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Training of Undergraduate Engineering Students in Sensing and Control Technologies*

AHMED RUBAAI
Howard University, Electrical Engineering Department, 2300 6th Street Northwest, Washington, DC 20059, USA. E-mail: rubaai@scs.howard.edu

This paper deals with the development of a microcontroller-based servomotor position control system for use in undergraduate engineering education. The system was developed to demonstrate a practical method of position sensing, a practical method of actuating the servomotor, and the effects of the use of different control algorithms on closed loop system performance. The work presented in this paper has involved complete design and construction of the microcontroller, the design of the interface with particular emphasis on student use in a laboratory environment, and the design and testing of the different control algorithms. The experimental setup, the processing of the data and the results are presented.

AUTHOR QUESTIONNAIRE

1. The paper discusses materials for a course in Control Systems, Microprocessor Applications, Digital Systems, Power Electronics, and Fundamental of Design Applications.
2. Students of the following departments are taught in this course: Electrical Engineering, Mechanical Engineering, Computer Engineering, System and Computer Sciences.
3. Level of the course (year): Junior/Senior.
4. Mode of presentation: The laboratory experiment is ideally suited for presentation on small, low cost, highly interactive computer systems for use in classroom and laboratory environment.
5. The material is presented in both regular and elective courses.
6. Class and hours required to cover the material: one semester, two hours/week, plus homework assignments/design projects.
7. This paper contributes a novel tracking microcontroller, which incorporates attractive features such as simplicity, good performance, and automation while utilizing a low cost hardware and software implementation.
8. The material is not adequately addressed in most textbooks.

BACKGROUND

INCREASING competitiveness and automation in today's manufacturing industry introduces new challenges in control and implementation. Interest in automation of industrial processes has been a factor in the rapid evolution of the control systems, in terms of both design and application. Consequently, the educational process of engineering students should include exposure to the concepts employed in the state-of-the-art control systems; it is felt that design and implementation of a microcontroller-based servomotor position control system would provide a suitable vehicle for such exposure. In response, a laboratory experiment coupled with state-of-the-art transducing and control methodologies is proposed for use in undergraduate engineering education. Several trends can be observed in the historical development of undergraduate control laboratories using motors rated at only few hundred watts [1–6]. Therefore, it is necessary to have powerful tools at the universities to give students this practical knowledge and, by this means, to increase their skills in this field of technology.

The primary objective of this paper is the design and implementation of a servomotor control system for use as an educational tool. The laboratory experiment is intended to demonstrate state-of-the-art control concepts and technology. The effort associated with such development could be broken into two major areas: the hardware design and implementation, and the design of the laboratory experiment and associated software. During the course of the execution of the laboratory experimental procedure the students study and evaluate the performance of two control algorithms. The two algorithms studied in the experiment were chosen to provide a cross section of control algorithms currently in use in practice. The algorithms considered here are bang-bang control, and proportional-plus-integral (PI) control. The point of the part of the laboratory

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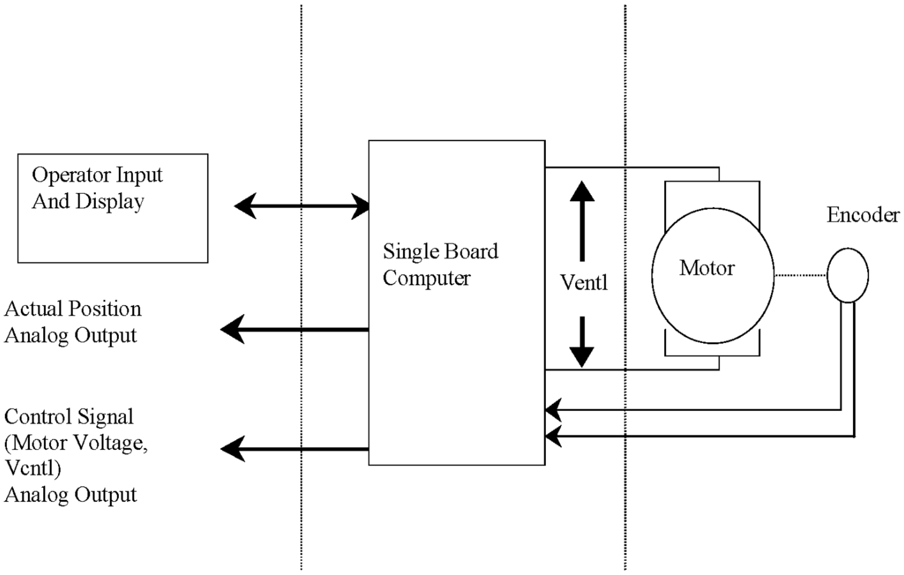

Fig. 1. Laboratory experiment hardware block diagram.

experiment dealing with these control algorithms is to select the best control method by evaluating closed-loop performance using each algorithm.

OVERVIEW OF THE LABORATORY EXPERIMENT

In the experiment, the student first examines the concept of potentiometers as a means of transducing a process. The student gains insight into a method for converting the output of a transducer into a form suitable for use by the microcontroller to determine the angular position. The method of generation of the control signal (digital/analog converter, DAC, rather than the use of PWM of a square wave) is also examined. The DAC method was chosen for several reasons:

- low power consumption;
- direct interface to all popular logic families with full noise immunity;
- cost effectiveness;
- high-speed performance.

With an understanding of the transducing and actuation details, the student begins a study of the effects of the different control algorithms on the goodness of control. In this regard, the experiment provides a 'hands-on' survey of two different control algorithms; bang-bang, and proportional-plus-integral (PI). For each of the two control methods, selections of values for control algorithm parameters are made in an effort to optimize closed-loop system response. The objective of the optimization is to minimize the time required to move the servomotor shaft from one setpoint position. The student manipulates controller parameters and observes the system response, ultimately arriving at optimal parameters for each of the two algorithms.

SYSTEM DESCRIPTION

The overall system is composed of five major elements: the controlled process (motor and reduction gearing), operator interface, feedback transducer, microcontroller, and the power amplifier. The basic system structure is shown in Fig. 1. The controlled process chosen to develop the experiment around is a permanent magnet (PM) DC servo gear motor. In order to improve the viable effects of the selection of control algorithm and the tuning of the controller, it was decided to drastically increase the inertia of the servomotor through the addition of a flywheel. The flywheel finally used increased the inertia of the motor by better than an order of magnitude. This modification brought the mechanical time constant of the motor from approximately 150 milliseconds to something closed to three seconds. The result of this increased time constant is that any oscillatory tendencies of the control system are much more readily observable to the student operating the experiments.

The operator interface provides for the entry of controller set-point information, for display of shaft present position, and for activation/deactivation of the controller. With the controller deactivated, set points are entered via a numeric keypad in units proportional to the angular position of the shaft. The controller set point is updated in memory upon completion of the entry to correspond to the operator input. The controller is then activated with the result being an apparent step set point change from the set point prior to the new entry. When the controller is operating and controlling the motor, the output shaft position may be displayed on the operator interface.

The microcontroller forms the core of the closed loop system. Aside from the duties of controlling the operator interface, it performs the acquisition

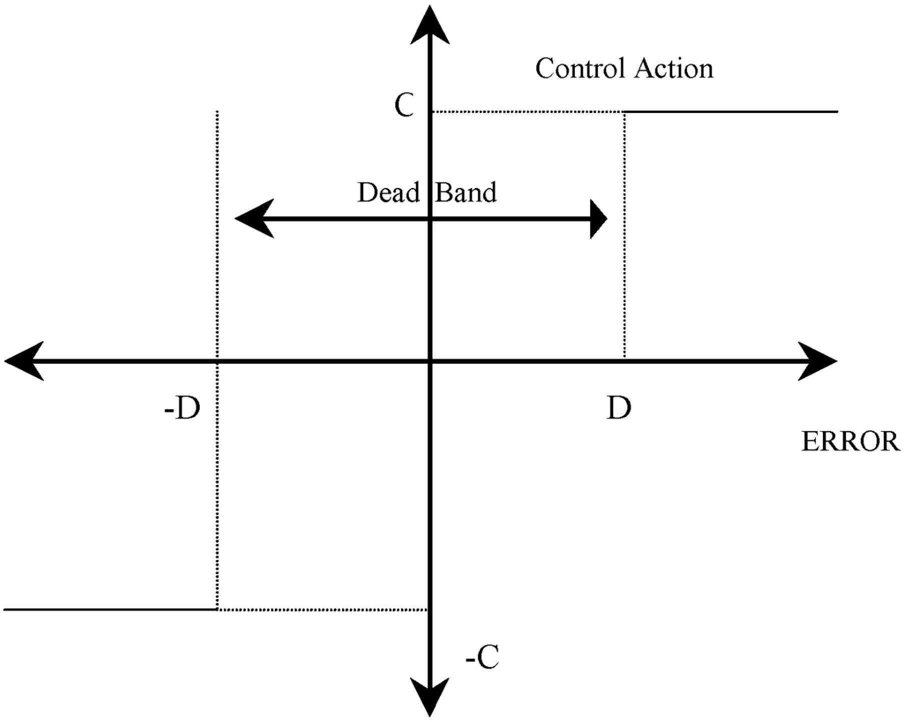

Fig. 2. Bang-bang controller output versus setpoint error.

of the feedback signal, computes an error signal, delivers the error signal to the control algorithm, and executes the control signal. The Motorola MC68HC11E9 microcontroller is used for the construction of the controller, because of cost considerations and availability of development systems. The MC68HC11E9 [7] microcontroller utilizes C-MOS technology, which provides a combination of smaller size and higher speeds with low power and high noise immunity. The chip memory system includes 8K bytes of ROM (read only memory), 512 bytes of EEPROM (erasable programmable ROM), and 256 bytes of RAM (random access memory). All interfacing by operators is performed via a keyboard and a display control.

SELECTION OF THE CONTROL ALGORITHMS

The first control algorithm the students study is the bang-bang control algorithm. It is an intuitively simple and direct control algorithm. The algorithm is included in the experiment as a lead-in to the more complex and effective algorithms utilized subsequently, and also to provide a basis from which the performance of all the algorithms may be evaluated. The bang-bang algorithm is described as:

$$u(k) = 0 \text{ for setpoint} - \text{output} < D$$
$$u(k) = -C \text{ for setpoint} - \text{output} < -D$$
$$u(k) = C \text{ for setpoint} - \text{output} > D$$

where $u(k)$ is the controller output for the k-th iteration of the control algorithm, $2D$ is the width of the controller's dead-band and C is the value of the control error exceeds the dead-band value. Figure 2 represents the input/output relationship of the bang-bang controller. The controller continually computes the position error (setpoint − output) and uses the error to decide on the control action. If the error is a positive value and greater than the dead-band value D, the controller will output a full positive control action causing the output position to increase. The magnitude of this control action is a constant, which can be programmed by the user. As the control action has effect, the position error will decrease until such time as the error no longer exceeds the user programmed dead-band value. When the error is within the dead-band, the controller will output zero control action. If the error initially is a large negative value, the controller will generate a negative value for the control action which will reduce the error until it becomes greater than the dead-band value $-D$; when the error is greater than the dead-band $-D$ the control action becomes zero.

The second algorithm implemented in the digital controller is a PI algorithm. This algorithm is chosen because it represents simple classical control. Also, by this point in the educational process, the students have had significant exposure to this type of controller and should be relatively comfortable in applying it to the motor position control problem. The algorithm is described as:

$$u(k) = z(k) + m(k)$$

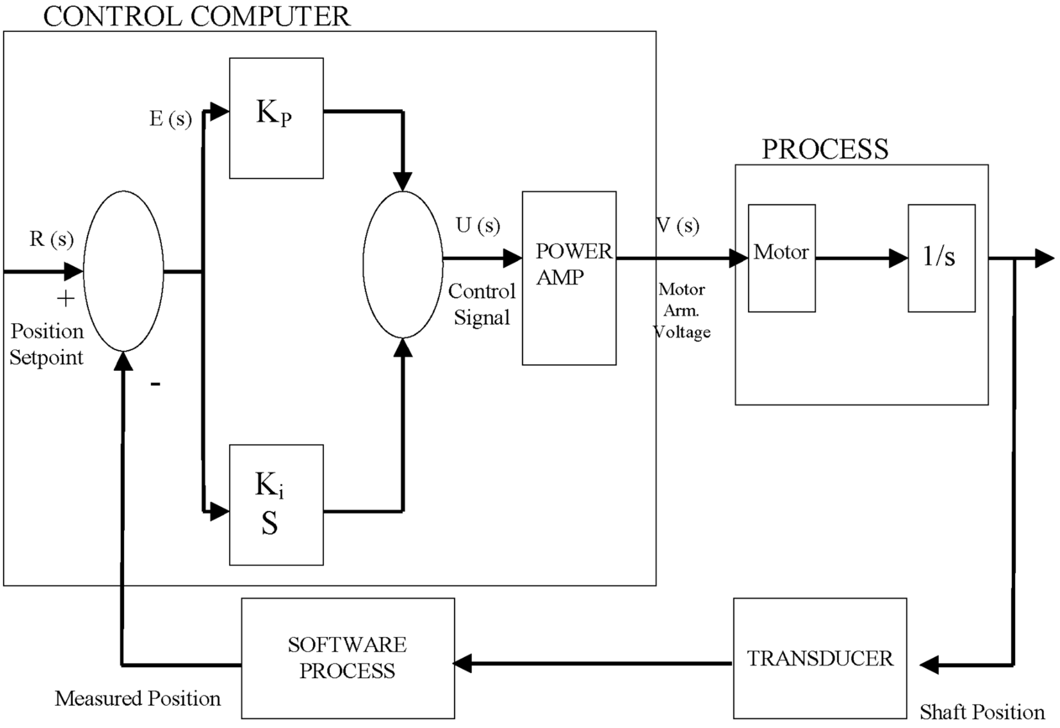

Fig. 3. Block diagram of PI position controller.

where

$$z(k) = k_p e(k)$$
$$m(k) = k_i v(k)$$
$$v(k) = v(k-1) + e(k)$$
$$e(k) = r(k) - \theta(k)$$

where $e(k)$ is the error in position, $r(k)$ is the current operator entered setpoint, $\theta(k)$ is the position output, $z(k)$ is the proportional component of the control action (generated by multiplying the error by the user-entered proportional gain factor k_p, and $m(k)$ is the integral component (computed by first adding the position error $e(k)$ to $v(k)$, a running summation of the error, and then multiplying that sum by the integral gain k_i). The proportional and integral components are summed, with the result forming the total PI control output. The block diagram of the control system utilizing the PI controller is shown in Fig. 3.

EXPERIMENTAL RESULTS

With the proposed tracking control system, the motor position should follow any arbitrary selected tracks. The only restriction is tracks must conform by the system dynamics to avert unnecessary stresses on the hardware, including the mechanical load. Figure 4 illustrates a block diagram of the control system. Several tests were performed during the course of this study. However, for brevity, only salient results are reported in this paper.

The first control algorithm the students study is the bang-bang algorithm. The students operate the laboratory hardware and observe the controller performance for different values of the algorithm's two parameters, the control magnitude C, and the dead-band D. Two typical cases are presented.

In Case 1, the rotor position track is composed of two segments: the first is a step command to advance the rotor position by 34 revolutions (forward rotation); and the second is a reverse step to return the rotor back to its starting position (reverse rotation). The time for forward and reverse rotation is 2.7 seconds each. Results of case 1 are shown in Figs 5 and 6. Figure 5 shows comparison between the actual measurement and the corresponding reference track for the rotor position. Figure 6 shows the control command sequence that goes into the converter to perform the actual modulation of the terminal voltage of the motor. The tracking response shown in Fig. 5 is for small control magnitude (C = 40) and a dead-band of D = 10. It should be noted that the value of C = 40 represents the lowest value of C that would insure motor rotation, yet even with this low value the motor inertia carried the motor through the dead-band surrounding the setpoint and caused slight steady-state error. This is due to the large inertial effects of the flywheel.

In Case 2, the same type of trajectory as in Case 1 was reconsidered. The dead band was held constant at D = 10, while the control magnitude was varied. Figures 7 and 8 show the tracking performance of the controller with a C of 250 and D of 10. Figures 7 and 8 illustrate the effects

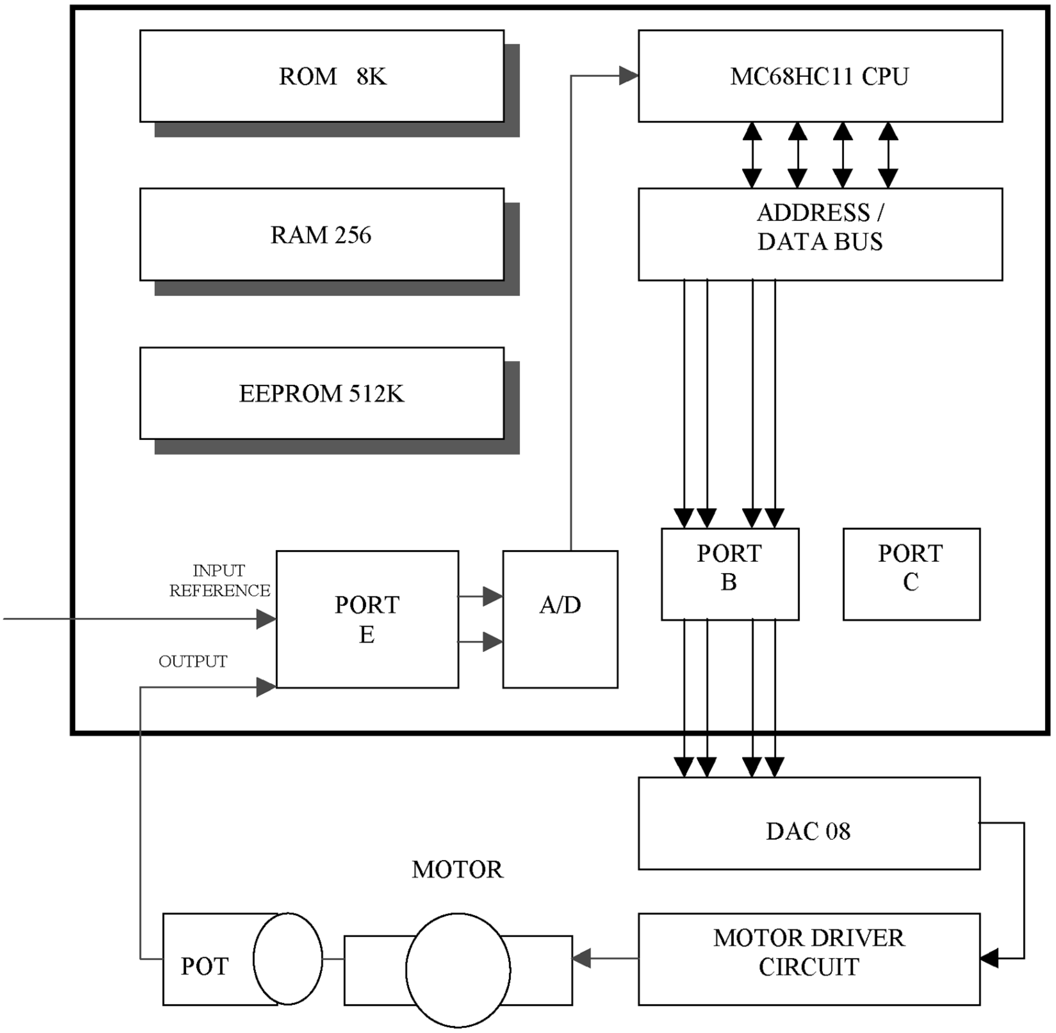

Fig. 4. Block diagram of PI position controller.

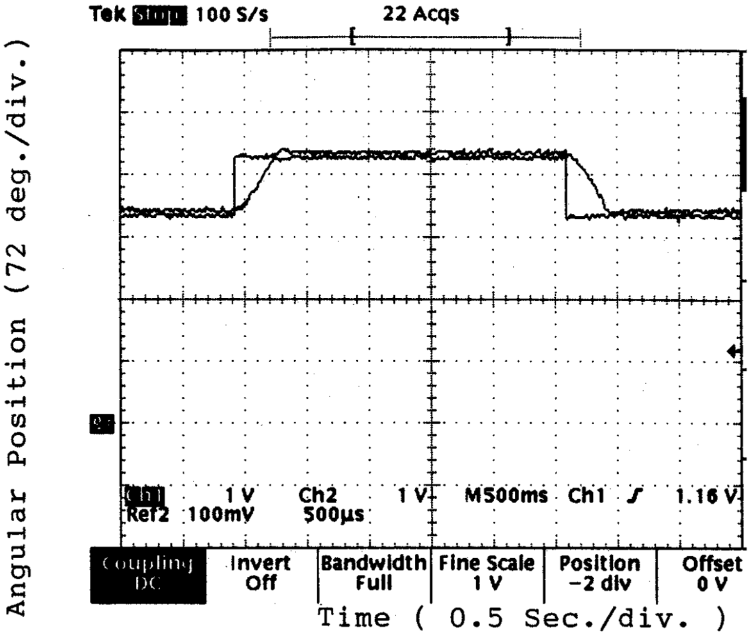

Fig. 5. Measured rotor position and reference track of Case 1.

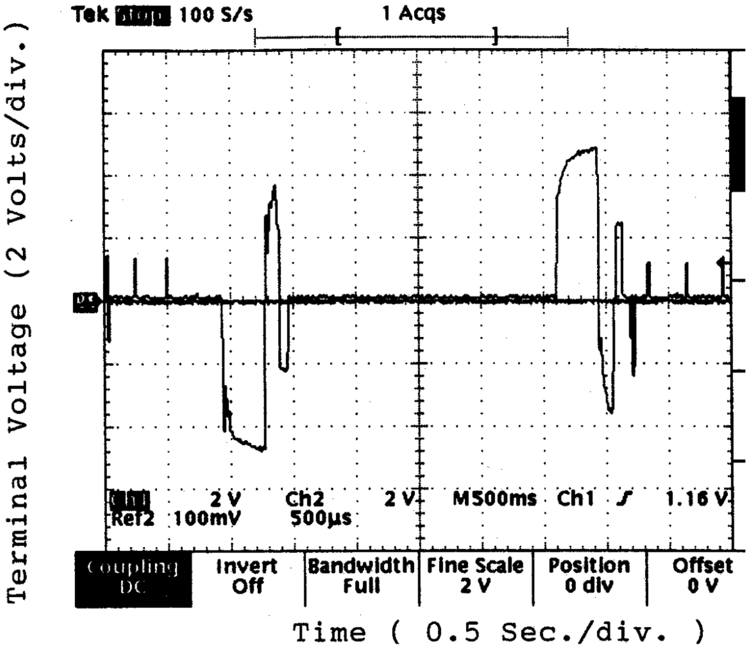

Fig. 6. Control command sequence of Case 1.

on closed loop performance of increasing control magnitude *C*. It is expected that with a large value of control magnitude ($C = 250$) the closed loop response will become oscillatory. Comparing Figs 7 and 8 to Figs 5 and 6, it is apparent that the percent overshoot of the response increases with increasing the value of *C*. The amount of ringing also increases as the control magnitude *C* goes up. It should be noted that the bang-bang algorithm does not utilize the capabilities inherent in the microcontroller-based control hardware: one would assume that utilizing this hardware to develop a more practical algorithm would produce better performance. This in fact is what is obtained with the algorithm described subsequently.

The second control algorithm whose performance is to be examined is the proportional plus integral control algorithm. To illustrate the generalization capability of the microcontroller, a sinusoidal reference track is introduced in this experiment. Figures 9–12 illustrate the position tracking for various combinations of the proportional and integral gains. Figure 9 shows the

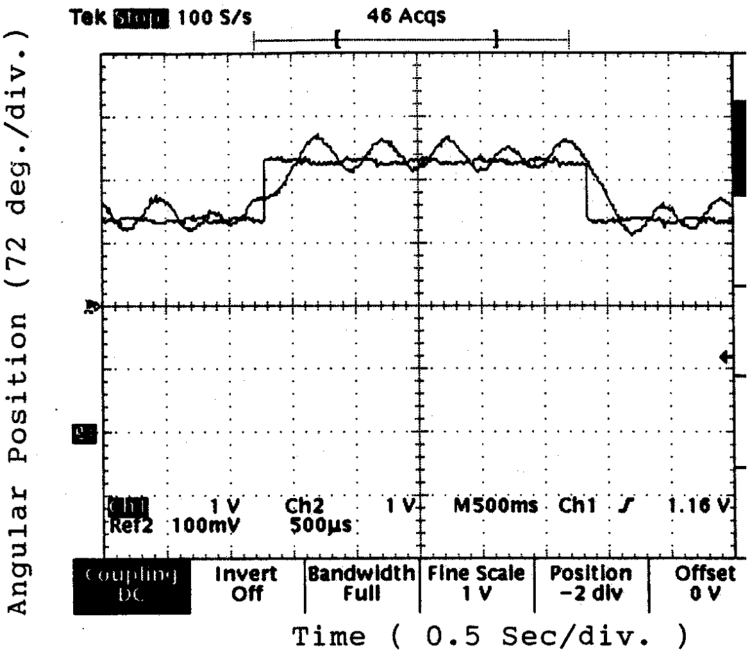

Fig. 7. Measured rotor position and reference track of Case 2.

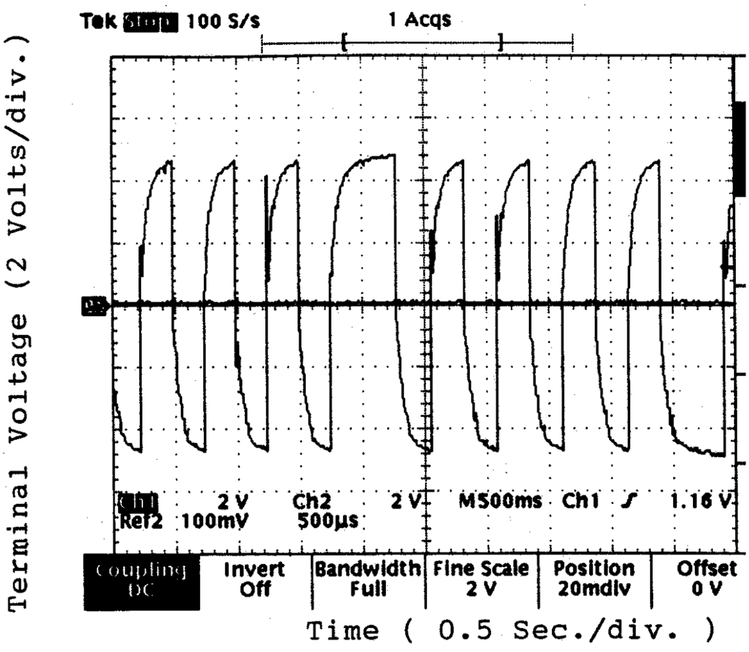

Fig. 8. Control command sequence of Case 2.

tracking performance of the controller with a k_p of 1 and k_i of 1. The actual angular position is superimposed on the specified reference position in order to compare tracking accuracy. Reasonable position tracking accuracy is displayed. The slight steady-state error indicates a need for increased integral gain in the control loop. Figure 10 compares the actual position of the motor with the specified sinusoidal type of position trajectory with a $k_i = 1$ and a $k_i = 8$. This figure shows better performance as compared to that in Fig. 9. The control signal was of sufficient amplitude to cause the motor to rotate, causing the actual position to follow the specified sinusoidal reference track. This is shown in Fig. 11. It is expected that with a large enough value of integral gain k_i the closed loop response will become unstable. Figure 12 shows the position tracking performance with a $k_p = 8$ and a $k_i = 16$. However, when a large value of integral gain ($k_i = 16$) was applied the controller could not maintain tracking accuracy. Unstable controller performance is observed. As can be seen from Fig. 12, the PM DC drive system becomes sensitive to large values of integral gain

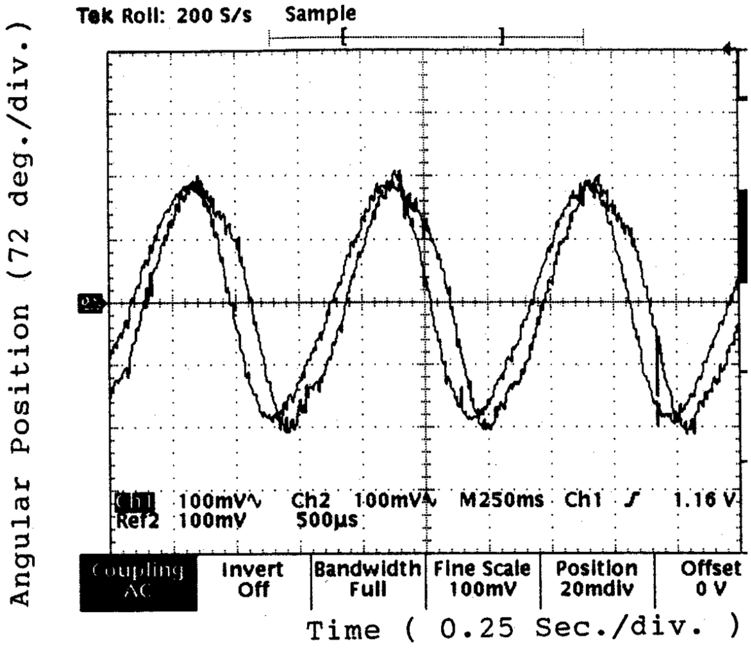

Fig. 9. Position tracking performance for a sinusoidal ref. track using $k_p = 1$ and a $k_i = 1$.

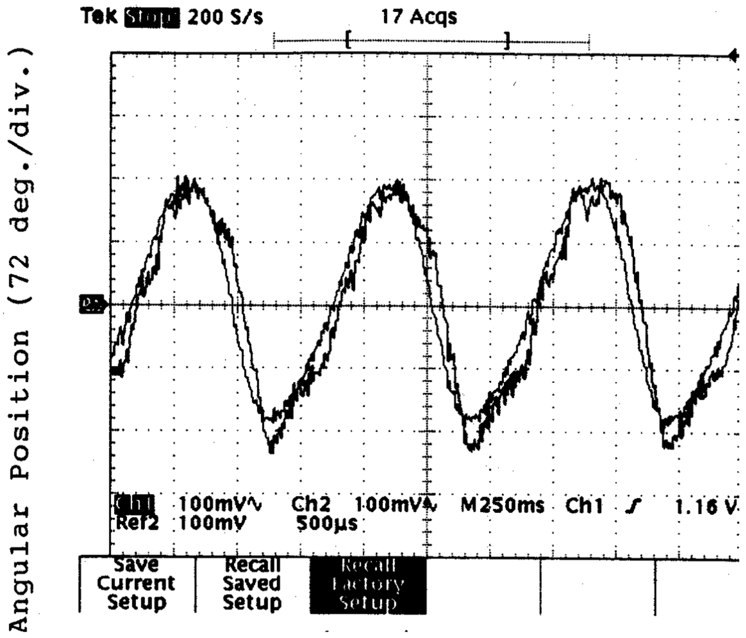

Fig. 10. Position tracking performance for a sinusoidal ref. track using $k_p = 1$ and $k_i = 8$.

and thus could not follow the specified reference track.

CONCLUSIONS

Several conclusions can be drawn about this laboratory experiment and how well its goals were met. The introduction stated that the aim of this paper was the design and implementation of a state-of-the-art control system for use in an undergraduate engineering education. This goal was achieved through the design and construction of a microcontroller. The design demonstrates technologies that are just gaining widespread support today in industry. The design illustrates that microcontrollers can form the heart of a flexible, cost-effective control system. The cost effectiveness of the design is apparent given that the tracking controller, including microcontroller, memory, power amplifier, transducer interface, operator interface, and power supplies cost less than $200 to build. The techniques employed in the controller designed for the laboratory experiment will likely

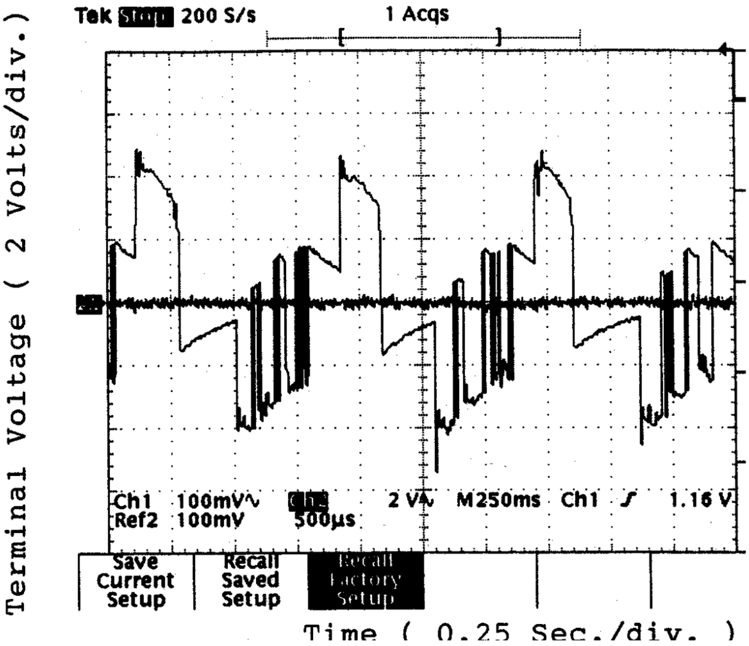

Fig. 11. Control command sequence for PI controller with $k_p = 1$ and $k_i = 8$.

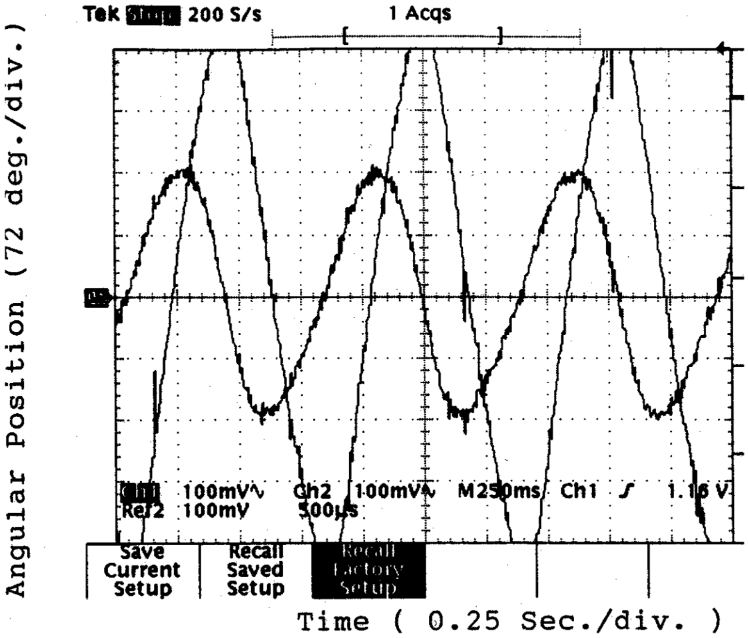

Fig. 12. Position tracking performance for a sinusoidal ref. track using $k_p = 8$ and $k_i = 16$.

be seen by the students in their subsequent employment after completion of their college careers.

In short, this paper discusses the use of a tracking microcontroller for undergraduate experimentation. The microcontroller incorporates attractive features such as simplicity, good performance, and automation while utilizing a low cost hardware and software implementation. Additionally, one important feature of the laboratory experiment is that the control function can be modified by simply changing the structure of the control algorithm without any change in the hardware. Thus, several control algorithms can be implemented in a short period of time, and with minimum effort.

The use of the laboratory experiment has generated many positive results. Student reaction to the experiment has been very good and interest has been increased. The students seem to appreciate the 'feel' that they gain from the laboratory experiment, as opposed to a computer simulation. The quality of graduates improved. Industry is receiving engineers trained in solving real-world problems. Our goal is to reduce or even eliminate the training period for the new engineers when they start to work in this area. Also the body of research and literature is growing and will be used as a base for future research and problem solving.

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Ahmed Rubaai received the MSEE degree from Case Western Reserve University, Cleveland, Ohio, in 1983, and the Dr.Eng. degree from Cleveland State University, Cleveland, Ohio, in 1988. The same year, he joined Howard University, Washington, DC, as a faculty member, where he is presently an Associate Professor of Electrical Engineering. His areas of funded research include high performance tracking control, fuzzy logic, and neural network applications to electric drives. Dr Rubaai is a member of the IEEE Power Engineering Society, the IEEE Industry Applications Society and the American Society for Engineering Education. He is an active member of the IEEE/PES Education Committee, the IEEE/PES Direct Current, Permanent Magnet and Special Machines Subcommittee, and Secretary of the IEEE/IAS Industrial Automation and Control Committee. Currently, he is serving as Technical Committee Program Chair and Transactions Editor for the IEEE/IAS Industrial Automation and Control Committee. Dr Rubaai is a recipient of the 1997 and 1998 Faculty Teaching Excellence Award.