Design, Control and Implementation of a Ball on Plate Balancing System

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Abstract—**The ball balancing system in a 2-degree of freedom platform is of unique importance in understanding the control system applications. It is a platform to test and identify different aspects of controls, as the non-linearities increases with the degree of freedoms. So far many techniques have been applied to sense the position of the ball on a plate in real time, most common of them is touchpad and audio video camera system. This paper describes the design, development and control strategy of balancing a ball on a plate using low cost phototransistor sensors. These Phototransistors are triggered by monochromatic sharp beams of laser light. The plate area is 1sq. foot and an array of 11 sensors each 1 inch apart is used on each axis making total of 121 points on the plate.**

To balance the ball, two motors are used one for each axis. The ground motor is fixed, while to control the other axis second motor is fixed on top of the ground motor. Hence the system utilizes two sets of independent control mechanisms, each operating in isolation for each axis.

ATMEGA16 microcontroller is used which is an Atmel AVR family controller with a flash memory of 16 kb. Since it has two independently switched PWM channels, therefore, it makes this controller ideal for the purpose.

Dynamic modeling of the system yields the digital controller capable of balancing the ball in any of the desired positions out of 121 points, on the plate.

Although the system becomes quite discrete but still it provides sufficient basis for implementing different control strategies and investigating different system parameters such as actuation mechanism, sensors, controller design and experimental testing, under the predefined condition of the ball diameter.

I. Introduction

"The ball on plate problem is a benchmark for testing control algorithms."

The ball and plate system is one of the most enduringly popular and important laboratory models for teaching control systems engineering [1]. The control of unstable systems is critically important to many of the most difficult control problems. Since the system is *Open Loop Unstable* that is the system output (the ball position) increases without limit for a fixed input (plate angle) so the control of such a system is significantly important [2].

The purpose of designing such a system is to build a model capable to test and verify different control systems aspects such as non-linearities and compensator design.

To control the ball on plate system, a servo control system is required. Such a system is one of the most important and widely used forms of control systems. The job of servo motor here is to maintain a specific angle corresponding to the ball position until the ball reaches its desired position. The control loop of the servo mechanism is shown in Fig1.1.

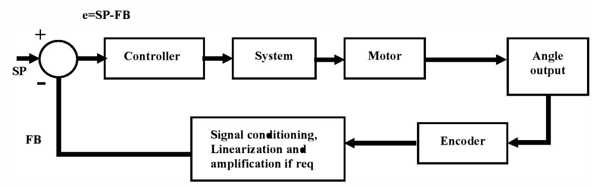

Figure 1.1: Control loop of the mechanism

Considering all the above mentioned factors, the design was developed to have following features:

a. Quick sensing mechanism for the position of the ball.
b. Efficient and light weight design.
c. High performance actuators/ motors.
d. Control mechanism using PID algorithm.

The first requirement was to sense the position of the ball in real time. For that purpose different techniques were considered. These are enlisted below with their limitations [3].

a. Touch pad.
Costly. Complicated integration technique with the design in hand.
b. Over head camera and image processing.
Cumbersome to develop a standalone system using this technique.
c. Resistive plate, a kind of 2-dimensional potentiometer.
Complicated mechanism and limited information was available.
d. Grid of sensors for each axis.
Although the mechanism required excessive wiring and provided limited resolution but due to low cost it was chosen to develop an experimental model.

II. Mechanical Design

The mechanical structure of any control systems model is the most crucial element of the entire design, which needs immense contemplation in dynamics [4] [5].

A. Degrees of Freedom

In the proposed design the system requires two separate motors to be acting on the plate independently at the same time, hence making it a 2-DOF system. Avoiding conflict between two such motors was a major design problem. To overcome this problem an additional platform between

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the plate and the base of the system (ground) was introduced. Consider motor ‘A’ as the base motor, fixed to the ground. Now the plate carrying sensor grids is mounted on top of motor ‘B’. This platform is then mounted on top of motor ‘A’. Hence, as motor ‘A’ rotates motor ‘B’ platform consequently moves along the same axis. This dependency is catered for by using separate closed loop feedback control systems for each axis/ motor.

B. Types of Motors

12 V, 1200 rpm DC servo motors coupled with custom made gear boxes of 1:100 have been used in order to reduce the speed of motors and increase their torque to the desired values. Each motor was coupled with dual in-line optical encoder of 288 lines for the feedback.

C. Dimensions of the Platform

The platform size was kept 1 sq ft (30.48 cm^2) because it is manageable in terms of size, weight and sensor integration. It provides sufficient space for ball displacement to testify the control mechanism. This platform is mounted on the motors at 38.1 cm (15 in.) above the base of the system.

D. Material Selection

Different materials were used in order to keep the system light weight. The platform was made from 3 mm plastic sheet. All motor arms and mountings were made from Aluminium since its lighter (density-2.7 g/cm^3), easily machineable, has high tensile strength and low in cost.

E. PRO-E Model

The stability and functionality of the design has been verified in Pro-Engineer (PRO-E) Wildfire. Each link was first constructed in PRO-E and then all the parts were linked together as an assembly. Finally each link was simulated in the “*mechanism mode*” of PRO-E.

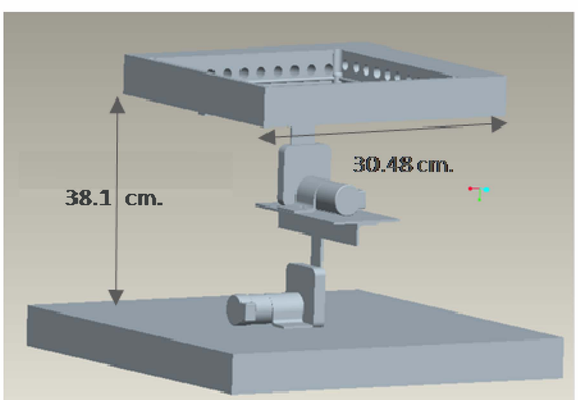

Figure.2.1: PRO-E model of the system

III. Electronic Control

The power elements have been chosen for the plate actuator systems after taking into account several limiting factors. These depend upon the velocity and the angular displacement desired of the motors. Some of the criteria used for the selection of power elements are:

a. Reliability and long term performance
b. Minimum power drain
c. Convenience, simplicity and reliability in maintenance and availability.

In order to control the speed of DC motors pulse controlled circuits are used, enabling capability of high-power handling. The motors in our application can be best controlled using PWM type signals. Since the power amplifiers associated with the PWM signal will operate in the pulsed mode which will result in minimum power loss. For better clarity a single DC motor driven by PWM signal along with its input voltage and motor current waveforms are shown in Fig 3.1.

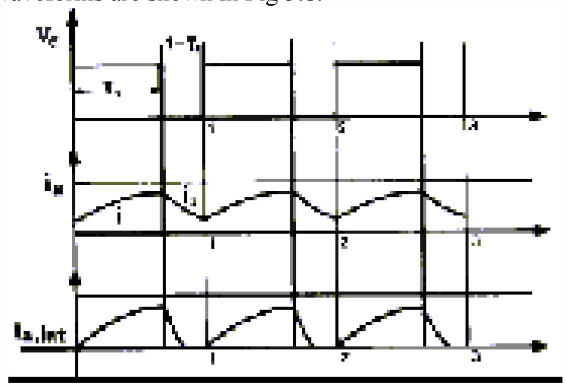

Figure.3.1: Characteristics of a DC motor driven by PWM technique.

In order to remain within the maximum continuous ratings of the motors and produce larger torques the advantage of PWM signals to produce high voltage and current peaks has been fully utilized. The current surge and voltage spike at startup has been catered for by the PWM control.

A. Sensor Mechanism

The position of the ball is being monitored by using a grid of 11×11 phototransistors, the distance between consecutive sensors being 1 inch. Each phototransistor is provided with a monochromatic beam of laser light. Whenever the ball passes in front of a particular phototransistor, its supply of light is interrupted and the voltage level varies. This variation is interpreted by the controller corresponding to each axes as x and y coordinates.

B. Control Circuit

The electronic circuit of the motors consists of two main parts:

a. Digital *Circuit.* This part of circuit constitutes all the TTL level circuit components. Signals from this part i.e., the controller, goes into the respective motor control circuits. Similarly the feedback being provided by the optical encoders
b. Power *Circuit.* Considering the voltage driven capability, better switching time and their availability at required ratings MOSFETs are the first choice. H-bridge configuration is utilized for full four quadrant operation Z-switching technique is employed [1].

C. Encoder Feedback System

As described earlier the feedback for the control algorithm is being provided by the optical encoders of 288 lines mounted on each motor. This means that 1° rotation of motor is represented by 1.25 lines of the encoder. The output of the motors after being coupled with gears reduces almost 10 times in each motors case. So the encoders provide a very accurate feed back of the motor.

D. Microcontroller

AVR ATMega16 microcontroller is employed to serve as the brain of the ball on plate system. The advantage of using an AVR microcontroller is that it is easy to program and is readily available at relatively low cost. It has 16 Kbytes of flash memory and a very fast response owing to its RISC architecture. The two separate PWM channels provided in this microcontroller also help in reducing the hardware required and sufficiently accomplish the purpose.

E. Digital Control

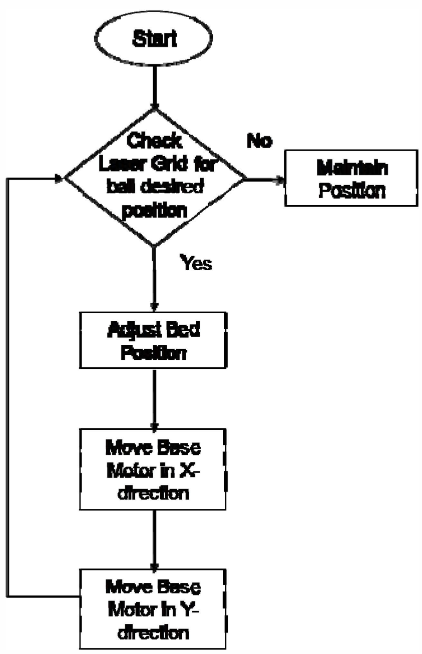

Figure.3.2: Digital Control Algorithm

Fig 3.2 shows the control algorithm for the platform. The sensor grid monitors the ball position which is already fed to the microcontroller [6]. Whenever there is any disturbance or change in position of the ball, the system readjusts its position by altering the motor position in x and y direction to attain the desired/ pre-defined position.

IV. PID Control

In order to control the position and velocity of the motors, PID algorithm is applied on each motor [7] [8] [9]. The gains of Proportional, integral and derivative compensators were tuned separately and then all three were simultaneously turned ON to get the best and fastest results.

$$T(S) = \frac{1}{2.5S + 3.6} \qquad (1)$$

Eq 1 gives the transfer function of the individual motor.

The overall step response for the system is given in Fig 4.1.

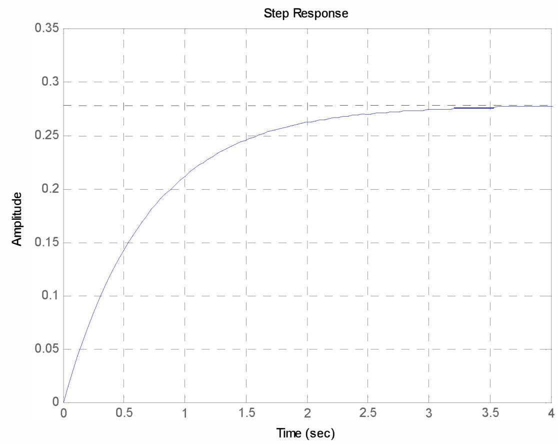

Figure.4.1: Overall step response of the system

The system transfer function is given in Eq 2. It gives the open loop response of the system using Fourier series.

$$T(S) = \frac{1}{6.25S^2 + 18S + 11.96} \qquad (2)$$

The overall response of the system for a random disturbance is shown in Fig 4.2 below.

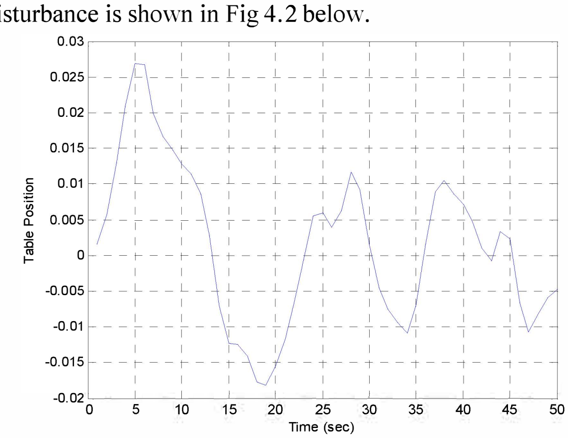

Figure.4.2: Open Loop response of the system

The above plotted curve shows that the system is open loop unstable and requires a controller for obtaining a stable position. In a closed loop system the transfer function of the system is given by Eq 3.

$$T(S) = \frac{1}{6.25S^3 + 18S^2 + 11.96S + 1} \qquad (3)$$

Fig 4.3 below shows the closed loop response of the system.

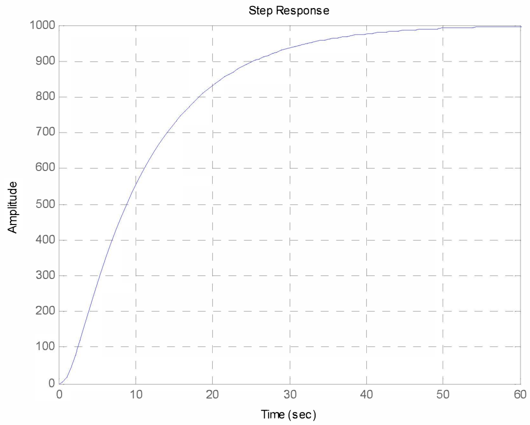

Figure.4.3: Output response of controller

The result shows that the system gets stable after 40 seconds. The time taken by the system is a constraint, as the position of the ball cannot be made stable on this settling time. This requires adoption of linear control method in order to achieve satisfactory results (see Fig 4.4).

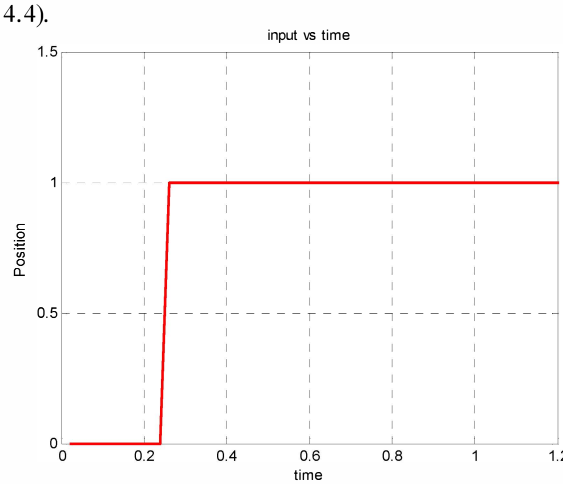

Figure.4.4: Input From Controller

After implementing linear control law for reducing the settling time, Fig 4.4 shows the disturbance input to the platform. The given input disturbs the bed of the table and as a result tilting the platform which results in the position of ball to change.

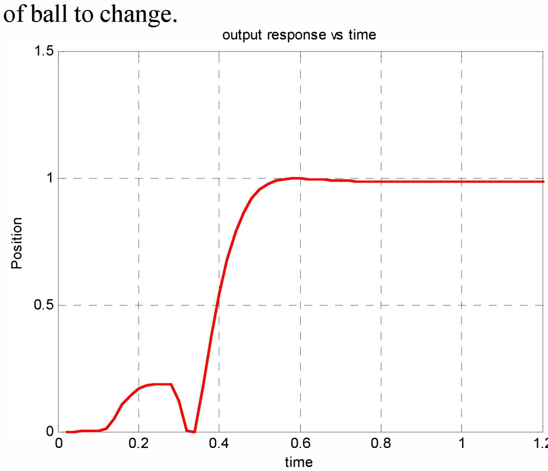

Figure.4.5: Output response of controller

Fig 4.5 shows the output response of the platform after the given disturbance input is passed from the PID controller. This result shows that the output under disturbance settles after 0.5 milli seconds and attains the original position of bed after the mentioned interval of time. Fig 4.6 shows the complete system.

Fig.4.6: Complete Assembly of the Mechanism.

V. Results

Due to the efficient placement of sensors, our mechanical design was able to react to the changing position of the ball proficiently providing sufficient resolution to implement the technique. PID algorithm proved to be very fast when the gains were tuned properly. The two platform strategy for placement of motors eliminated any chance of conflict between the two degrees of freedom. However, it was concluded that a simpler design with more efficient results can be achieved in future by placing two independent motors on the same plane but having different axes. This system thus succeeded to balance the ball on the desired position on the plate using comparatively economical design.

VI. Conclusion and Future Plans

This paper describes the method of constructing a ball on a plate control system algorithm testing equipment. It not only introduces to the latest microcontroller technology but also to the closed loop position control of DC servo motors. The main objective of this paper remains the control of an unstable system (Ball on a plate: 2 D.O.F PID controller). As described earlier our future work aims at developing a simpler yet robust mechanical design which could be able to test and verify control system techniques in real time. This will be achieved by integrating the system with a (Graphical User Interface) GUI capable of handling the compensators in real time. It will be further coupled with a real time ball position graph to testify the results on GUI.

VII. References

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