbooks [5, 10, 11, 14].

Another change in the laboratory course was that each lab became a problem solving session. In each lab, the students were challenged with new control design problems. Guidance was provided to the students so that they could develop the solutions by themselves. The descriptions of the labs are provided in the next section.

In 2002-2003, the enrollment of the controls laboratory course increased to twelve students. The students evaluated the revamped laboratory course very favorably. They learned much in designing and prototyping their own controllers in the form of op amp circuits as well as in C programs that ran on the microcontrollers.

In 2003-2004, the demand for this course multiplied and the course had to be offered twice in the academic year. The total enrollment increased to thirty-eight and could have been more had we not put a cap on the class size due to limited number of stations available. A large number of students wanted to get into the course but could not. The increase in enrollment was mainly due to the new course materials. The core course requirement has not had enough time to put many students into the class.

Through these three control courses, the students received a package of fundamentals in the theory, simulation, and the practical applications of controls. The students have become better prepared for their future career or graduate study in control engineering.

## II. Equipment used in the controls laboratory course

In this section we list the equipment used in the controls laboratory. The purpose is to inform the readers what equipment was available to the students.

There had been eight stations of equipment housed in the controls laboratory. In spring 2004, the lab was moved into a bigger room in the new engineering building. There are now thirteen stations of equipment in the new laboratory. Each station consists of the following:

1. one Feedback Mechanical Unit, model # 33-100 [1]
2. one Axiom M68HC912B32 microcontroller evaluation board, model # CME12B/BC [2]
3. one Feedback Analog Board, model # 33-110 [1]
4. one oscilloscope (either Tiepie virtual oscilloscope model # HS-508
or Tektronics TDS3012 DPO oscilloscope)
5. one E&L CADET II prototyping station
6. one Feedback triple-output dc power supply, model # 01-100
7. an ImageCraft ICC12 C compiler
8. an Axiom AxIDE HC12 assembly language programming development system
9. one Pentium IV computer
10. an array of electronic components

## III. Description of the controls laboratory course

This section describes the labs in this controls laboratory course and the students' learning experience. It also provides some of the experimental results.

The list of laboratories is shown below:

Laboratory 1: Introduction to the equipment
Laboratory 2: DC motor, tachogenerator, and brake characteristics
Laboratory 3: Design of proportional controllers, part 1
Laboratory 4: Design of proportional controllers, part 2

Laboratory 5: Velocity feedback
Laboratory 6: Speed control
Laboratory 7: PID controller
Laboratory 8: Signal conditioning circuits
Laboratory 9: Digital proportional control using Motorola MC68HC912B32 microcontroller
Laboratory 10: Digital proportional controller with velocity feedback using Motorola MC68HC912B32 microcontroller
Laboratory 11: Digital speed control using Motorola MC68HC912B32 microcontroller

The first lab introduced the students to the equipment that would be used in the subsequent labs. The equipment was the mechanical unit (Feedback model # 33-100), the Tiepie virtual oscilloscope, and the analog board (Feedback model # 33-110).

The mechanical unit is a classical position servo control system with block diagram shown in Figure 1. It was used in every lab except the signal conditioning lab. In the figure, the summer and the controller do not belong to the mechanical unit. The students designed and prototyped new summer and controller circuits so as to satisfy the new performance requirements in every lab.

The Tiepie virtual oscilloscope has several functions, namely, oscilloscope functions, transient recorder, voltmeter, and others. The students learned how to use the virtual scope in this lab. The virtual oscilloscope ran on a Pentium IV computer.

The analog board consists of a collection of uncommitted electronic components including op amps, resistors, capacitors, and other components. The students used the analog board in the first two labs only. They used it for wiring up simple circuits to investigate the characteristics of the dc motors, tachogenerators, and the magnetic brakes.

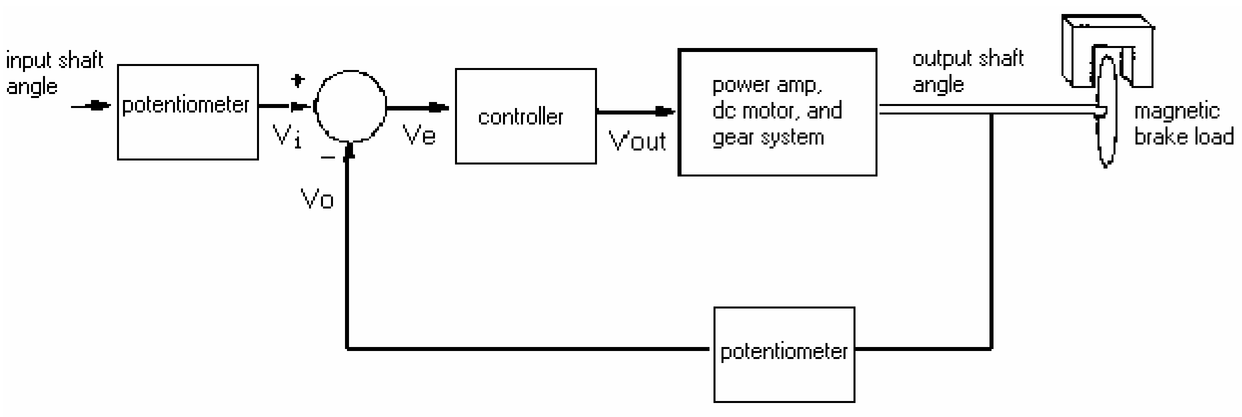


Figure 1: block diagram of the mechanical unit.

In the second lab, the students experimentally investigated the characteristics of a dc motor, a tachogenerator, and a magnetic brake. Their findings were as follows. For the dc motor, the speed of the motor increased linearly with the applied dc voltage and saturated to a certain speed for sufficiently large voltage. They also noticed the dead zone of the dc motor.

For the tachogenerator, the finding was that the dc voltage generated by the tachgenerator was proportional to the speed.

For the magnetic brake, the finding was that when the magnetic brake covered a larger spot of the brake disk, the larger was the eddy current generated and therefore greater braking effect.

In the second lab, the students also obtained the transfer function of the mechanical unit based on the step response of the unit. The transfer function was the ratio of the Laplace transform of the output shaft angle to the Laplace transform of the voltage Vi (see Figure 1), with the feedback loop disconnected.

The third lab required the students to design two proportional controllers. The first controller made the output shaft angle of the mechanical unit to follow the input shaft angle exactly. When the input shaft angle was changed by a certain amount, the controller should make the output shaft to turn the same amount of angle and in the same direction as the input shaft. The controller was constructed as a difference amplifier with output voltage Vout as specified in the equation below:

$$Vout = K\,(Vi - Vo)$$

Different values of gain K were used. The effect of the magnitude of K was observed. When K was large enough, overshoots occurred with oscillations. The step response for each K was also recorded.

The second controller made the output shaft to rotate in the direction opposite to the input shaft but the number of degrees turned by the output shaft should be the same as that of the input shaft.

In the third lab, the students learned the applications of proportional controllers in controlling the positions of the output shaft. They also learned how to design and prototype proportional controllers as electronic circuits.

The fourth lab required the students to design a controller such that the output shaft angle of the mechanical unit is always 15º leading the input shaft angle regardless the position of the input shaft.

A solution was to build an op amp circuit for the equation

$$Vout = K\,(Vi + V_{15^\circ} - Vo),$$

where $V_{15^\circ}$ is the voltage corresponding to 15º and K is the gain chosen experimentally.

The step response obtained by one of the groups of the students is shown in Figure 2. The lower signal is the input shaft angle (indicated as a voltage through a potentiometer) and the upper signal is the output shaft position (indicated as a voltage through another identical potentiometer). It is observed that the output shaft was always above the input shaft by the same voltage, therefore leading the input shaft by the same angle.

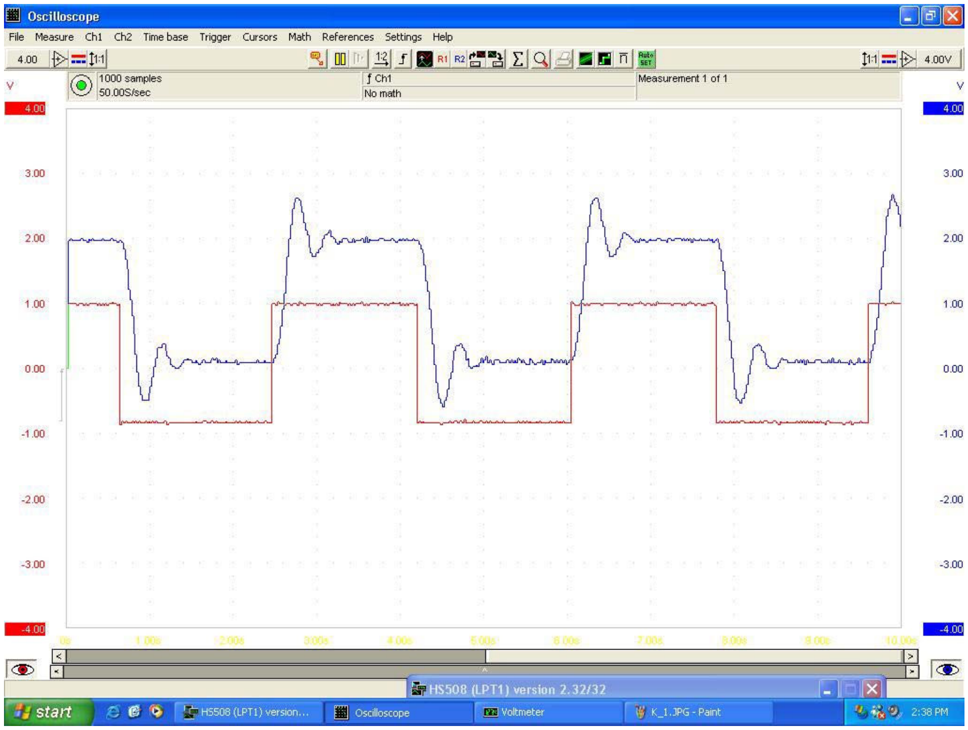

Figure 2: step response for Lab 4.

In the fourth lab, the students learned another application of proportional controllers and their realization as electronic circuits.

The fifth lab required the students to design the circuits for two controllers. The first controller should make the output shaft angle to follow the input shaft angle but without overshoots even when the gain was very high.

A solution was to add velocity feedback into a proportional controller. The controller was an op amp circuit that implemented the equation

$$Vout = K1\ (Vi - Vo - K2*V_{tacho}),$$

The velocity signal $V_{tacho}$ was obtained from the tachogenerator. The gains K1 and K2 were determined experimentally. The step responses obtained by one of the groups are shown in Figures 3 and 4.

The second controller to be designed in this lab should do the same thing as the first controller except that the tachogenerator could not be used. The students were required to design a circuit that produced the velocity signal. A differentiator circuit was used to estimate the velocity signal. Results obtained were similar to those of the first controller.

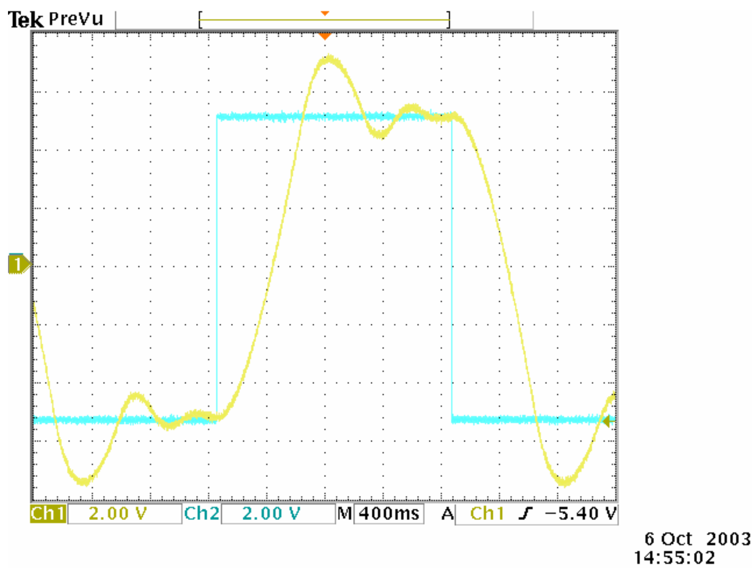

Figure 3: proportional controller without velocity feedback for Lab 5.

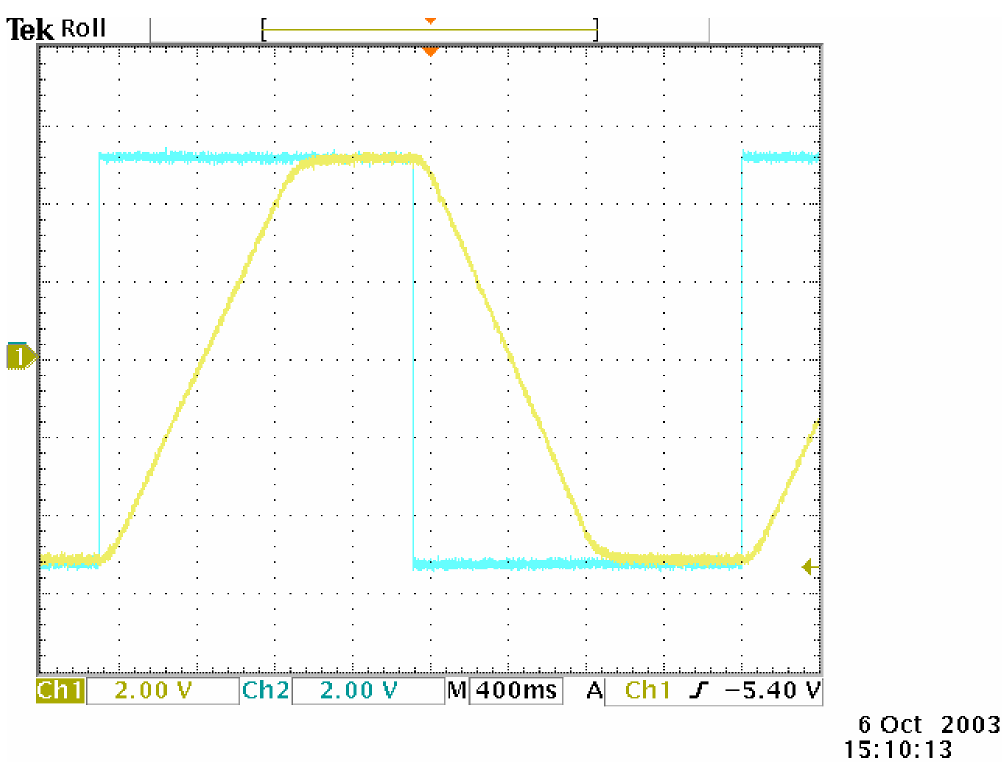

Figure 4: proportional controller with velocity feedback for Lab 5.

In the fifth lab, the students learned that a proportional controller with a high gain produced oscillations and overshoots. They learned that velocity feedback was a possible solution to remove the oscillations and overshoots. They also learned that the velocity signal could be generated from a tachogenerator or by using a differentiator op amp circuit.

The sixth lab required the students to design a controller so that the motor would be running at the constant speed of 1000 rpm without regard to the brake setting. The block diagram for a solution to this design problem is shown in Figure 5. Vs is the voltage produced by the tachogenerator and is proportional to the motor speed. Vr is a constant input voltage equal to the voltage generated by the tachogenerator for the case that motor is spinning at 1000 rpm.

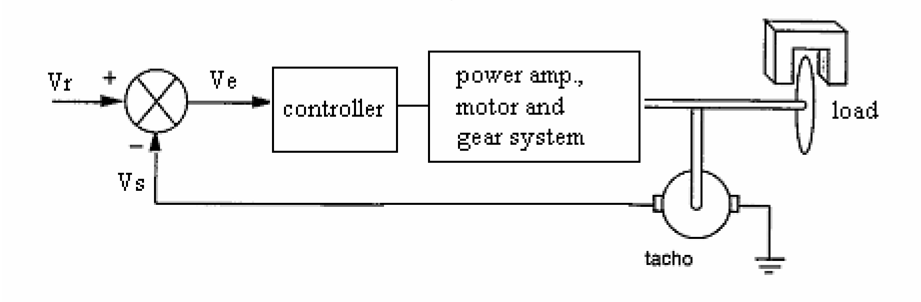


Figure 5: block diagram of speed control, Lab 6.

The controller in the block diagram was chosen to be a PI controller. The PI controller was implemented as a summing amplifier circuit with two inputs. The first input is Ve scaled by a gain factor. The second input is the integral of Ve scaled by another gain factor. All the students were able to control the speed to be constant under varying load condition using the integral controller circuit.

In this lab, the students gained another application of closed-loop control, which was maintaining motor speed to be constant under fluctuating load condition. They also saw the effect of an integrator in reducing the steady state error to zero.

The seventh lab required the students to design a controller such that the output shaft angle followed a triangular (ramp) input Vi (in Figure 1) with zero error. A solution to this problem was using a PID controller. Integral control increased system type number by 1 and therefore removed the steady state error to ramp input. Derivative control removed the overshoots and oscillations. The combination of proportional, integral, and derivative control eliminated the steady state error and removed the overshoots and oscillations. The students built operational amplifier circuits that implemented the PID equation below.

$$Vout = K1 * Ve + K2 * \int_0^t Ve(u)du + K3 * \frac{dVe}{dt}.$$

The gains K1, K2, and K3 were determined experimentally.

The result of the PID controller in the tracking of the triangular waveforms is shown in Figure 6. Notice that the output shaft signal overlapped with the triangular input. The tracking was very close.

Through the seventh lab, the students learned that a PID controller could make the output to track a triangular input with zero steady state error and no oscillation. The only error that could occur was at each peak of the triangular waveform. This was because the motor could not stop and change direction of rotation instantaneously.

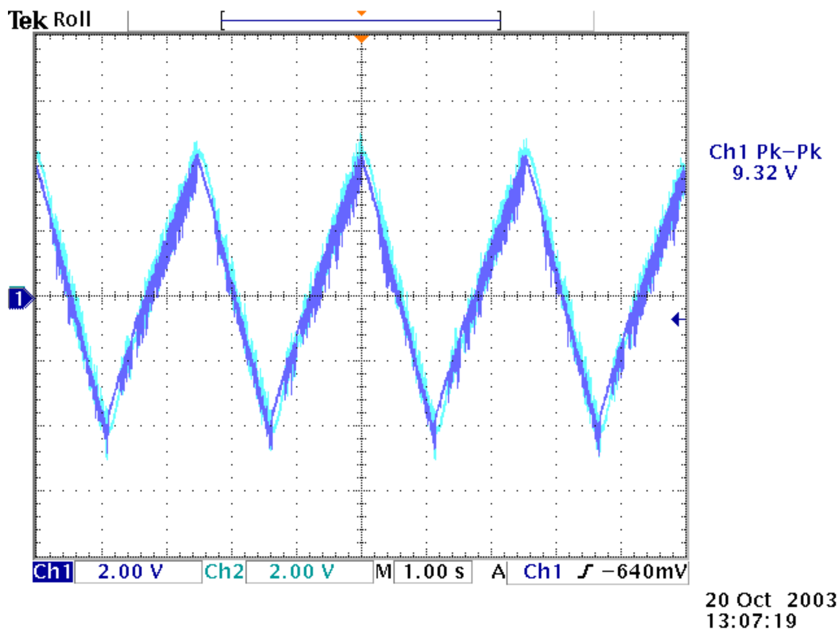


Figure 6: PID controller tracking a triangular waveform in Lab 7.

The eighth lab required the students to design and build three signal conditioning circuits. These circuits would be used in the subsequent labs where the Motorola MC68HC912B32 microcontroller would be used to implement all the controllers.

The first signal conditioning circuit was to interface Vi (in Figure 1) to one of the analog-to-digital converters of the microcontroller (in particular, the one which is accessed through PAD0 socket in the MCU_PORT connector on the Axiom CME12B/BC evaluation board [2]).

Vi was in the range of –10V to +10V. PAD0 accepted input in the range of 0 to +5V only. The signal conditioning circuit converted the range of –10V to +10V to the range of 0 to +5V.

The second signal conditioning circuit was to interface Vo to another analog-to-digital converter of the microcontroller (in particular, the one which is accessed through PAD1 socket in the same MCU_PORT connector).

Vo was in the range of –10V to +10V. PAD1 accepted input in the range of 0 to +5V only. Another signal conditioning circuit is required to convert the range of –10V to +10V to the range of 0 to +5V. This signal conditioning circuit was identical to the first one.

The third signal conditioning circuit was to interface the tachogenerator voltage to the third analog-to-digital converter of the microcontroller (in particular, the one which is accessed through PAD2 socket in the same MCU_PORT connector).

The tachogenerator voltage was in the range of –5V to +5V. The voltage was positive for clockwise rotation and negative for counter-clockwise rotation. A signal conditioning circuit was required to convert the range of –5V to +5V to the range of 0 to +5V.

The equation to convert the range -10V to 10V to the range 0V to 5V was

Vout = 0.25Vin + 2.5.

Vout was the output of the signal conditioning circuit. (It is not the Vout in Figure 1). Vin was the input, which was Vi or Vo in Figure 1. One of the student's circuit design for this equation is shown in Figure 7.

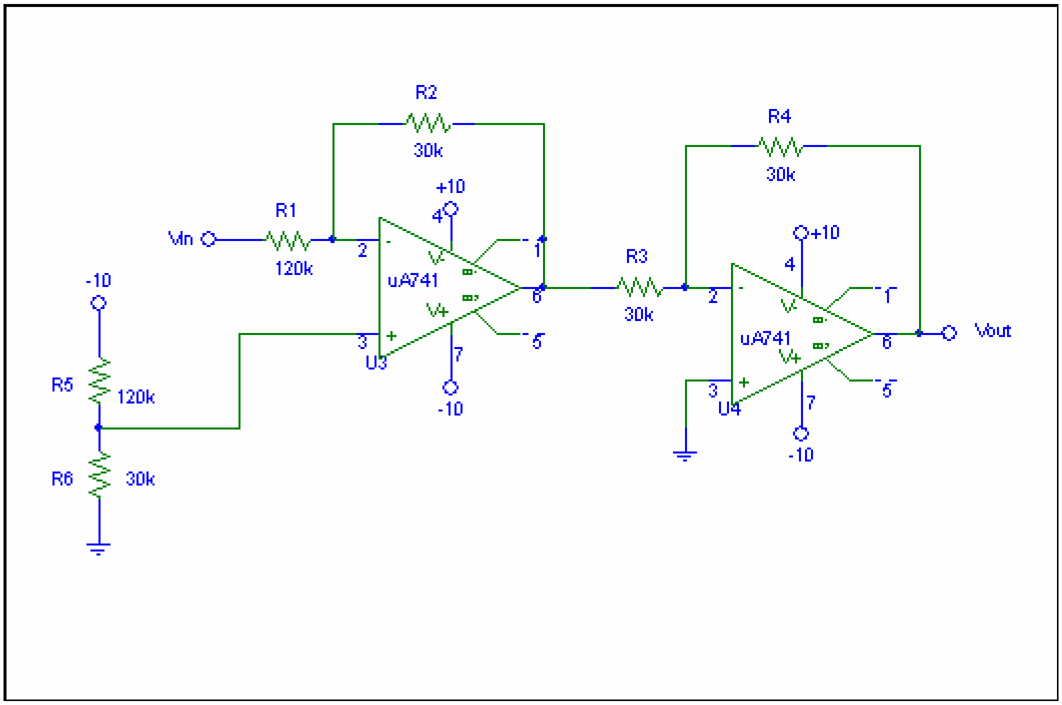


Figure 7: signal conditioning circuit for Vout = 0.25Vin + 2.5.

Measurements were taken to check the performance of the conditioning circuit. The results are shown in Table 1.

| Inout Vin (V) | Expected Vout | Actual Vout (V) |
|---|---|---|
| -10.00 | 0.00 | 0.04 |
| -8.00 | 0.50 | 0.50 |
| -6.00 | 1.00 | 1.05 |
| -4.00 | 1.50 | 1.62 |
| -2.00 | 2.00 | 2.10 |
| 0.00 | 2.50 | 2.66 |
| 2.00 | 3.00 | 3.15 |
| 4.00 | 3.50 | 3.62 |
| 6.00 | 4.00 | 4.12 |
| 8.00 | 4.50 | 4.54 |
| 10.00 | 5.00 | 5.00 |

Table 1: Vout vs. Vin for the signal conditioning circuit shown in Fig. 7

A similar circuit as Figure 7 was designed and built to convert the range of -5V to 5V to the range of 0V to 5V. The circuit implemented the equation: Vout = 0.5Vin + 2.5. The circuit diagram is shown in Figure 8.

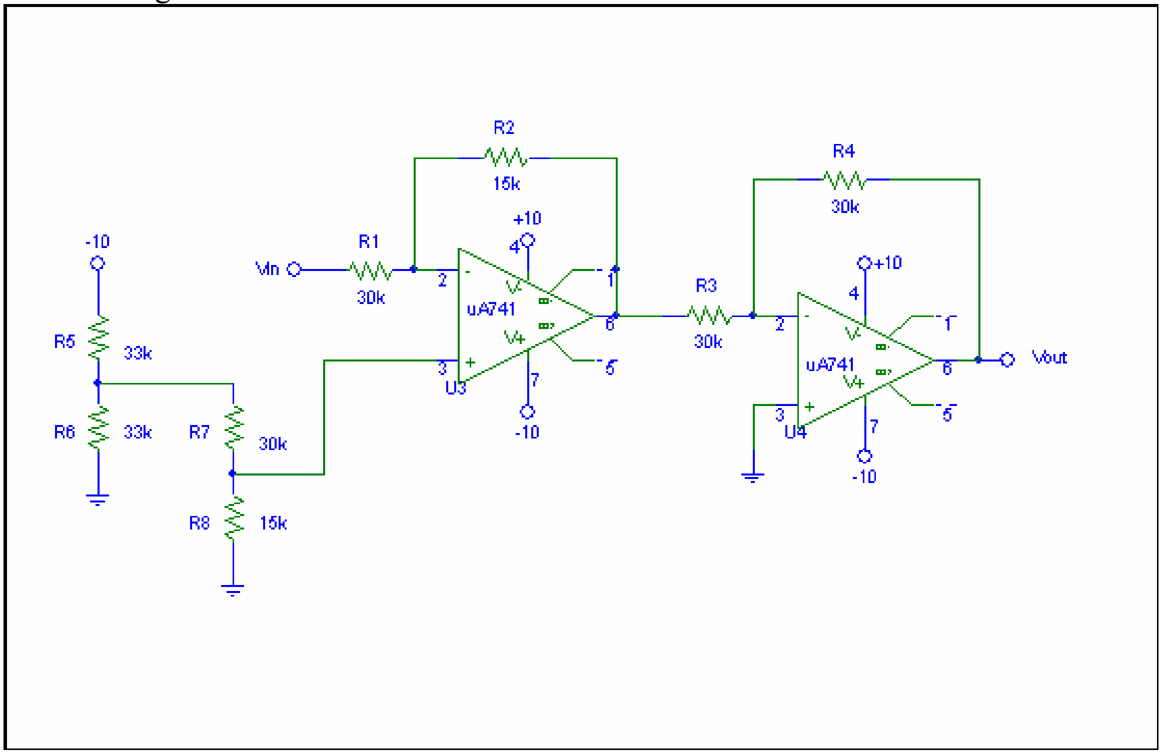


Figure 8: signal conditioning circuit for Vout = 0.5Vin + 2.5.

Measurements were taken to check the performance of the conditioning circuit in Figure 8. The results are shown in Table 2.

| Input Vin (V) | Expected Vout | Actual Vout (V) |
|---|---|---|
| -5.00 | 0.00 | -0.08 |
| -4.00 | 0.50 | 0.42 |
| -3.00 | 1.00 | 0.98 |
| -2.00 | 1.50 | 1.48 |
| -1.00 | 2.00 | 1.97 |
| 0.00 | 2.50 | 2.50 |
| 1.00 | 3.00 | 2.99 |
| 2.00 | 3.50 | 3.51 |
| 3.00 | 4.00 | 3.95 |
| 4.00 | 4.50 | 4.47 |
| 5.00 | 5.00 | 4.94 |

Table 2: Vout vs. Vin for the signal conditioning circuit shown in Fig. 8

Through the eighth lab, the students gained knowledge of designing signal conditioning circuits and understood their necessity in the interface of analog signals to a microcontroller.

The ninth lab required the students to design three proportional controllers as three separate C programs that ran on Motorola's M68HC912B32 microcontroller.

The first program made the output shaft angle signal Vo to track the input shaft angle Vi. It was the same requirement as Lab 3 except that the controller was implemented as a C program ran on the microcontroller instead of operational amplifier circuit.

Vi was connected to the input of the first signal conditioning circuit built in Lab 8. Vo was connected to the input of the second signal conditioning circuit. The output of the first signal conditioning circuit was connected to PAD0, which is the input to one of the on-chip analog-to-digital converter. The output of the second signal conditioning circuit was connected to PAD1, which is the input to another on-chip analog-to-digital converter.

The C program processed the digitized signals and output a PWM signal on PP0 (from one of the on-chip PWM modulators) driving the dc motor in the mechanical unit. A block diagram of the system is shown below.

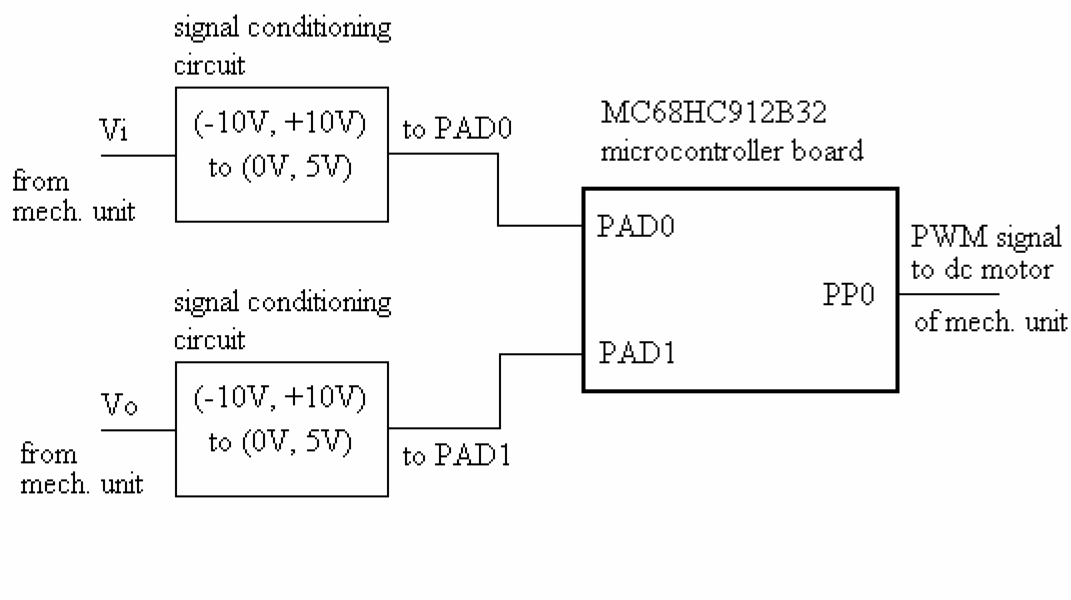


Figure 9: block diagram of digital controller for Lab 9.

The result obtained by the controller is shown in Figure 10. The input Vi was a square wave. The output shaft signal Vo became equal to Vi in the steady state.

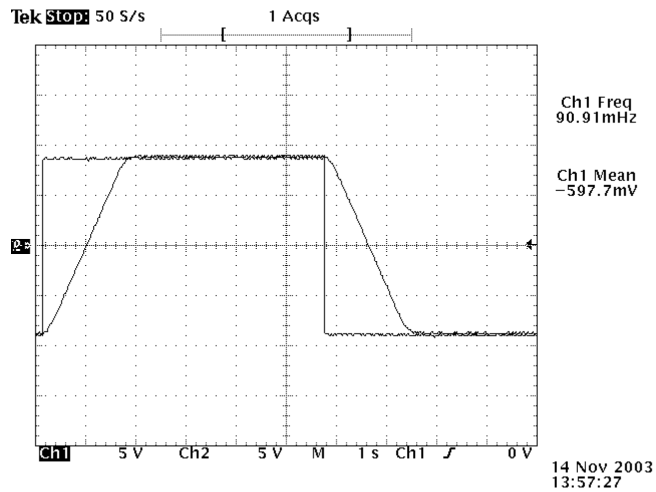


Figure 10: the output shaft and the input shaft signals, Lab 9.

The second C program in Lab 9 was the same as the first one except that the output shaft would turn in the opposite direction instead of the same direction as the input shaft. The angle rotated by the output shaft was required to be equal in magnitude to that of the input shaft.

The result obtained by the controller is shown in Figure 11. Notice that the output shaft angle voltage is equal and opposite of the input shaft angle voltage.

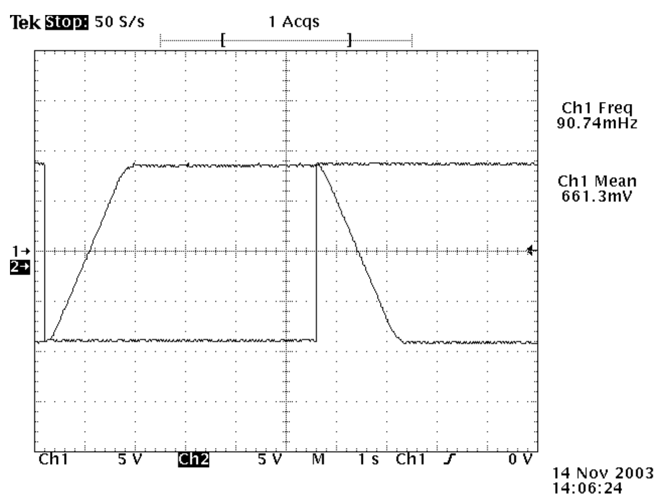


Figure 11: same angle opposite direction, Lab 9

The third C program implemented a proportional controller that made the output shaft always 15 degrees ahead of the input shaft. This requirement was the same as Lab 4. The result obtained by the controller is shown in Figure 12. Notice that the output shaft signal is shifted up as compared to the input shaft signal. The amount of shift corresponded to 15 degrees.

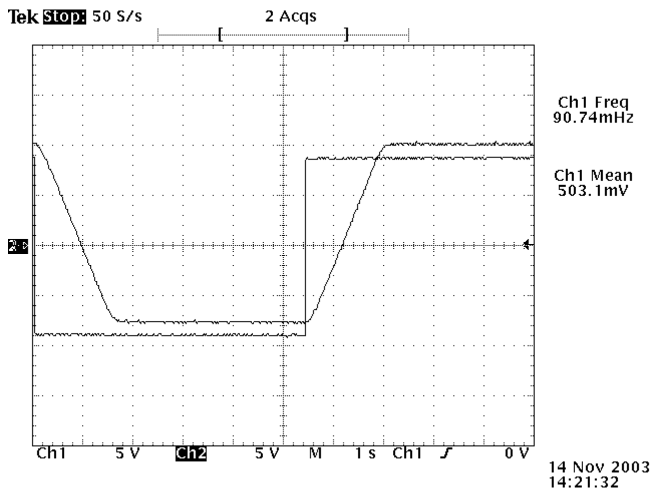


Figure 12: same direction 15 degrees ahead, Lab 9.

Through Lab 9, the students learned how to write C programs to implement proportional controllers. They noticed that it was easy to implement a new controller to do a new operation by simply modifying the code with no hardware change. They quickly saw the convenience and flexibility offered by using a microcontroller in control applications.

The tenth lab required the students to write two C programs that implemented a proportional controller with velocity feedback so as to remove the overshoots and oscillations in the response.

In the first C program, the velocity signal came from the tachogenerator through the third signal conditioning circuit, which output was connected to the third on-chip analog-to-digital converter. The result of this C program controller is shown in Figure 13. Notice that there is no overshoot and oscillation. Without the velocity signal, there were overshoots and oscillations.

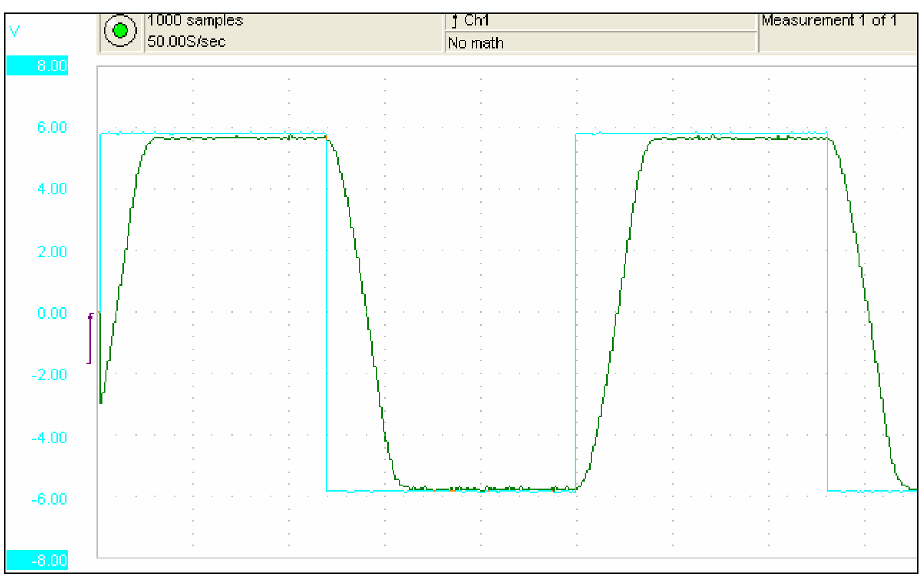


Figure 13: digital proportional controller with velocity feedback derived from tachogenerator.

In the second C program, the velocity signal was derived mathematically in the C program. The result is shown in Figure 14. Notice that there was a small non-zero error. This was caused partly by a small proportional gain.

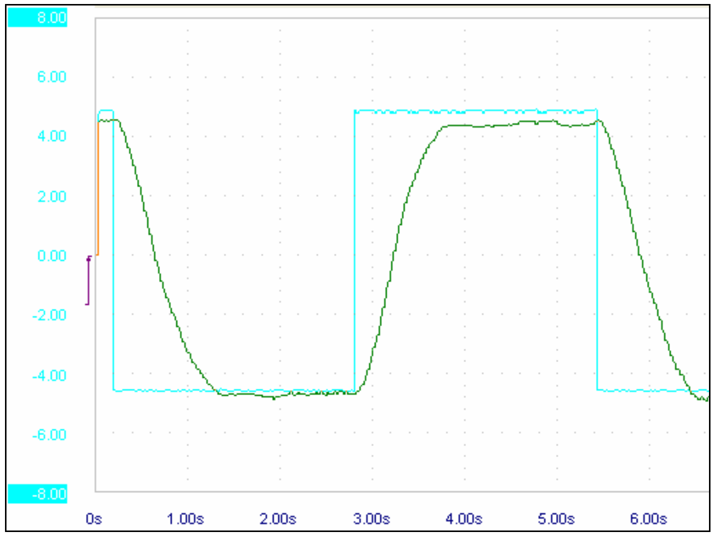

Figure 14: digital proportional controller with velocity signal derived mathematically.

Through Lab 10, the students learned to implement a proportional controller with velocity feedback as a C program ran on the microcontroller, with and without a tachogenerator present. They also learned that overshoots and oscillations could be removed by the controller with proper choice of proportional and velocity gains in the C program.

The eleventh lab required the students to design a controller as a C program that controlled the speed of the dc motor to be constant despite rapidly varying amounts of load. The C program implemented a PI controller. The equation is the same as Lab 6. The result is shown in Figure 15. The signal was the output of the tachogenerator. The load was varying but the speed was controlled to be fairly constant by the microcontroller.

Through Lab 11, the students learned to develop a C program to control the speed to be constant. They also learned that the effects of an integrator can be produced by hardware or software.

IV. Support needed for the lab

With a recent class size of twenty six students, at least one teaching assistant is needed to assist the instructor in helping the students during the lab meetings. The students need help on designing and debugging their electronic circuits, on using the C compiler development environment, and on writing and debugging C programs.

A set of well written lab handouts is necessary. Our students found that our lab handouts were thorough and helpful and made the set up a minimal part of the lab. With a good set of lab handouts, it allows the students to get to the heart of the lab problems quickly. This also saves the instructor the time for clarifying the lab details during the lab meetings.

Local equipment repair support is necessary. Some of the equipment breaks down every now and then. For example, in the Feedback Mechanical Unit (model # 33-100), the coupling joining the tachogenerator to the output shaft breaks easily and the LCD panel is not working sometimes. For these simple problems, it is usually not practical to ship the faulty equipment to the manufacturer for repair because it takes time and can be costly. The instructor can repair them and has been doing so. However, for problems that require much time to diagnose, it is suggested that the faulty equipment be shipped back to the manufacturer for repair. It is also necessary that there is spare equipment to support the lab.

Some of the difficulties that we have encountered in this lab were:

1. Not enough spare equipment. At one time we had several Tiepie virtual oscilloscopes and the Mechanical Units broken down at the same time. Some students had to wait until some other students finished their labs before they could start theirs. Some just chose to come back to the lab at another time to do the labs. This problem was solved with additional funding for acquiring extra equipment. We now have some spare equipment for this lab.
2. Over enrollment for this lab course. In the fall 2003, we had thirty-eight students wanted to take this lab course but the lab could support only twelve due to limited space and number of stations. The students who could not get in to the lab were disappointed. This problem was solved with the lab moved to a much bigger space in the new engineering building in spring 2004 and the purchase of extra stations of equipment.
3. We have noticed that some of the students had difficulty in designing analog electronic circuits such as the signal conditioning circuits described in Lab 8. We helped them by first deriving the equations needed for conditioning the signals. Then we showed them the basic op amp configurations that could implement the equations. The students then proceeded by themselves and built and tested their circuits.
4. In the design of PID controllers as C programs, it was not obvious for the students to see that differentiation could be done as finite difference between two successive samples and that integration could be done as recursive summation. Once the students understood the concepts, they quickly finished writing the C programs.

## V. Concluding remarks and future improvements

The students evaluated this laboratory course highly. At the end of the course, they left with skills for designing and prototyping of controllers implemented as op amp circuits and also as C programs, and of signal conditioning circuits. They also learned the theory behind the workings of the controllers so that they could implement the controllers in other technologies such as digital signal processors. They responded to the microcontroller-based labs extremely well. The students saw the flexibility offered by the microcontrollers over the analog controllers. Also they acquired open-ended engineering design experience and saw that there were many different design solutions to the same problem. Through this laboratory course the students have become better prepared for their future career in control engineering than before. Future improvements of this laboratory course may include the use of digital signal processors, e.g., Texas Instruments TMS2000 series of DSPs, and programmable systems on a chip for controls applications.

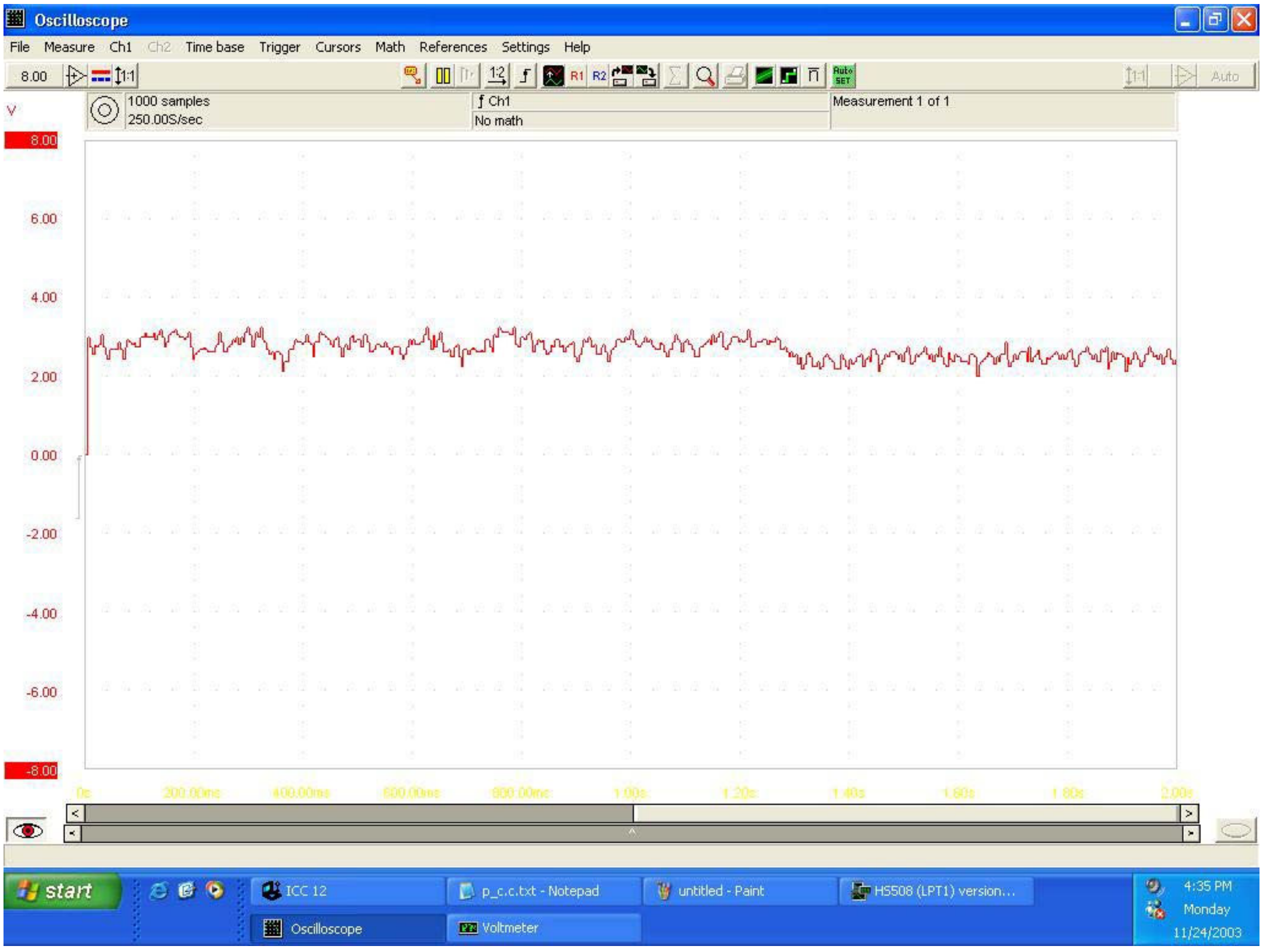

Figure 15: speed signal of the motor as the load was changing.

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