Investigation of the Stability of the Ball and Beam by the PID Controller

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Abstract: The purpose of this research is to construct and investigate the stability of the ball and beam control system with PID coefficients derived from the simulation and compare them. In this research, by first obtaining the mathematical model of the mechanical system and its simulation, the best PID coefficients are selected for it to minimize the settling time and the error. Then, to create this system, the types of mechanisms provided for the ball and beam control system are examined. Depending on the equipment and facilities available, the best design is chosen and built. The best design is the use of the four_bar mechanism using the servo motor and the ultrasonic sensor. The appropriate design is first developed in SolidWorks software to provide accurate measurements for the production of components. Laser cutting and 3D printers are used to produce system components. After the control system is built, the simulation coefficients in the MATLAB software are inserted into the system microcontroller program to check the system responses to the various control coefficients obtained. So doing multiple experiments indicated that the best PID coefficients for this system are PD coefficient. The difference between the experimental graph and the simulation graph is their overshoot. They also have different settling times. One of the reasons for this difference is the use of some approximations as well as disregarding friction.

Keywords: Ball and Beam, PID Controller, Servo Motor, Ultrasonic Sensor

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Research paper

1 INTRODUCTION

Automated control systems play an essential role in all fields of science and engineering. Automated control is an important and integral part of spacecraft systems, rocket guidance, robots, and modern industrial processes, including pressure, temperature, humidity, adhesion, flow, and more. Most engineers and researchers are familiar with the theory and application of automatic control.

The first significant work in the field of automatic control, the James Watt centrifugal regulator, is to control the speed of steam engines in the 18th century [1]. Frequency response methods and the root locus are the core of classical control theory. These methods lead to systems that are stable and meet a set of more or less arbitrary performance demands. These methods are generally acceptable, but not optimistic in any sense. From the late 1980s onwards, the emphasis has been on designing an efficient system for designing optimal systems. The ball and beam system is referred to as the ball balance system on the beam. This control system is commonly available in most university control laboratories. The system is a simple example of simulating real-life issues such as the aircraft's horizontal stability during landing or in turbulent weather. It is a two-degree-of-freedom system in which the ball with the left and right rolls represents one degree, and the rotational motion of the beam is another degree of freedom. The purpose of this system is to control the position of the ball at an optimum point and resist external noise, such as mechanical noise and electrical noise. The rotary motion of the beam is caused by the actuator motor being driven. The signal received by the motor is affected by the program of the control system, which is reported by a sensor to the position of the ball. The proper torque applied by the motor to the beam causes the ball to be positioned according to the sensor feedback.

In 2004, Rosales [2] at MIT university designed and built a ball and beam system. The system uses a potentiometer as a goniometer to measure the deviation of the beam from the horizontal axis. High-strength wires are also used to measure the location of the ball inside the groove. The main structure of the device is the polycarbonate sheet. The motor used is a simple DC motor. In this research, the first simulation is performed in MATLAB software and then the obtained coefficients are applied to the device. Quanser is a company that introduced a ball and beam control system in 2006 called the Ball and Beam Module. The system includes a resistance wire for ball positioning and a DC servo motor with a reducer gearbox. The system is controlled by a PID controller or a steady-state controller [3]. Wang developed another example of a ball and beam control system using a resistor wire sensor at the University of Adelaide in 2007. In this system, a high-resistance wire is used inside the ball movement groove to change the resistance of the ball by varying the connection between two parts of the two pieces of the wire and the rolling of the ball in a different location. In this system, the variable resistance indicates the current location of the ball. Zavala and his colleagues [4] in 2008 developed a system consisting of two ball and beam design systems that were both synchronized with neural compensation. The system uses two DC motors to drive both systems separately. In this system, the control of each system directly affects the control of the other system. Initial experiments of this system have been investigated with linear controllers.

Xiaohui and his colleagues [5] in 2018, investigated concerns with the stability analysis of the sampled-data nonlinear Active Disturbance Rejection Control (ADRC)-based control system. Firstly, a class of Single-Input-Single-Output (SISO) continuous plant is discretized using Zero-Order-Hold (ZOH), and several kinds of digital implementation methods for the Nonlinear Extended State Observer (NLESO) are newly proposed. Then the sampled-data nonlinear ADRC (NLADRC) based closed-loop system is transformed into a discrete-time Lurie-like system, to which linear matrix inequality (LMI)-based sufficient conditions for absolute stability and robust absolute stability are obtained. The sufficient conditions provide convenient and effective methods for determining the stability and its relationship with the parameters of the controller, the plant and the sampling period. Using the ball-beam system as an example, the proposed results are verified in both simulations and experiments. Ibrahim Mustafa and his colleagues [6] in 2019, investigated two Degrees of Freedom fractional-order control of the ball and beam system. It involves the model-based method to design controllers' parameters for the corresponding linear model. The fractional-order controllers are specially tuned to have a constant phase margin of the open-loop. This characteristic ensures the robustness of the controllers to the variations of system gain.

This paper presents a proper evaluation and comparison between integer and fractional-order controllers. The performance of each controller is evaluated in terms of set-point tracking, disturbance rejection, and robustness. The comparison between two controllers is validated through both simulation and experimental results. Strengths and weaknesses in real-time control are also indicated. Hasanzade and his colleagues [7] have investigated the control of the ball on the beam by a visual machine. In this study, direct data acquisition by MATLAB software and xPC Target module is used, as well as two serial computers are used to communicate with the system. The first computer (user computer) is used for data capture, and the second computer (target computer) is used for user communication. The camera data is taken every 10 seconds. Communication between the system and the computer is performed by a DAQ (Data Acquisition System) card. The present study analyses the construct and investigates the stability of the ball and beam control system with PID coefficients derived from the simulation and compares them.

2 MATHEMATICAL MODELING

Mathematical modeling of any system provides a way for scientific study and a better understanding of system performance. Before proceeding to control the ball and beam system, it must be thoroughly examined in terms of mathematical modeling. Theoretical analysis of this system is the first step to obtain a mechanical and control view of it. Usually, the analysis of the processes of a system requires a robust engineering approach based on physical laws. In a ball and beam system, the ball is rolling on a beam that is driven by an electric motor. The mechanism of this system and the system used in the present study are shown in “Fig. 1”. To control the desired position of the ball, the beam must rotate properly around its connection axis. With these interpretations, mathematical modeling should represent the relationship between the electrical and mechanical components of the system [8].

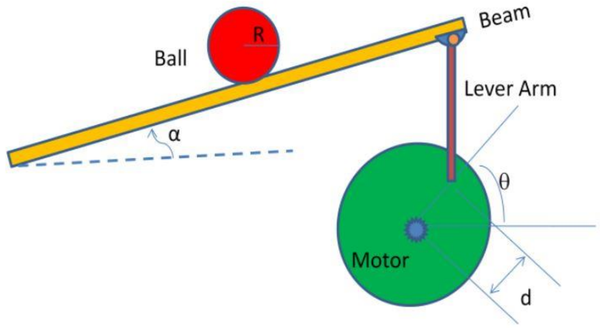

Fig. 1 Schematic of the ball and beam system [9].

The ball and beam control system can be divided into two control subsystems, evaluating the performance of each system based on its input and output and feedback, and finally analyzing both systems as a comprehensive control system. From the control point of view, the transfer function of each system is determined by the Laplace transform function ratio of output to input. According to Newton's second law and the ball free diagram shown in “Fig. 2”, the equation of the ball and beam system can be derived. Then using this equation, the system transform function is obtained. For the mathematical modeling of this system, the relationship between the location of the ball and the beam inclination angle as well as the relationship between the input voltage and the rotational angle of the DC motor are required; Therefore, the system transform function is obtained by combining the transform functions of the slope of the beam to the ball position and the input voltage at the rotational angle of the motor [9].

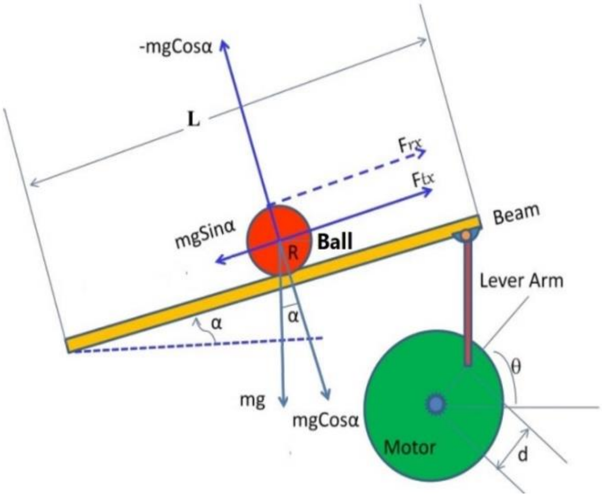

Fig. 2 Dynamic balance of forces on the ball as it moves [9].

Moving the ball over the beam is a combination of transitional and rotational motion. Accordingly, it gives the acceleration of the transitional motion of the ball to “Fig. 2”. The force applied to the mass (m) is represented by F. The rotational moment of the ball is denoted by τ where ω is the angular velocity and J is the moment of inertia of the ball around its center of mass.

$$F_{tx} = m\ddot{x} = m\frac{d^2x}{d^2t} \tag{1}$$

$$\tau = J\frac{d\omega}{dt}, \qquad \ddot{x} = R\frac{d\omega}{dt} \tag{2}$$

According to “equation (3)”, the rolling force of the ball is expressed:

$$F_{rx} = \frac{T}{R} = \frac{J}{R^2}\ddot{x} \tag{3}$$

According to “Fig. 2”, we will have:

$$F_{rx} + F_{tx} = -mg\sin\alpha \tag{4}$$

$$(\frac{J}{R^2} + m) = -mg\sin\alpha \tag{5}$$

Since the slope angle α for the beam is controlled by the θ angle variation of the motor and the θ angle is dependent on the input voltage to the motor, the transfer function and the relationship between the voltage and θ for the motor must be investigated; but since the motor used in this study is a DC servo motor with an internal control system, the control equations for the motor will not be considered, and the servo motor is assumed to have a controllable angle without error. Using the approximations, the angle α is related to the angle θ, and it should be borne in mind that the angle θ must vary between -20 to 20 degrees for these approximations to be reliable:

$$\sin\alpha \approx \alpha, \quad \alpha \approx \frac{d}{l}\theta \tag{6}$$

Replacing the “equation (6)” in 5 will have:

$$\left(\frac{J}{R^2}+m\right)\ddot{x} = -mg\frac{d}{l}\theta \tag{7}$$

Using the moment of inertia will have the ball:

$$J=\frac{2}{5}mR^2 \tag{8}$$

With the approximation of -9.8 m/s2 for the Earth's gravitational acceleration and summarization (8) we will have:

$$\ddot{x} = -\frac{5}{7}\left(g.\frac{d}{l}\theta\right) = 7\frac{d}{l}\theta \tag{9}$$

Using Laplace's take on both sides of “equation (9)”, we assume that the initial condition is zero:

$$\frac{x(s)}{\theta(s)} = \frac{7d}{l}\left(\frac{1}{s^2}\right) \tag{10}$$

“Equation (10)” shows that the ball and beam control system is not dependent on the weight of the ball due to this power transfer mechanism, and only the length of the system links determines the stability of the ball.

3 DESIGN AND CONSTRUCTION

The laboratory system can be divided into two main mechanical and electronic parts. The mechanical parts of the system include the servo beam, frame, Servo motor arm, and Lever arm (coupler in four-wheel-drive mechanism). The electronic part of the system includes a DC servo motor, an ultrasonic sensor, and a microcontroller. The design of the system, especially it is a mechanical part, is done by SolidWorks software. The final design by SolidWorks software is shown in “Fig. 3”.

Fig. 3 Ultimate 3D system design in SolidWorks software.

The selection of appropriate material for a mechanical part is an essential element of all engineering projects. The main mechanical parts of the system are the base support, ball and beam, as shown in “Fig. 4”.

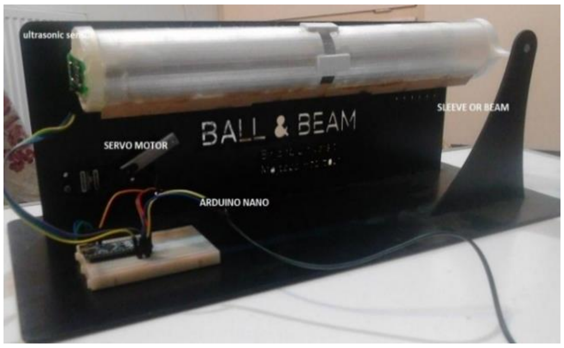

Fig. 4 Laboratory system for ball and beam control.

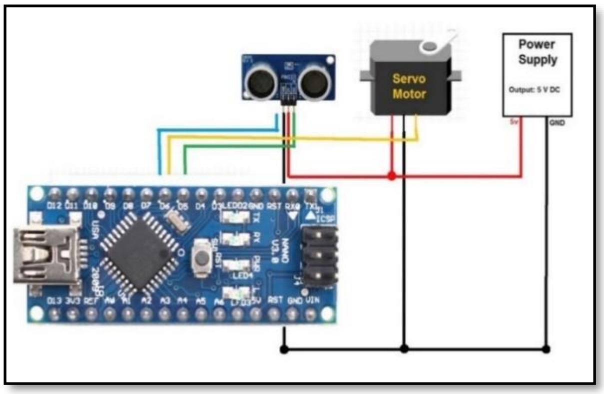

Fig. 5 Ball and Beam Control System Electrical network [10].

The sensor used in the system is SRF05 type and according to the information provided by the manufacturer, it has an accuracy of 3 mm. The DC servo motor (DM-S0900M) has a torque of 15 kg.cm with the lowest gearbox clearance. The microcontroller used in the system is ATmega328P. The ultrasonic sensor connected to the microcontroller reports the position of the ball, which is the centimeter of the reported data. The microcontroller then commands the appropriate angular momentum to control the ball based on the PWM waves according to the input data to the PID controller and calculates it. The electrical circuit connections of the system are shown in “Fig. 5”.

4 PID CONTROLLER DESIGN

It is difficult to design a controller with Ziegler Nichols for a major reason; it was found that the overall system is a fifth-order system which means difficult to design a controller for a higher-order system. To make the control design easy, the whole system is separated into two feedback loops; inner loop and outer loop as shown in “Fig. 6”. The purpose of the inner loop is to control the motor gear angle position so that the gear angle (θ) tracks the reference signal (ref θ). The outer loop uses the inner feedback loop to control the ball position [10]. The controller is designed in a variety of ways. These methods are usually based on trial and error or computational methods such as Ziegler-Nichols. Using MATLAB software and simulating the controller system, the trial and error method is a low-cost and high-speed method. TAhe control system mainly consists of two parts: Angle Control and motor Control, since the motor used is a servo-type digital engine with internal control, we skip the simulation. The closed-loop network system is shown in “Fig. 6”. The inner loop corresponds to the internal control of the motor and the outer loop to the ball position feedback for the PID controller.

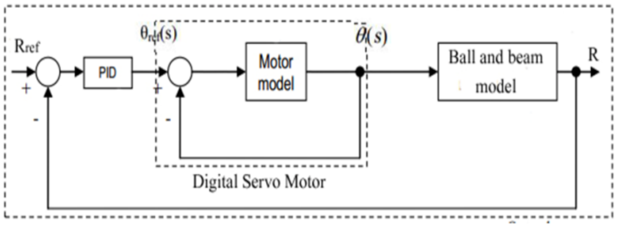

Fig. 6 Overall system [10].

In general, the gains of K_p, K_i, and K_d will need to be adjusted by the user to best serve the system. While there is no static set of rules for which the values should be used for any system, following the general procedures should help in tuning a circuit to match one’s system and environment. In general, a PID circuit will typically overshoot the setpoint value slightly and then quickly damp out to reach the setpoint value [10]. Manual tuning of the gain settings is the simplest method for setting the PID controls. However, this procedure is done actively (the PID controller turned on and properly attached to the system) and requires some amount of experience to integrate fully. To tune the PID controller manually, first, the integral and derivative gains are set to zero. The proportional gain is increased until observing oscillation in the output. After the proportional gain is set, the derivative gain can then be increased. The derivative gain will reduce overshoot and damp the system quickly to the setpoint value or near it. If the derivative gain increased too much, a large overshoot would be seen. Once the derivative gain is set, the integral gain is increased until any offset is corrected for on a time scale appropriate for the system. If the gain is increased too much, a significant overshoot of the setpoint value and instability in the circuit would be observed [10]. After the proportionality coefficient is determined, the derivative and integral coefficients increase or decrease according to “Table 1” and until the system reaches the desired result.

Table 1 Changes in PID coefficients and their effects on system stability

	Rise time	Overshoot	Settling time	Steady-state error
Increase K_P	Decrease	Increase	324.78	Decrease
Increase K_I	Decrease	Increase	Increase	163.16
Increase K_D		Decrease	Decrease	103.43

5 EXPERIMENTAL RESULTS

The details of the mechanical system built and modeled in MATLAB software are given in “Table 2”. “Table 3” presents the results of manual tuning the PID coefficients in MATLAB software for system stability.

Table 2 Details of the mechanical system

Parameter	Value	Unit
Ball Mass (m)	0.065	kg
The radius of the ball (R)	0.04	m
Servo arm length (d)	0.05	m
Beam length (groove) (L)	0.33	m

Table 3. The PID parameters

Experiment No.	Controller Parameter		
	K_D	K_I	K_P
1	0	0	1
2	0	0	2
3	0	1	1
4	0	1	2
5	1	1	2
6	2	1	2
7	2	1	1
8	1	0	1

The latest trial and error in Experiment 8 is considered the best response to the operating system, shown in “Fig. 7”.

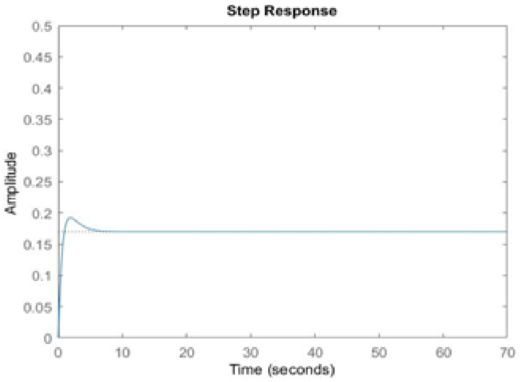

Fig. 7 System response with Experimental Test No. 8.

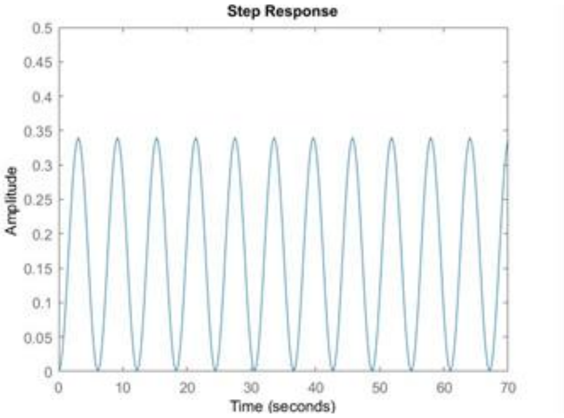

Fig. 8 System response with Experimental Test No. 1.

According to the diagram below, the increase in coefficient I causes instability in the system.

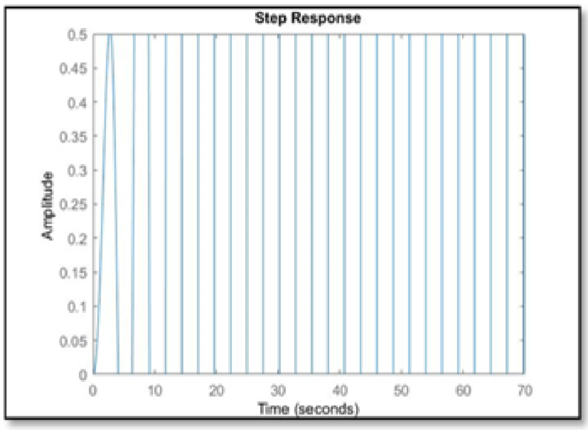

Fig. 9 System response with Experimental Test No. 3.

The system response diagrams for the coefficients P and PI are shown in “Fig. 8” and “Fig. 9”. According to the controller parameters tuning strategy, the coefficient P is one (P=1) assigned to the oscillation system. The coefficient I is then increased to reduce the error and the rise time. The results of these changes are shown in “Fig. 10”. By tuning coefficient D and other coefficients simultaneously, the best PID coefficients will be obtained.

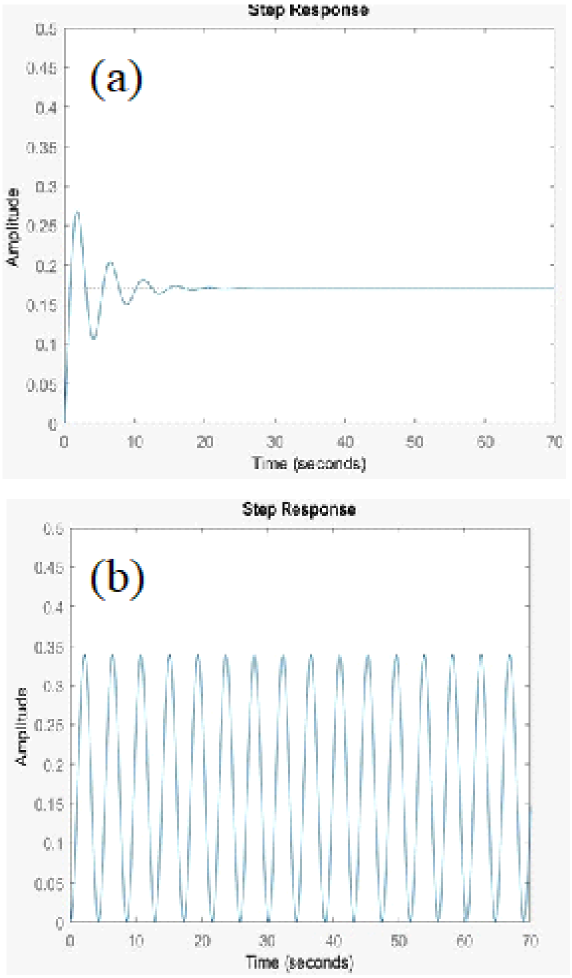

Fig. 10 System response with: (a): Experimental Test No. 5, and (b): Experimental Test No. 2.

Adding coefficient D and tuning coefficient I in the controller reduce the settling time as well as decreasing the overshoot. The results of these changes are shown in “Fig. 11”.

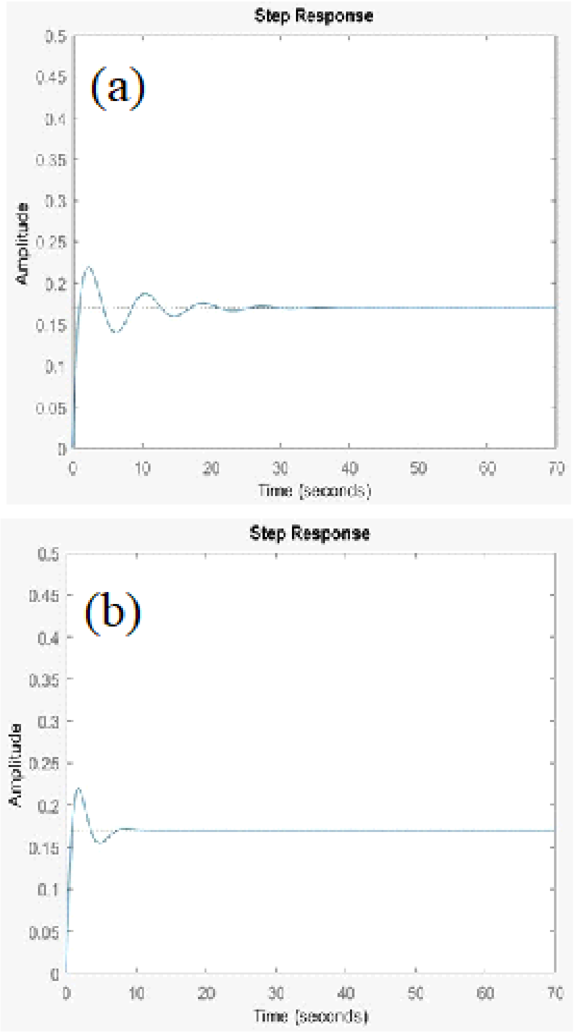

Fig. 11 System response with: (a): Experimental Test No. 7, and (b): Experimental Test No. 6.

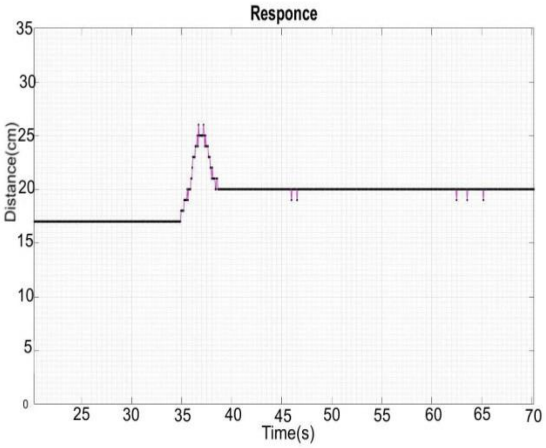

Fig. 12 System response with Experimental Test No. 8 and editing experimental coefficient.

Therefore, the coefficients obtained from Experiment 8 are used for the laboratory system, but according to the experimental tests performed with the simulation control coefficients in Experiment 8, the steady-state error in the system due to the K_I coefficient being zero will not be eliminated and therefore a value of 0.3 is assumed for this coefficient, the experimental graph of which is shown in “Fig. 12”.

According to this graph, the system reaches stability after 3 seconds, which is the slowest time of the coefficients. In the experimental test, the ball is positioned 17 cm from the sensor, with a step function to reach 20 cm. The overshoot of the ball is 6 cm and then reaches stability.

6 CONCLUSION

In this research, first it was attempted to develop a laboratory system that has the best response to perturbations for the controller used; but due to the application of the coefficients obtained from the simulation results to the laboratory system, in some cases, complete instability has been observed by the system due to the lack of factors such as clearance and friction in the modeling. The most important point to be considered in the laboratory results is the use of the KI coefficient for system stability as opposed to the simulation results. The use of this coefficient guarantees that the system will be able to eliminate error and instability.

The difference between the experimental graph and the simulation graph is their overshoot. They also have different settling times. One of the reasons for this difference is the use of some approximations as well as disregarding friction.

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