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Designing and Building a Ball-on-Beam Balance System using an Infrared Sensor

Hamzah Ali Alkhazaleh [1]*, Rebeya Anzum [2], Harikumar Pallathadka [3], Hassan Bediar Hashim [4]

[1] College of Engineering and IT, University of Dubai, Academic City, 14143, Dubai, UAE
[2] Postgraduate Student, Kulliyyah (faculty) of Engineering, International Islamic University Malaysia (IIUM). P.O. Box 10, 50728 Kuala Lumpur, Malaysia
[3] PhD, Manipur International University, Imphal, Manipur, India
[4] Middle Technical University, Baghdad, Iraq

Abstract

Automatic control has played a vital role in scientific development and is the integral part of manufacturing and industrial processes. One of the major problems in different industries is unstable systems control. Aircraft pitch angle control or vehicle roll angle control during cornering a bend can be obvious examples of instability control. Ball on beam balancing system is a laboratory sample for an unstable system so that by the better balance of this sample, the ability to improve the control of unstable systems can be obtained. The main purpose of this research is to build and develop the ball on beam balancing system by applying the infrared sensor and microcontroller. The challenge of ball on beam balancing system is to keep the rolling ball on a specified point of the track. For optimal control of the ball in the desired position, a proportional algorithm in BASIC programming language is written. In this program position of the ball observed in real time via infrared sensor and according to the position of the ball, angle of servo motor gets adjust until the ball be reach to the set point.

Keywords: Ball on beam, Infrared sensor, Microcontroller, Position control, Stability

1. Introduction

Ball-on-beam balance mechanism is a clear example of feedback control systems. As the name suggests, the ball-on-beam balance system consists of a rail on which a ball rolls freely. The ball and beam mechanism is an unstable system that is used as an experimental model to investigate and improve the control of industrial and real processes. The control of unstable systems is possible through the closed loop (feedback) control system, in this method the output of the system is always observed and according to the difference between the output value and the desired value, the input of the system changes until the output reaches the desired value. In the system designed in this research, an infrared sensor at the end of the rail is used to observe the output, which is the position of the ball on the rail. The ball and beam mechanism has two degrees of freedom, one is the movement of the ball on the rail and the second is the rotational movement

***Corresponding author:** Hamzah Ali Alkhazaleh, College of Engineering and IT, University of Dubai, Academic City, 14143, Dubai, UAE, E-mail: halkhazaleh@ud.ac.ae

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of the rail. The tool to restrain the ball in this system is to change the angle of the rail around the axis of a rail head, which is done by a servomotor.

One of the important problems in various industries is the control of unstable systems. Among the obvious examples of instability control, we can mention the control of the twisting angles of the airplane or the control of the twisting angles of the car when going around the corner. The ball-on-beam balance system is a laboratory example of controlling an unstable system, and by balancing this laboratory example as best as possible, the ability to improve the control of real unstable systems is also achieved. In real conditions, the angle of a car when passing through a curve is out of horizontal due to centrifugal force, so that the side that is outside the curve is pulled down and the inside side of the curve is tilted up. This problem can be solved by adjusting the height. Each wheel is fixed in modern active suspension systems. In Pajpach et al., (2022), the design and modification stages of an open-ended ball balance laboratory project have been presented, so that a ready sample of the ball and beam balance system has been provided to improve various elements of this system. Berkeley Robotics Lab presented a system called ball on a balance beam, in which a resistance wire sensor was used to detect the position of the metal ball. The working principle of the wire resistance sensor is similar to a potentiometer, which gives a specific voltage for the position of the conductive ball. The negative points of the system were that the beam was made of acrylic material and therefore fragile against sudden twists and also the angle of the beam could not be measured and controlled Hadipour et al., (2021).

In Kotarski et al., (2021), various types of ball and beam mechanisms have been investigated. According to Wink and White's research, different structures of the ball and beam system can be designed, but the basis of the system is the same, so that the ball rolls freely on the beam and the angle of the beam changes to control the position of the ball. The control system used by Kotarski et al., (2021) consists of common components such as sensors and actuators. Infrared distance sensors are used in this system. In this system, the error signal is calculated by the microcontroller and the microcontroller has controlled the beam angle according to the error signal. The structure of the system used by Csurcsia et al., (2022) includes a ball and beam mechanism, a stepper motor, two infrared sensors, and an electronic controller based on a 32-bit microcontroller that is connected to the Simulink MATLAB software and the control algorithm is implemented through the software. Is In this system, the microcontroller is responsible for adjusting the state of the stepper motor and the ball, and all the positioning algorithm and control law are implemented in Simulink in real time. The main goal of this research is to build and develop a ball-on-beam balance system using an infrared sensor and a microcontroller. The specific objectives of the research are as follows:
1- Designing and building a complete hardware of this system
2- Designing and building the interface circuit between microcontroller and sensors and drive motor
3- Designing a suitable controller and implementing it on a microcontroller
4- The stability of the ball at the desired point is designed by the controller

In the continuous, the theory of the ball-on-beam balance system will be explained in more detail and related definitions will also be presented. In the fourth chapter, the process of designing and manufacturing the ball-on-beam balance system will be explained. In the fifth chapter, the results of the control of the balance system of the ball on the beam will be shown in the form of a diagram.

2. Method

2.1 The basis of the operation of the ball-on-beam balance system

The structure of the ball-on-beam balance system consists of a rail mounted on a rotating axis. On this rail there is a ball that can roll freely throughout the rail. The smallest slope of the rail causes the ball to roll down the slope, as it is known that the movement of the ball on the rail occurs due to the force of gravity. The ball and beam mechanism has two degrees of freedom, one is the movement of the ball on the rail and the second is the rotational movement of the rail (Figure 1).

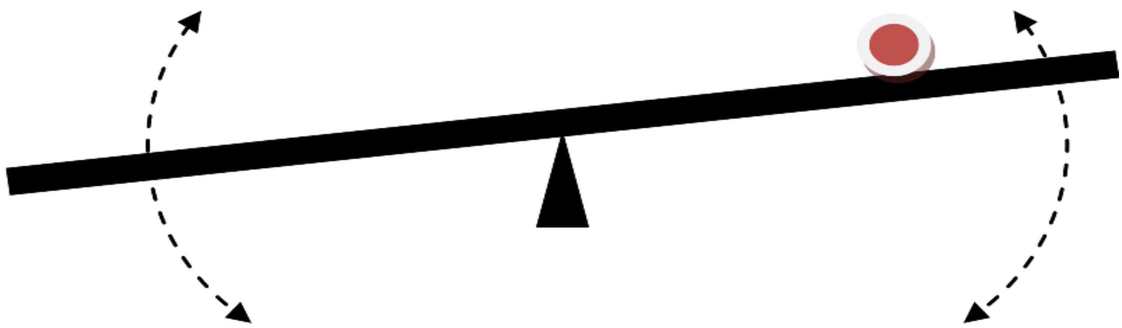


Figure 1: Schematic of the balance system of the ball on the beam (rotation from the middle)

2.2 Mathematical Modelling

Before proceeding to control the ball and beam system, we must have a complete understanding of this system, the first step for this purpose is to analyze the theory of the system. The best way to investigate such a system is to analyze it based on the laws of physics. Here, the mechanism of the ball on the beam with the axis of rotation from the middle is analyzed. In the ball and beam system, the ball rolls on a rail that is rotated by a motor. In order for the ball to be in the desired position, the rail must rotate correctly around its central axis. Therefore, it is necessary to express the relationships between all components through mathematical modeling of our system. The conclusion of this mathematical model includes the balance force of the ball and the balance moment of the rail (Csurcsia et al., 2022) (Figure 2).

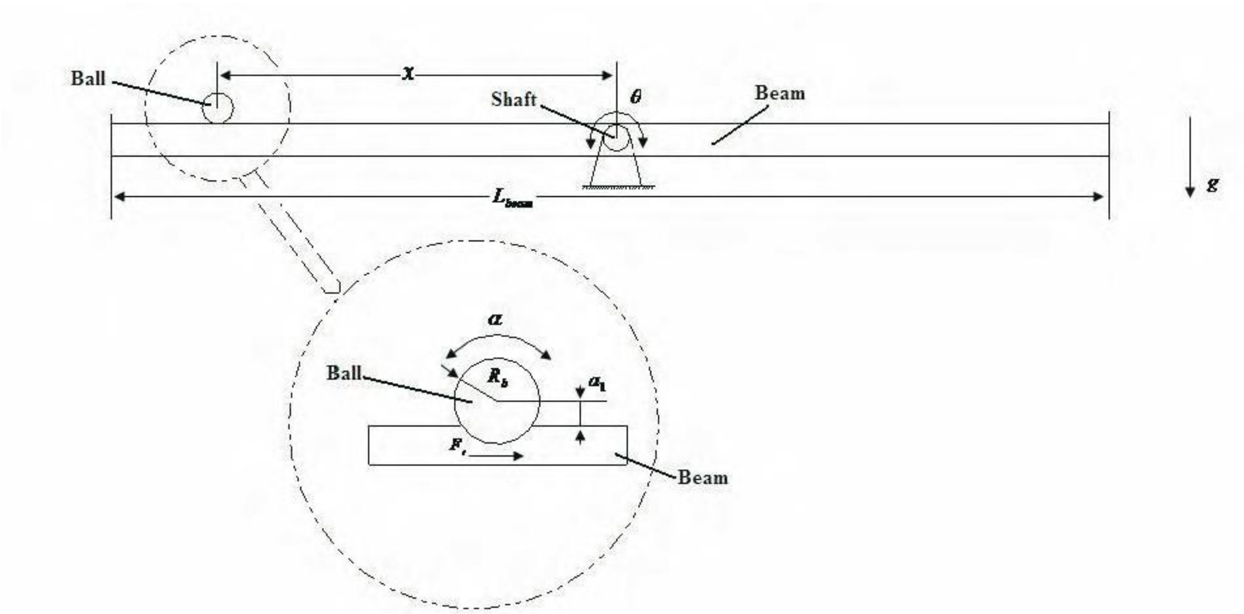


Figure 2: free diagram of the ball on the beam (rotation from the middle)

2.2.1 Ball balance force analysis

The following equation is obtained from the analysis of the balance force of the ball using Newton's law (Csurcsia et al., 2022).

$$\sum F_b = M_{ball}\, g \sin\theta - F_r = M_{ball}\ddot{x} + b_1\dot{x} \tag{1}$$

So that M_{ball} is the mass of the ball, g is the acceleration of gravity, x is the distance between the center of the ball and the center of the axis, b_1 is the friction constant when the ball rolls on the rail, θ is the rotation angle of the rail relative to the horizontal position, and F_r is the inertial force of the ball. The position of the ball is equal to the rotation angle of the ball α multiplied by the rotation radius of the ball a_1:

$$x = \propto \times a_1 \qquad (٢)$$

So that a_1 is the vertical distance between the center of the ball and the point of contact between the ball and the rail. The equilibrium torque of the ball is expressed as follows:

$$\sum \tau_b = F_r \, a_1 = J_{ball} \, \ddot{\alpha} \qquad (٣)$$

So that α¨is the angular acceleration of the ball, $\sum \tau_b$ is the total torque on the ball, J_{ball} is the moment of inertia of the ball, which is obtained in this way.

$$J_{ball} = \frac{2}{5} M_{ball} \, {R_b}^2 \qquad (4)$$

So that R_b is the radius of the ball. From equations (1) to (3), the following result can be deduced.

$$\left[1 + \frac{2}{5} \times \left[\frac{R_b}{a_1}\right]^2\right] \ddot{x} + \frac{b_1 \, \dot{x}}{M_{ball}} = g \sin\theta \qquad (٥)$$

Equation (5) describes and shows the relationship between the position of the ball and the angle of the rail. The high slope of the rail leads to high acceleration and high speed of the ball. Due to the fact that the values of R_b ، a_1، b_1 ، M_{ball} all have specific values, so these values are placed as equation (6):

$$1 + \frac{2}{5} \times \left[\frac{R_b}{a_1}\right]^2 = \mathrm{A}; \; \frac{b_1}{M_{ball}} = \mathrm{B}; \; \mathrm{A}\ddot{x} + \mathrm{B}\dot{x} = g \sin\theta \qquad (6)$$

From the solution of this second-order nonlinear homogeneous equation, the roots are obtained as follows.

$$\begin{cases} t_1 = 0 \\ t_2 = -\frac{\mathrm{B}}{\mathrm{A}} \end{cases} \qquad x_c = C_1 + C_2 e^{-3t} \qquad (7)$$

$$x_p = \frac{-Bg}{(A^2+B^2)} \cos t - \frac{Ag}{(A^2+B^2)} \sin t \qquad (8)$$

2.2.2 Torque analysis of engine and rail balance

The following equation is the result of the engine balance torque analysis.

$$T_{motor} = K\,I - J_{motor}\,\ddot{\theta} - b\,\dot{\theta} \qquad (9)$$

So that K is the electric excitation force constant, I is the current inside the motor, J_{motor} is the moment of inertia of the DC motor, b is the damping constant of the rotating system, T_{motor} is the torque produced by the DC motor, $\ddot{\theta}$ is the angular acceleration of the rail, $\dot{\theta}$ is the angular velocity of the rail. The torque produced by the ball can be expressed as the following equation. The torque produced by the ball can be expressed as the following equation:

$$T_{ball} = -x\, M_{ball}\, g \cos\theta \tag{10}$$

$$\mathrm{T_{beam}} = \mathrm{T_{motor}} + \mathrm{T_{ball}} \tag{11}$$

where $\mathrm{T_{beam}}$ is the torque on the rail. The moment of inertia of the rail and motor is expressed as follows:

$$J_{bm} = J_{beam} + J_{motor} \tag{12}$$

So that J_{beam} is the moment of inertia of the rail, J_{bm} is the sum of the moment of inertia of the rail and the motor.

$$J_{beam} = \frac{1}{12} M_{beam}\, L_{beam}^2 \tag{13}$$

So that M_{beam} is the mass of the rail and M_{beam} is the length of the rail assuming that the rail is a rectangular object. From equations (6) to (13), the following result can be deduced:

$$\ddot{\theta} = \frac{K\,I - x\,M_{ball}\, g \cos\theta - b\,\dot{\theta}}{J_{bm}} \tag{14}$$

which describes the angular acceleration of the axis.

2.2.3 DC motor equation

Since the DC motor is armature controlled, and based on the combination of Newton's law with Kirchhoff's law, the following equation can be deduced.

$$L\frac{dI}{dt} + R\,I = V - K_e\,\dot{\theta} \tag{15}$$

as L is the induction of the armature, I is the electric current inside the motor, V is the input voltage applied to the armature, K_e is the constant of the motor related to the return electric excitation force, and R is the resistance of the armature. This equation shows the relationship between the supplied electric current and the voltage. Therefore, the equation (15) after sorting becomes the following Rosales et al., (2004):

$$\dot{I} = \frac{V - R\,I - K_e\dot{\theta}}{L} \tag{16}$$

2.2.4 System design and construction process

To design and build the ball-on-beam system, it is necessary to examine the components involved in this mechanism. Like many other projects, an operator, a number of sensors, mechanical parts and a control circuit are the main components of this system. The control board consists of a circuit that provides communication between the input and output of the system with the system processor. The processor is the main part of the control board whose task is to receive information as system input and then process them based on the commands recorded in the memory and finally send the control signal to the system operator. In this research, AVR Atmega16 microcontroller is used as a processor. The input of the system is the information of the infrared sensor that detects the distance of the ball and informs the microcontroller. Since the infrared sensor information is in terms of voltage changes, these values are connected to the analog to digital ports of the microcontroller. The output of the system is applied to the servo motor in the form of PWM waves. An LCD display is provided to view the values (Figure 3).

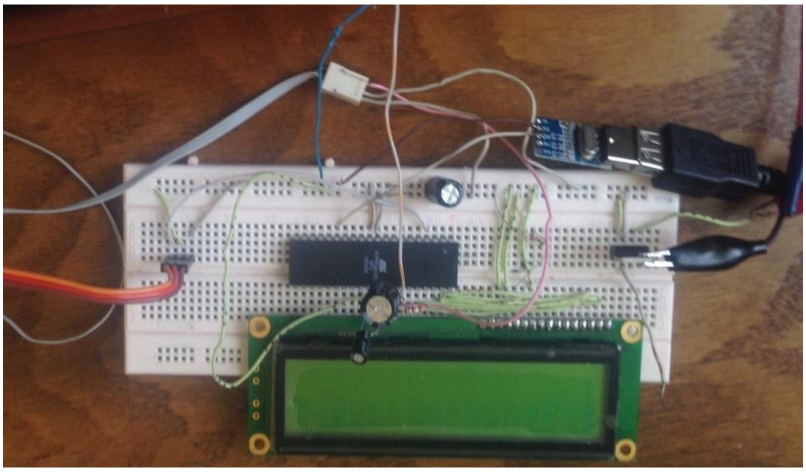


Figure 3: Control board

2.3 The mechanism made in this research

In this mechanism, an L-shaped aluminum profile is used as a rail, one end of which is mounted on the base as a hinge, and the other end is connected to the axis of the servomotor through a lever. With the rotation of the output axis of the servomotor, the angle of the rail changes and in this way the conditions for controlling the ball in the desired position are provided (Figure 4).

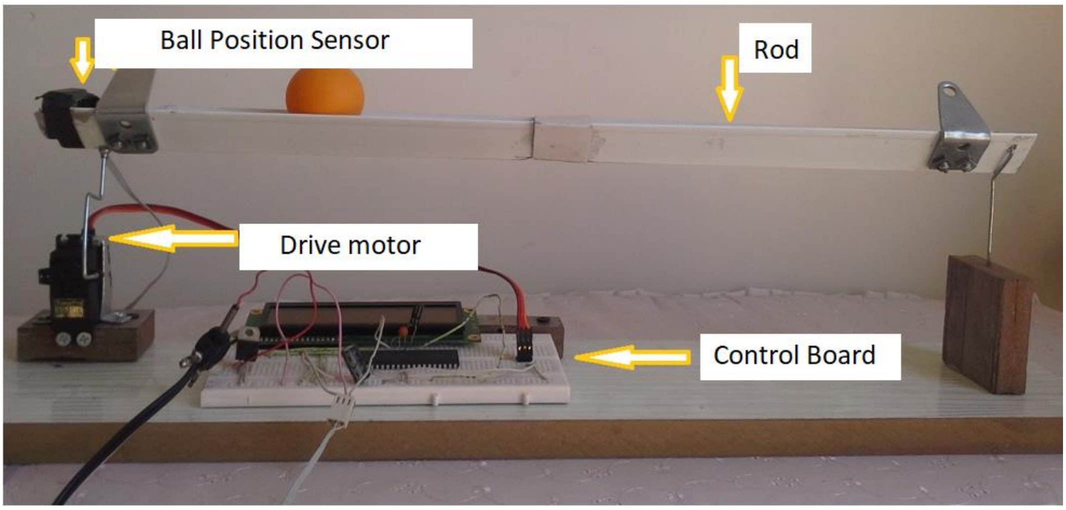


Figure 4: The built mechanism

2.4 Innovation and advantage of the system designed in this research

Some similar systems have used an infrared sensor to detect the position of the ball, but with the difference that the range of the ball's movement is covered by two opposite sensors, the disadvantage of this method is that when the ball is in the middle of the range, due to the interference of the sensors, information is lost. The opposite is achieved with low accuracy, so in the current system, by covering the entire range with an infrared sensor, in addition to better detection of the ball, the waste of unnecessary equipment has been avoided. Also, lighter materials have been used in the construction of this mechanism, which makes it possible to control the system through a small servo motor.

2.5 System stabilization by microcontroller

Microcontroller is a small computer that consists of three main parts, namely central processing unit and memory and input and output unit. The processing unit is the brain of the microcontroller, which is under the control of the programs stored in the memory (Eckert, 2018). According to the requirements of the control system of the ball on the beam and by checking the capabilities of the Atmega16 microcontroller, it is clear that this microcontroller is a suitable option for stabilizing the current system. In the system designed in this research, it is necessary to receive the information of the infrared sensor (ball position) continuously, it is noteworthy that the information of this sensor is analog. Another essential requirement of the system designed in the current research is that the process of receiving input information and performing processing on the information and issuing the control signal must be done in the shortest possible time and without delay, because the delay of the controller makes it impossible to stabilize the system. Considering that the servomotor can be controlled by PWM square pulses, therefore the output signal of the controller must be in PWM format. Also, the system controller should provide the possibility of extracting information so that the results of stabilization can be observed.

Atmega16 microcontroller at 16 MHZ operating frequency is able to execute up to sixteen million instructions per second, which increases the processing speed of this microcontroller. The aforementioned microcontroller has an ADC converter with eight channels, the accuracy of which is ten bits. These eight pins are called port A. Microcontroller uses successive approximation method to convert analog to digital. In this method, the digital value is obtained from the formula $Digital = \frac{V_{in}}{V_{ref}} * 2^n - 1$. In this formula, V_{in} is the value of the infrared sensor that is converted into a digital signal, and V_{ref} is the reference voltage, which is 2.56 by default in micro. Also, n is also the accuracy or degree of resolution, which in this microcontroller is 10.

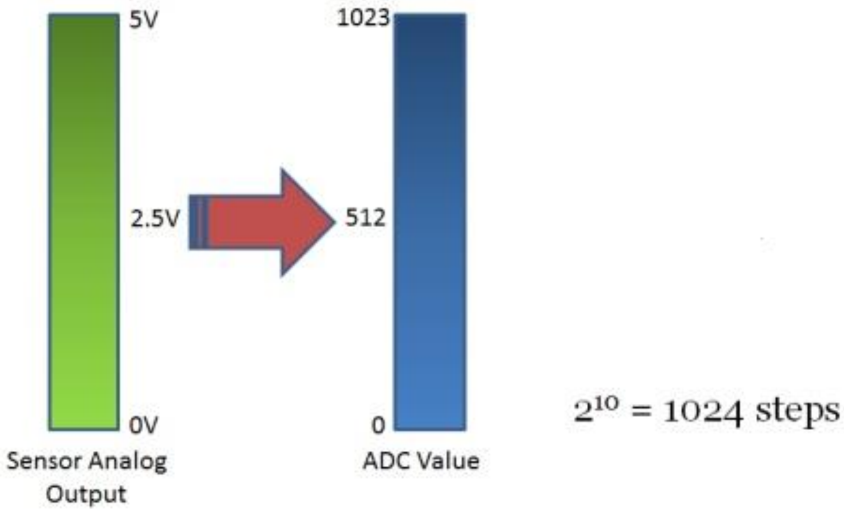


Figure 5: Analog to digital voltage conversion

Given Figure 5, the Atmega16 microcontroller has two eight-bit counters and one sixteen-bit counter. The working frequency of these counters is set separately. These counters have a comparison unit that is used to create a PWM pulse. To generate PWM pulse in this controller, OC0 counter is used, which outputs PWM from pin number three of port B (PB3). Universal Synchronous Asynchronous Receiver Transmitter (USART) serial communication capability is one of the other features of this microcontroller, by which the required information can be extracted. For this purpose, the base of a D port (PD1) called TXD is used.

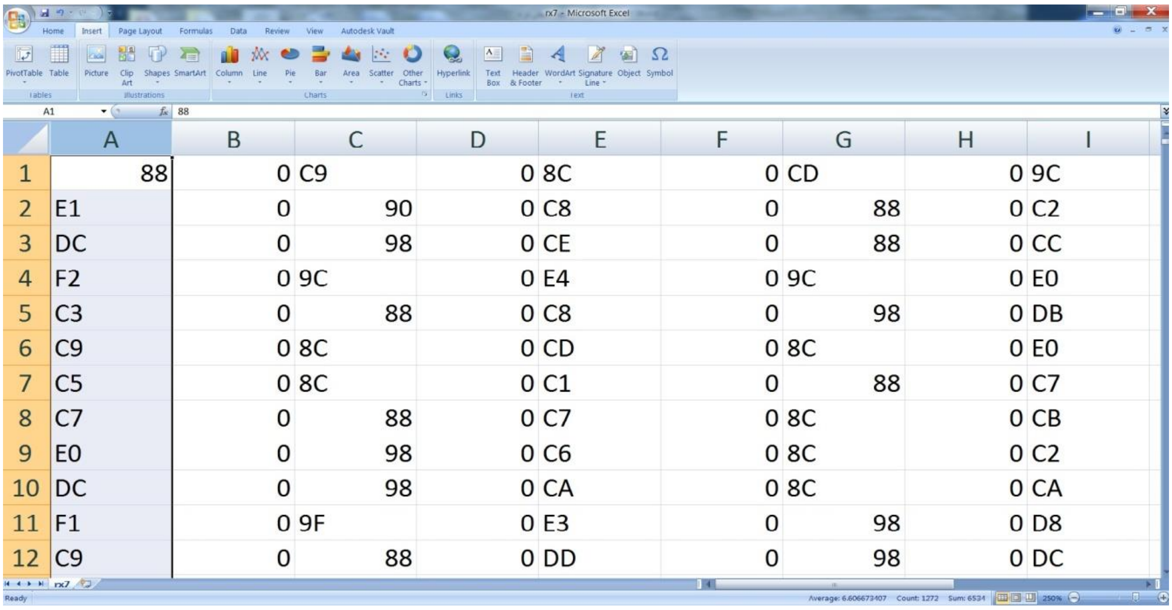
3. Results

3.1 Proposed algorithm to control the ball on the beam

For optimal control of the ball in the desired position, a proportional algorithm has been written with BASIC programming language. In this program, the position of the ball is observed instantaneously through the infrared sensor, and relative to the position of the ball, the axis angle of the servomotor is adjusted until the ball tends to the designated point. In the proportional control algorithm at the beginning of the program, the microcontroller is introduced, then the ports used by the microcontroller are determined. Port A is introduced as an analog to digital converter. Port D is designated as data output for information extraction. Then the servo motor is introduced to receive the signal from the PB3 base. As explained before, pin PB3 is the output of counter OC0, which is used to generate PWM pulses. The pulse width is set by setting the value in front of the servo expression in the program. The output voltage of the infrared sensor is converted to digital and received by the Getadc command and is defined by variable A, which indicates the position of the ball. Since the accuracy of the ADC channel is ten bits, the converted value is on the scale of 2^10 or 1024, and therefore, to make the scale smaller, the variable A is divided by 4. Then variable A is linearized and becomes variable S1. The variable S1 is sampled three times in a loop with a time interval of 10 milliseconds. The position and direction of the ball movement is determined by three values S1(1), S1(2) and S1(3). After this width, servo pulses are issued according to the variable values of S1. If the values of S1 indicate that the ball is in the far half of the rail, i.e. the range of 15 to 25 cm, based on the algorithm, the value of 230 (4.6 V) is commanded to the servo and then with an interval of 200 milliseconds to Servo value of 175 (3.5 volts) is given to stabilize the horizontal position of the rail. Now, in the opposite situation, if the values of S1 indicate that the ball is in the closer half of the rail, i.e. the range of 5 to 15 cm, based on the algorithm, the servo is commanded to 120 (2.4 V) and then with a distance of 200 millimeter. A value of 175 (3.5 volts) is given to the servo in order to stabilize the horizontal position of the rail. However, after repeating the conditional loops inside the algorithm, the ball tends to the desired point and stabilization takes place.

3.2 Extracting results from the system

The results of stabilizing the ball on the beam system are of two types, one is the data that the infrared sensor sends to the microcontroller from observing the ball in the defined range of the rail while the system is running, and the second is the data that is applied to the servo motor in the form of a command signal to direct the ball to the desired point. During the execution of the system, the microcontroller is informed about the position of the ball using the input data and processes the input data based on the defined commands in the memory. Then it applies the command signal resulting from the processing to the servo motor. Now, to extract the results of system stabilization, a serial port is connected to the microcontroller, through which both the infrared sensor data can be received during the control operation and the command signal applied to the servomotor can be received. The information received from the microcontroller is in the form of hexadecimal numbers, so after extracting the results in hexadecimal format, it is necessary to convert them into decimal format. Excel software is used for this purpose (Figure 6).



	A	B	C	D	E	F	G	H	I
1	88	0	C9	0	8C	0	CD	0	9C
2	E1	0	90	0	C8	0	88	0	C2
3	DC	0	98	0	CE	0	88	0	CC
4	F2	0	9C	0	E4	0	9C	0	E0
5	C3	0	88	0	C8	0	98	0	DB
6	C9	0	8C	0	CD	0	8C	0	E0
7	C5	0	8C	0	C1	0	88	0	C7
8	C7	0	88	0	C7	0	8C	0	CB
9	E0	0	98	0	C6	0	8C	0	C2
10	DC	0	98	0	CA	0	8C	0	CA
11	F1	0	9F	0	E3	0	98	0	D8
12	C9	0	88	0	DD	0	98	0	DC

Figure 6: The extracted results in hexadecimal format

3.3 Comparison of results with previous results

In [8], the ball has been controlled in several modes, and the presented results are as follows:

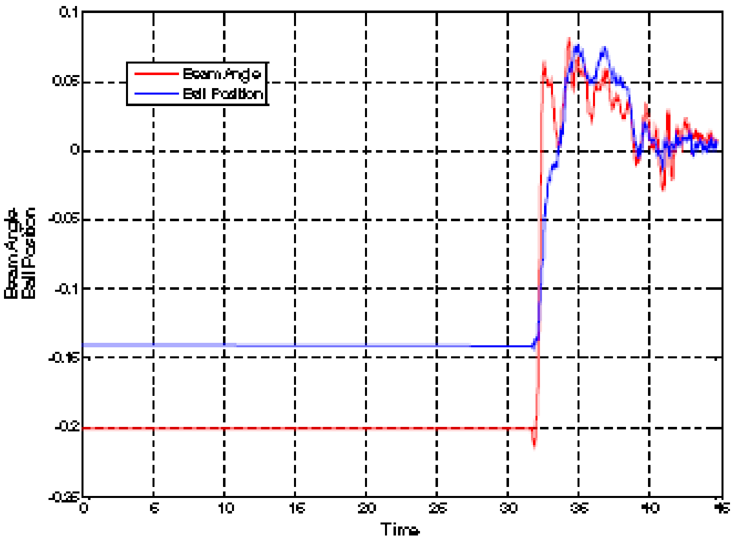


Figure 7: The diagram presented in Eckert (2018) the ball at a distance of 14 cm

According to Figure 7, the ball is placed at a distance of 14 cm from the desired point, and the system has started to guide the ball to the desired point in the 33rd second, and after 10 seconds, the ball has reached the desired point.

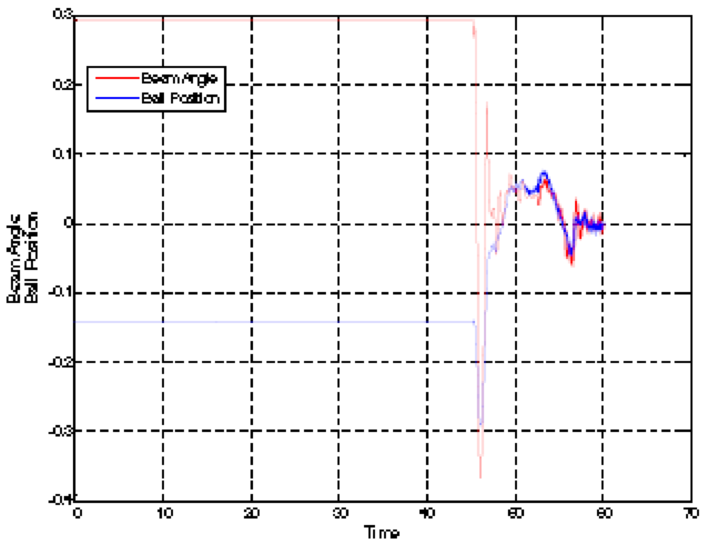


Figure 8: the diagram presented in Eckert (2018), the ball is at a distance of 13 cm

According to Figure 8, the ball is located at a distance of 13 cm from the desired point, and the system has started to guide the ball to the desired point in 47 seconds, and after 10 seconds, the ball has reached the desired point.

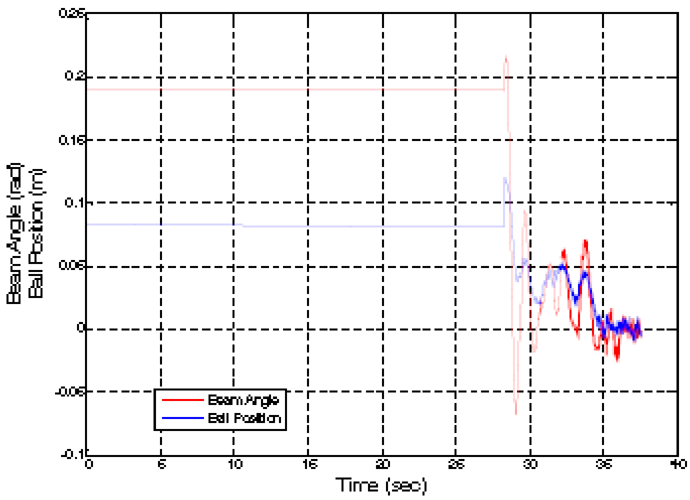


Figure 9: Diagram presented in Eckert (2018) ball at a distance of 8 cm

According to Figure 9, the ball is placed at a distance of 8 cm from the desired point, and the system has started to guide the ball to the desired point in 28 seconds, and after 7 seconds, the ball has reached the desired point. Now, by comparing the results presented in [8] with the results of the current research, it is clear that the system designed in this research has a better performance because the ball reaches the desired point in less time (4 seconds).

3.4 System test results

The length of the ball's movement range, which is covered by the infrared sensor, is extracted as an analog-to-digital (ADC) value, which is between 0 and 250. Based on the curve of the distance with respect to the output voltage of the infrared sensor and its placement in the successive approximation formula that was presented in part 4-8 of the previous chapter, the value of 235 is obtained for the distance of 5 cm from the object and the value of 50 for the distance of 25 cm from the object. - Come Of course, according to the mentioned curve, these values are obtained based on the reflection of the beam from the surface of the

white paper, so due to the spherical surface and also the different reflection coefficient of the ball surface, there is a small difference in the values obtained from the measurement of the ball position.
In the first case, the ball is placed at a position 25 cm from the sensor, and based on the output of the infrared sensor, it can be seen that the ball has reached the point determined in the middle of the range, i.e. the 8 cm point (Figure 10).

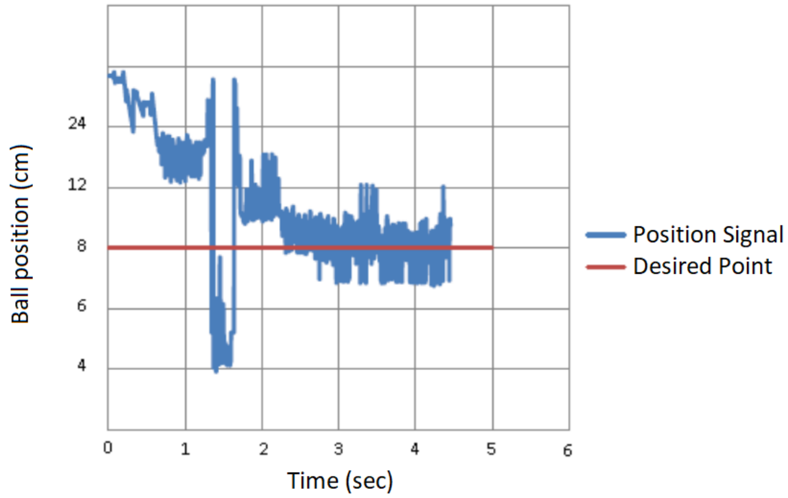


Figure 10: The process of changing the position of the ball with the starting point 25 cm from the sensor

In the second case, the ball is placed at a position 20 cm from the sensor, and based on the output of the infrared sensor, it can be seen that the ball has reached the designated point in the middle of the range, i.e. the 8 cm point (Figure 11).

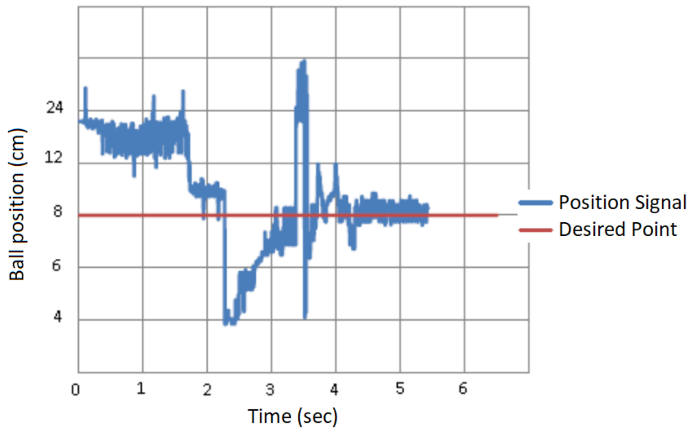


Figure11: The process of changing the position of the ball with the starting point 20 cm from the sensor

In the third case, the ball is placed at a position 5 cm from the sensor, and based on the output of the infrared sensor, it can be seen that the ball has reached the point determined in the middle of the range, i.e. the 8 cm point (Figure 12).

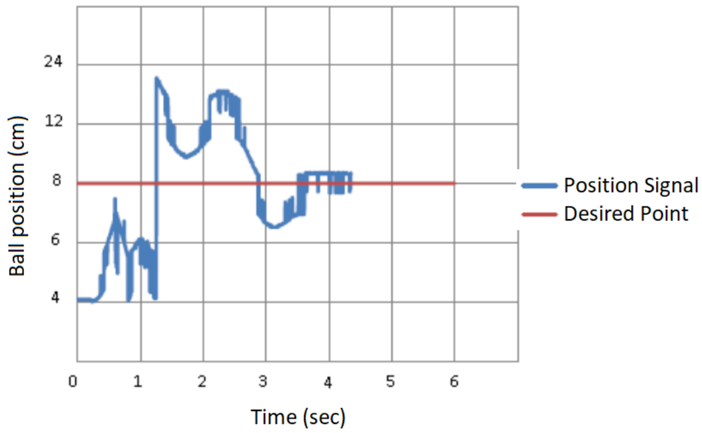


Figure 12: The process of changing the position of the ball with the starting point 5 cm from the sensor

Considering the curves extracted from three different starting points and observing the process of moving the ball, it is obvious that the controller is able to stabilize the ball and stabilize it at the desired point. In the test where the ball is placed at a position of 5 cm from the sensor, the voltage of the pulses sent to the servomotor is as follows, during which the ball is stabilized at the desired point (Figure 13).

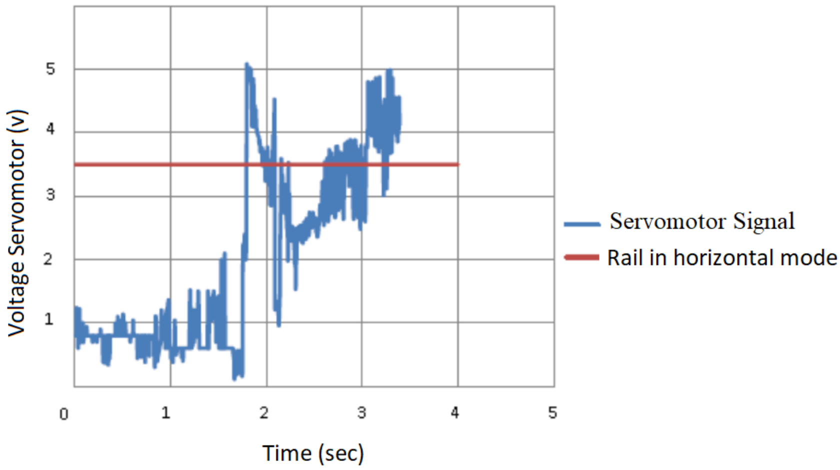


Figure 13: The process of changing the voltage of the pulses sent to the servo motor with the starting point 5 cm from the sensor

In the test where the ball is placed at a position of 20 cm from the sensor, the voltage of the pulses sent to the servo motor is as follows, during which the ball is stabilized at the desired point (Figure 14).

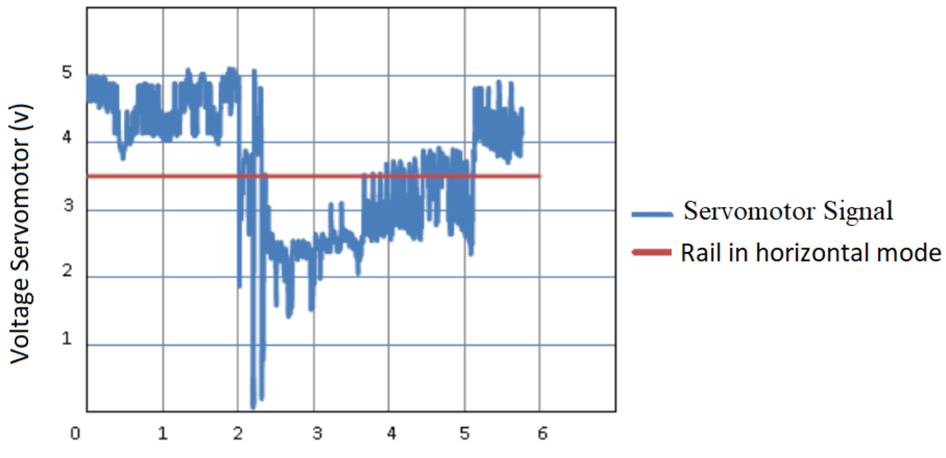


Figure 14: The process of changing the voltage of the pulses sent to the servo motor with the starting point 20 cm from the sensor.

The voltage of the pulses sent to the servo motor is in the range of 0.2V to 5V, and pulses with a voltage greater than 3.5V turn the motor axis clockwise and pulses with a voltage less than 3.5V. It rotates the motor axis counter-clockwise. Based on the extracted curves, it is clear that in the test where the ball is placed at a position 5 cm from the sensor, in the first half of the curve, the controller by sending a pulse in the range of 1 V to 2 V causes the maximum rotation of the servo in the direction is counter-clockwise and the result is a slope in the direction of bringing the ball to the middle of the rail. The opposite of the mentioned process occurred in an experiment where the ball was placed at a position of 20 cm from the sensor, so that in the first half of the curve, the controller by sending a pulse width of 5 volts caused the maximum rotation of the servo in the clockwise direction and the result was the slope is in the direction of bringing the ball to the middle of the rail. Now, by examining the process of changing the voltage of the pulses sent to the servo motor, it can be seen that the signals are sent proportionally and in the direction of stabilizing the ball at the desired point.

4. Conclusion

The main challenge in the ball-on-beam balance system is keeping the ball rolling at a certain point on the track. The open-loop ball and beam mechanism is an unstable system because if the system is unaware of the position of the ball, it will not know the amount of spatial difference between the ball and a certain point, and as a result, it will not be able to give a suitable angle to the rail to restrain the ball. On the other hand, it is necessary that the system is always aware of the angle of the rail. In this regard, the current research is looking for the most accurate tool for real-time observation of the process, as well as the most appropriate method to balance the system.

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