AC 2008-651: LABORATORY IMPLEMENTATION OF BANG-BANG CONTROLLER-BASED MOTOR DRIVE MODULE FOR MODELING AND CONTROL COURSES

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Laboratory Implementation of Bang-Bang Controller-Based Motor Drive Module for Modeling and Control Courses

Abstract

This paper describes a novel methodology for development of real-time control design and implementation of an enhanced bang-bang controller with particular emphasis on student use in a laboratory environment. The students designed and implemented their controller using a dSPACE DS1104 digital signal processor (DSP)-based data acquisition control (DAC) system, and MATLAB/Simulink environment. The controller is implemented in real-time, using the position control of a brushless drive system as a testbed. Experimental results show that the improved bang-bang controller produces adequate control performance, particularly in handling nonlinearities and external disturbances. The real-time design of the controller is integrated with previously taken lectures in linear control systems course offered every spring semester. The paper also presents a hardware platform used during the course.

Introduction

Since James Watt developed his centrifugal governor for steam engine speed control in the eighteenth century, automatic control has become increasingly important in the advancement of science and engineering, and has applications in most areas of technology[1]. A control system is defined as a device or combination of devices which regulates the behavior of other devices or systems. Control systems enable optimal performance of dynamic systems and increased productivity. There are several types of controllers which are classified by their control action. These include but are not limited to stair logic, proportional plus integral, proportional plus integral plus derivative, dual-loop, bang-bang, etc. The bang-bang controller, also known as the on/off controller is very useful in the control of non-linear digital systems which make decisions based on target and threshold values and decides whether to turn the system on or off. The eighteenth century engineer proposed a simple version of the bang-bang controller. He proposed a contrivance whereby a horse pulling a cart, mill, etc. would activate an automatic goad which would prick him if his speed was lower than some favorable limit until a satisfactory speed was reached[2]. Despite the simplicity of the controller, it has many useful applications, such as temperature control in a furnace or thermostat, motor switching control[3] and impact control in robots[4]. The relative effectiveness of bang-bang controllers versus linear controllers was investigated by comparison to human behavior in an experiment which investigated the tendency of human operators to behave in bang-bang fashion when controlling some high-order systems when a linear alternative was available[5]. It was concluded that for the class of systems for which fine motor control about the referrence is unnecessary, bang-bang control is more intuitive and can be performed without sacrificing performance.

In response to concerns that the study of control systems is too dependent on abstract mathematical theory and not enough emphasis on "hands-on" projects related to current industrial technology [6], an increasing number of universities have introduced laboratory courses which utilize state of the art technology tools to solve relevant real world problems. Many of the undergraduate courses in the Mechanical Engineering Department at the Dutch University

Technische Universiteit Eindhoven, place great emphasis on the modeling of control systems[7]. Most of the Master of Science students at the Department of Automatic Control at the Lund Institute of Technology in Sweden are required to complete a basic control course and lab that utilize mobile desktop processors. The Institute is known as a pioneer in the teaching of real-time programming and systems[8]. The University of Maryland, College Park, has implemented an all-digital controls lab which is used for a multidisciplinary course which combines information technology with digital control and networks[9]. The Electrical and Computer Engineering Department at Howard University requires that undergraduate students take a linear control systems course[10]. In this course, students are able to design an enhanced bang-bang controller using MATLAB/Simulink environment. The Simulink Real-Time Workshop, in conjunction with DSPACE Control Desk allows students to use their own control system designs to control actual servomotors in real-time. The combination of Simulink and ControlDesk eliminate the need for excessive programming in languages such as C or Java, and allows Howard students more time to "fine-tune" their controllers and produce practical results.

Description of Bang–Bang Controller

The actuating element of a bang-bang controller has only two fixed positions, which it switches abruptly between. This controller is often used to control a system with binary input, such as a thermostat which can only be on or off. Figure 1 shows the basic function of a bang-bang controller. In our case, the position error is measured.

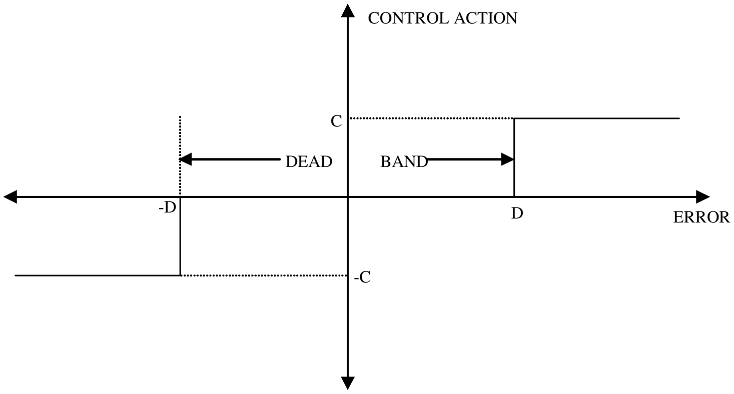

Fig. 1 Bang-bang controller

The bang-bang algorithm is generally described as:

$u_c(k) = 0 \quad \text{for} \quad |\text{error}| < D$

$u_c(k) = -C \quad \text{for} \quad \text{error} < -D$

$u_c(k) = +C \quad \text{for} \quad \text{error} > D$

where u_c (k) is the output of the controller, D is half the width of the controller dead-band region, the error is the difference between the set-point value and the motor position, and C is the magnitude of the output of the controller when the error lies outside of the dead-band range. The error (set-point – motor position) is the only factor that the controller uses to determine the controller output. If the error lies outside the dead-band region and is positive, then the controller output is a fixed user-defined positive value. If the error is negative and less than the dead-band, the controller output will be a fixed user-defined negative value. If the error lies within the dead-band range, then the controller output will be zero. The control action moves the motor in the proper direction to correct any error conditions measured. Control action is stopped when the error is within the dead-band region.

Enhanced Bang-Bang Control Structure

The bang-bang controller developed in this paper was created using Simulink™ blocks as shown in Fig. 2. The input to the controller is the reference signal, R, from the Signal Generator. This is combined with actual position, Θ, from the motor & drive system to produce the error signal. The error signal is fed into the If block as e and compared to the dead-band setting which is D. An if statement compares the signals and activates the appropriate Subsystem. For example, if ($e>D$) then the signal is sent to the If Action Subsystem which sends the control_action as Out1 (u_c) to Merge. A saturation block is next which passes the control signal u(k) up to a given saturation setpoint (±5 volts for this experiment). This is the control signal u(k) for the Motor & Drive System indicated as control_sig. Similarly, for the case when ($e<-D$), the elseIf Action Subsystem sends the control_action as Out1 ($-u_c$) to Merge. Otherwise, the control_action is 0. In order to protect the motor drive system from excessive control voltages, saturation is often used to limit the controller output $u_c(k)$ as follows:

$$u(k) = \begin{array}{lll} u_{max} & \text{when} & u_c > u_{max} \\ u_c & \text{when} & u_{min} \leq u_c \leq u_{max} \\ u_{min} & \text{when} & u_c < u_{min} \end{array}$$

where u_c is the input to the saturation block and u_{max} is the upper limit and u_{min} is the lower limit of the saturation block.

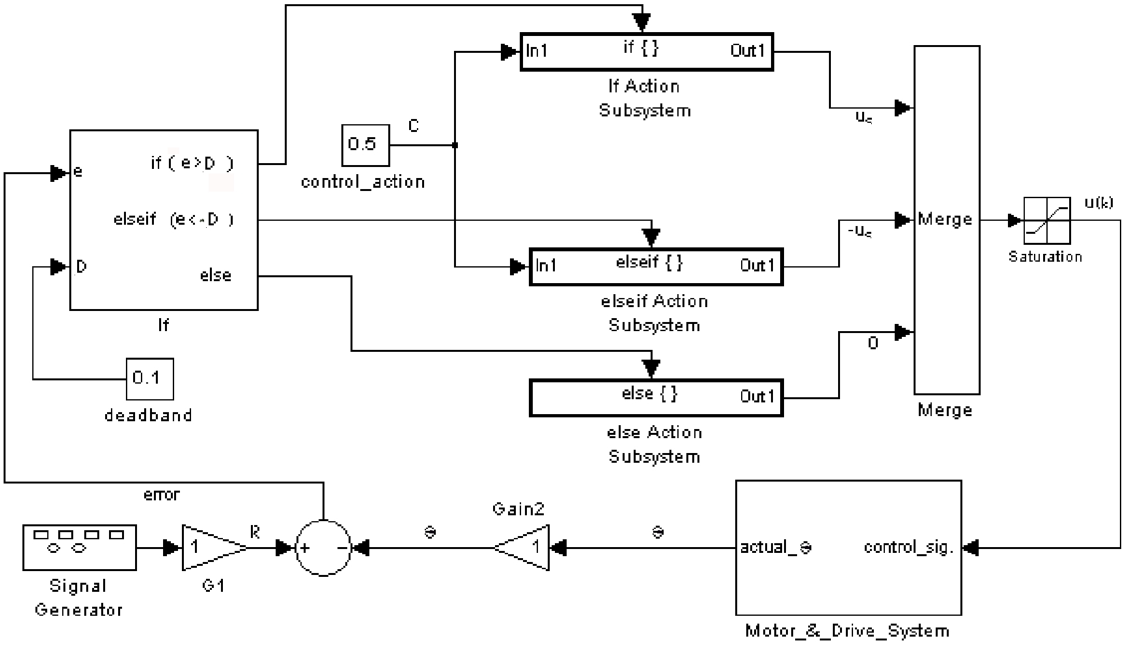

Fig. 2 Simulink model implementing bang-bang controller where all coefficients are tunable online

Laboratory Setup

The actual laboratory hardware setup is shown in Fig. 3a. It consists of four major elements: a dSPACE DSP1104 DSP board, a controlled process (3-phase brushless dc motor), a Moog T200-410 Adjustable Speed Drive and a Personal Computer with Simulink^{TM} and Control Desk Software.

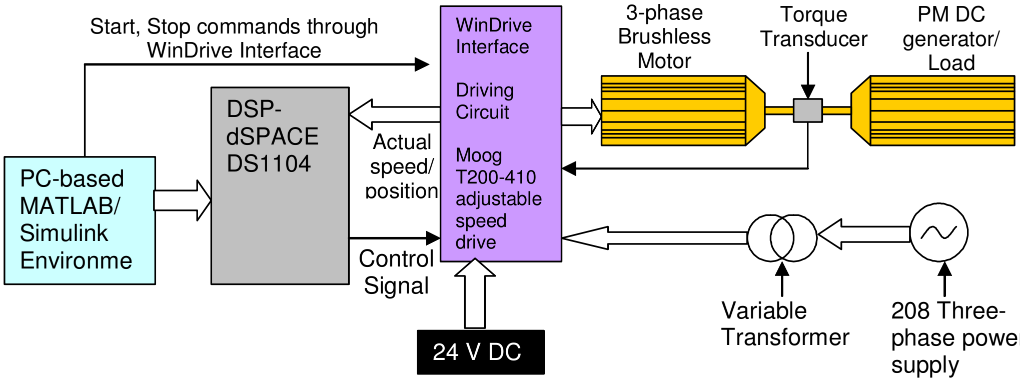

Fig. 3a Block diagram of the laboratory setup

The dSPACE DS-1104 DSP board [11] forms the core of the closed loop system. The motor is 1-hp 3000 rpm three-phase brushless DC servomotor, which was manufactured by Moog Aerospace [12]. It is equipped with resolver, and is coupled via a torque transducer. The motor is also coupled with a PM DC Generator as a dynamic load. To achieve sudden change in the torque load, the voltage of the PM DC generator is varied. The adjustable speed drive is also a Moog T200-410 designed for brushless servo drives [13]. A variable auto-transformer is used to supply the driving circuit with ac voltage of 230V. A power supply is also used to supply the inverter component of the driving circuit with 24V DC. The PC is a Pentium D 2.8-GHz with Windows XP. Figure 3b displays a photo of the laboratory setup.

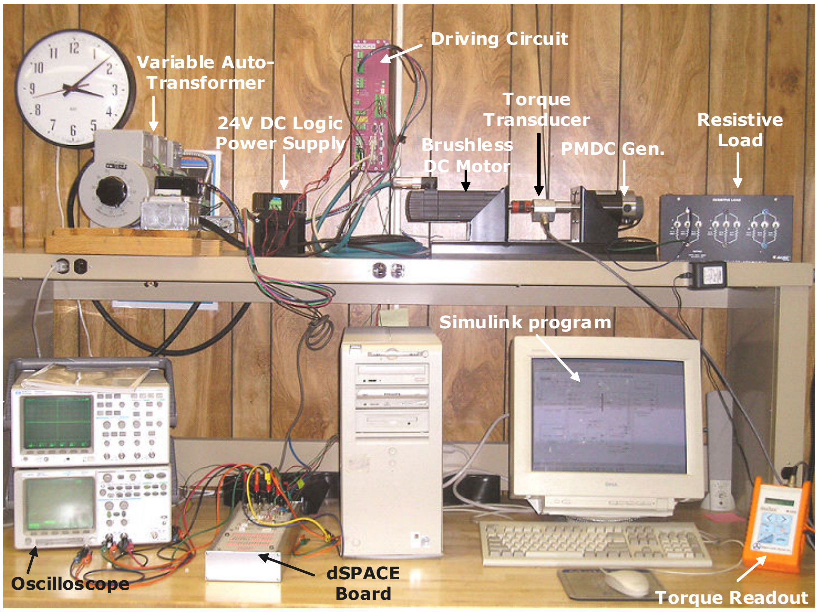

Fig. 3b Photo of the laboratory setup

Experimental Results

In order to evaluate the performance of proposed control scheme, the students completed several test cases under different operational conditions. However, only salient results are reported in this paper. In all cases, the actual position is superimposed on the desired reference position in order to compare the tracking accuracy. The students are required to tune the controller parameters such that the closed-loop control system is stable and meets given design specifications associated with the following:

1. Stability robustness.
2. Set-point following and tracking performance at transient, including rise-time, overshoot; and, settling time.
3. Regulation performance at steady-state, including load disturbance rejection.
4. Robustness against environmental uncertainty.

A. Baseline Condition

The students selected a baseline condition to be used as a reference for comparison. For the baseline, the signal from the signal generator was set to amplitude of 0.2 volt (20 revolutions) and frequency of 0.15 Hz. The dead-band of the controller was set to ± 0.01 volt (1 revolution) with its output (control signal) set to ± 1 V. Figure 4a displays the baseline condition, while, Figs. 4b and 4c show both responses of motor position trajectory and the control signal.

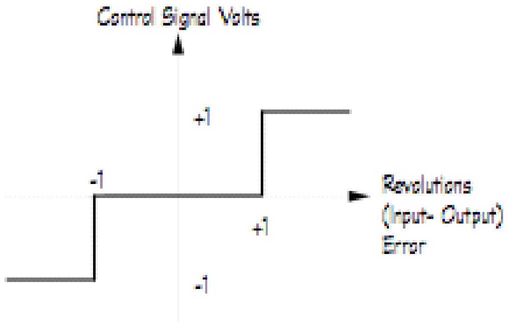

Fig. 4a Baseline Bang-Bang Settings (1 revolution error)

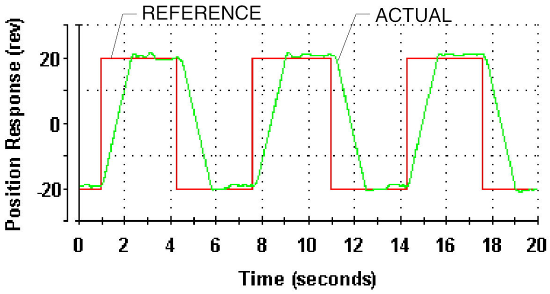

Fig. 4b Position tracking

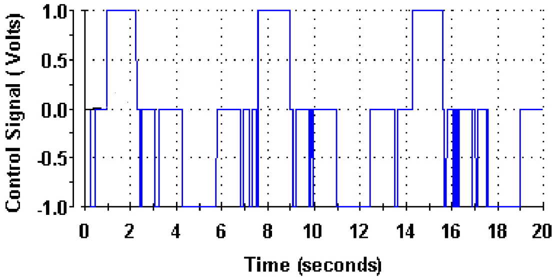

Fig. 4c Corresponding control signal

These baseline conditions were selected by the students because the motor position tracked the reference signal very well. Note that at time t=1 the reference signal shifted from –20 revolutions to +20 revolutions. Since the actual motor position was still at –20, the controller sensed an error greater than its setting of 1 revolution so the control signal stepped up to 1 volt. The control signal remains at 1 volt until time t~2.4 seconds when the error decreases to less than 1 revolution and then the control signal returned to 0 volts. This cycle is repeated in the opposite direction when the reference signal reverses at time t~4.1 seconds. Note that there is an intermittent cycling of the controller output at time t~2.5 and t~3.1. This is due to the noise in the position response signal. When the noise magnitude is large enough to exceed the controller error setting (1 revolution in this case) the controller responds to correct the error. Since the noise does not persist, the controller quickly returns to 0.

B. Variation of Controller Output

For the next set of tests, the students kept the dead-band constant (± 0.01v or 1 revolution) and changed controller output between 1 and 20V. When the position error exceeds 1 rev, the controller output responds with a ± 2V control signal (Figs. 5a through 5c). A similar test was conducted with the bang-bang controller set to an output of ± 20V. Since a saturation of ± 5V was placed within the closed loop system, the control signal settles at the limits of saturation, ± 5 volts in an attempt to get to ± 20V setting. Figure 6a exhibits the system performance, while, Fig. 6b displays the change in the controller output.

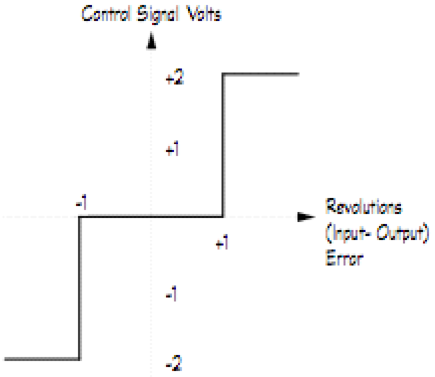

Fig. 5a Bang-Bang Settings (1 revolution error)

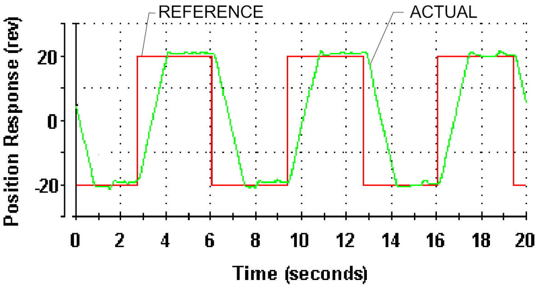

Fig. 5b Position tracking

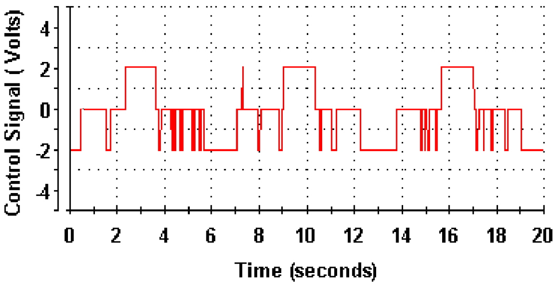

Fig. 5c Corresponding control signal

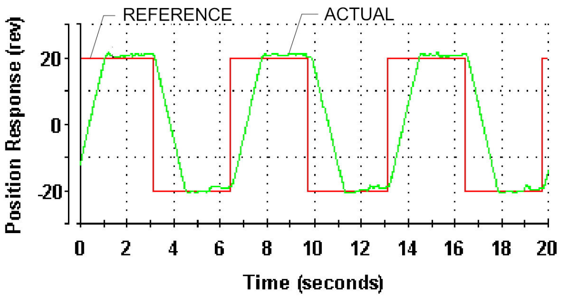

Fig. 6a Position tracking

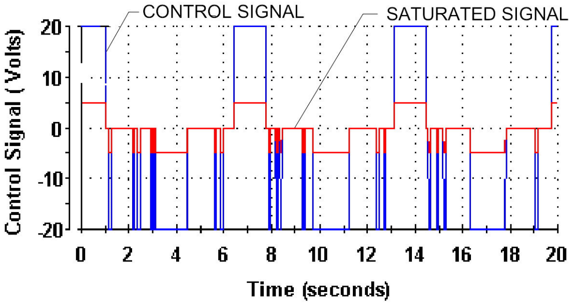

Fig. 6b Corresponding control signal

C. Application of External Force

The students introduced an external force in the system by physically preventing the motor from rotating; holding the shaft for 5 seconds starting at time t=3 seconds. For this test, the students kept the dead-band constant (± 0.01v or 1 revolution) with its output (control signal) set to ± 1 V. From t=3 to t~3.8 the controller did not detect an error so the signal remained at 0. At t~3.8 the error signal was detected and the controller sent a +1 volt signal which persisted since the shaft was being held. When the students shifted the reference signal at t~7, the actual position was less than the reference position so a positive control signal was sent. When the students let the shaft go, the motor moved to react to the control signal but overshot the reference until it reversed at t~8 seconds and moved to meet the reference signal. At t~9.5 the shaft was again held by the students and a similar response was observed. At t~17 the students released the shaft and the motor started tracking as before when it was not under external influence. Figure 7a exhibits the effect of external force, while, Fig. 7b displays the corresponding control signal.

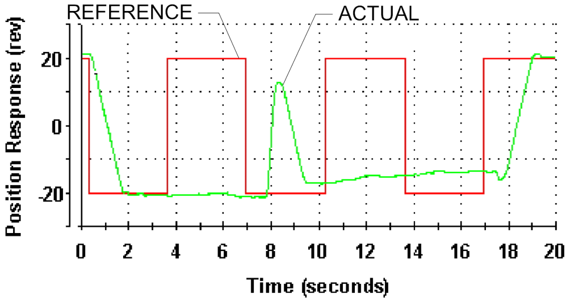

Fig. 7a Response under external force

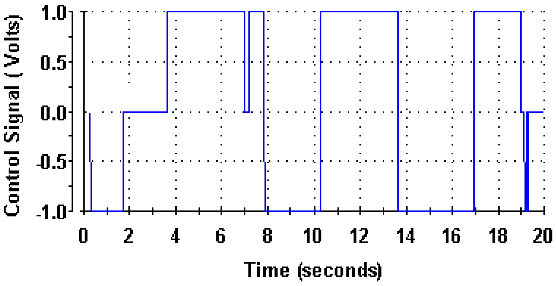

Fig. 7b Corresponding control signal

Students Self-Scoring Survey

A student self-scoring survey was developed and implemented to assess the effectiveness of the required linear control course. Table I demonstrates the course evaluation survey taken at the end of spring 2007 semester. The answer to each question is a number 1 to 5. In addition, the students were encouraged to write supplementary answers and comments. Out of the 32 students taking the linear control course, 28 responded to the survey.

Table I Course Evaluation Survey

Question	1	2	3	4	5	
	Strongly Disagree	Disagree	Unsure	Agree	Strongly Agree	Average
1. Was the course challenging and motivating?	0	0	3	5	20	4.6
2. Did the course meet your expectations?	0	0	3	8	17	4.5
3. Is the lab experiment easy to follow?	0	0	3	15	10	4.3
4. Are the course materials easy to comprehend?	0	0	8	10	10	4.1
5. Are you comfortable using MATLAB/Simulink?	0	0	1	4	23	4.8
6. Are you comfortable using ControlDesk of dSPACE?	0	0	2	6	20	4.6
7. Is the laboratory platform versatile?	0	0	3	6	19	4.6
8. Is the laboratory platform easy to use?	0	0	3	8	17	4.5
9. Does the Implementation of a bang-bang controller in dSPACE DSP help your understanding of industrial controls?	0	0	4	9	15	4.4
10. How do you rate this course?	0	0	2	8	18	4.6
11. Would you recommend other students to take this Course?	0	0	4	6	18	4.5
I learned the most from the control lab that:						
I learned the least from the control lab that:						

The survey indicated that the design project did a good job of supporting the outcomes of the course. The students are enthusiastic about the laboratory sessions with practical experiments. They believe that control laboratory experiments help them to learn the material from lectures, which satisfies the first part of our educational goal. Not only have students developed better experimental skills, they also gain an understanding about the design, implementation, and testing of different control algorithms. The use of the laboratory experiments has generated positive results. The students' reaction to the experiments has been very good and interest in the course has been increased. The students seem to appreciate the "feel" that they gain from the laboratory course. Additionally, the students commented that more formal instruction of MATLAB/Simulink in courses prior to the laboratory control course would be helpful. The responses were generally positive, but considering the supplementary answers and comments in particular, they do constitute a good basis for minor improvements of the course. As evidence of this, the hands-on component of this design project will be kept, or possibly expanded.

Conclusions

Students graphically designed their real-time controller in MATLAB/Simulink and dSPACE DSP environment without being distracted by software implementation issues. The

MATLAB/Simulink environment allowed the student to experiment interactively and in real-time by modifying any of the Simulink blocks without the need to rebuild and download a new Simulink model to the dSPACE DSP. Different test cases were used to evaluate the performance of the bang-bang controller. The students observed from the experiment that the smaller the dead-band the more sensitive the control signal in tracking the reference signal. Students gained better understanding of control theory and bang-bang control, by tuning their controller to obtain results for different test cases using the MATLAM/Simulink graphical interface and ControlDesk of dSPACE DSP. Results for all test cases have been presented in the implementation and results section. This helped students focus more on the characteristics of the controller to better understand the functionality of the bang-bang controller.

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