Design and development of a ball-plate balancing system with a smart phone human-machine interface

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Abstract. Technology is so ahead that sophisticated processes could be accessed and controlled by a smart phone through which human-machine interaction is made easy and taken to the next higher level. A classic example of a highly unstable non-linear mechatronic process is a ball-plate balancing system. This paper presents the mathematical model and design of a typical two axes ball-plate balancing system, where the roll and pitch of the plate is controlled by the actuation of two servo motors. An image processing algorithm acts on the video feed obtained by a vision system, to read the position of the ball on the plate in real time. A proportional-integral-derivative controller is implemented to position the ball on a desired location on the plate. A mobile application forming an intuitive human-machine interface is developed to interact, monitor and control the operation of the ball-plate balancing system. The developed system has an error of 1.29 % in positioning the ball with a settling time of about 26.4 seconds.

1. Introduction
Scientific principles are applied in various disciplines to build systems and to regulate their behaviour to get a desired response. The objective of a control system is to analyse the operation of a particular system and to maintain stability of the system by eliminating errors and disturbances. There are several models or physical systems developed to understand the concept and working of control algorithms. One such basic model is a ball-beam balancing system, in which the position of the ball on a beam is maintained at a desired location by varying the angle of the beam. This is an example of a typical one-axis control mechanism, where the angular tilt of the beam is controlled by varying the actuating angle of the motor connected to the beam. The same principle when extended to two axes forms a ball-plate balancing system. A ball-plate balancing system is an example of a highly nonlinear typical mechatronic system. Several different forms of ball-plate balancing systems are available which vary in their mechanical design, fabrication technique, materials used, number of axes of control, nature of sensors and actuators used in the system, type of control algorithm implemented, method of interface developed for interacting with the system, etc.

The ball-plate balancing system is a common control design experiment used to study the implementation of different control techniques like Proportional-Integral-Derivative (PID) control, sliding mode control, fuzzy logic control, etc. and for its performance analysis [1]. The mathematical
model and simulated results of a touch screen-based plate and PID control of movement of the ball is available [2]. Physical modelling and control of a two axis self-balancing platform on a cart is achieved using PID control [3]. A detailed procedure for construction of the physical system [4], modelling and kinematic constraints [5] are presented.

A completely vision-based control system [6] and a fuzzy logic-based control of ball on plate using vision as a means to read the current position of the ball on plate [7] are discussed. Implementation of a switching control mechanism for a non-linear ball-plate system, provided better stability and superior control compared to a PID controller [8]. Implementation of trajectory tracking sliding mode control for ball-plate balancing system improves precision by reducing friction between the ball and plate [9]. A vision-based system to retrieve the ball’s current position and use of stepper motor to operate the movement of the plate is presented in [10], which used a lead compensator to control the ball’s position and stabilize the system. The idea of using android devices like smart phones as mobile extensible Human Machine Interface (HMI) is also proposed [11].

This paper presents the mathematical model and physical design of a two degree of freedom ball-plate balancing system which uses vision system as a means to read the real time position of the ball on the plate. A PID controller is implemented to maintain the position of the ball on a desired location on the plate. The interaction with the system is enabled by a dedicated mobile application that provides the convenience of operation via a smart phone from anywhere.

2. Description

This section discusses the description of the ball-plate balancing system presented and its mathematical model, mechanical design and fabrication.

2.1. System overview

A two degree of freedom ball-plate balancing system is developed with control on rotation about the x and y axes. Figure 1 shows the block diagram representation of the ball-plate balancing system that gives a detailed description of its working.

Figure 1. Block diagram of the ball-plate balancing system.
The position of the ball on the plate is read through a vision system formed by a web camera connected to the computer through universal serial bus (USB), focusing the plate from the top. An interactive smart phone-based HMI is developed to display the position of the ball on plate at any time and also to give the user input command, to set the ball on the plate at any desired location. A PID control algorithm is implemented to control the ball position on the plate, to the centre of the plate by default or to the desired user input position as read from the HMI. The control signal for the required motor angle, to adjust the roll and pitch of the plate is sent to the microcontroller via serial communication.

2.2. Mathematical modelling

The mathematical model of the ball-plate balancing system is developed by using Lagrangian – Euler method whose general representation is shown in equation (1).

\[ \frac{\partial}{\partial t} \left( \frac{\partial L}{\partial \dot{q}} \right) - \frac{\partial L}{\partial q} = 0 \]  

To obtain the mathematical model of the ball-plate balancing system for validating its behaviour, the following assumptions are made: the ball chosen is symmetric and smooth, the ball is not slipping, the ball remains in contact with the plate surface all the time, friction between the ball and the plate surface and all other frictions in the system are neglected, the minute translation movement of the system is neglected.

The identified system parameters are length of the square plate \( L \), radius of the ball \( r \), length of motor arm \( d \), acceleration due to gravity \( g \), mass of the ball \( m_b \), linear velocity of the ball \( v_b \), angular velocity of the ball \( \omega_b \), moment of inertia of the ball \( J_b \), moment of inertia of the plate \( J_p \), plate angle in \( x \) and \( y \) axes \( \phi_x \) and \( \phi_y \) and motor angle in \( x \) and \( y \) axes \( \theta_x \) and \( \theta_y \). The Lagrangian term of the system is the difference between kinetic energy (linear and rotational) and potential energy and is given in equation (2).

\[
L = \frac{1}{2} (x_b^2 + y_b^2) \left( m_b + \frac{J_b}{r^2} \right) + \frac{1}{2} (\dot{x}_b^2 + \dot{y}_b^2) (J_b + J_p) + \frac{1}{2} m_b (x_b \dot{\phi}_x + y_b \dot{\phi}_y)^2 - m_b g x_b \sin \phi_x + m_b g y_b \sin \phi_y
\]  

where \( x_b \) and \( y_b \) are the coordinates of the ball. The dynamic equations for each axis are obtained by differentiating equation (2). The second and third order derivative of angular velocity is assumed to be zero as its value is very small and for simplification, it is considered that \( \sin \theta \approx \theta \) and \( \cos \theta \approx 0 \). Equation (3) shows the simplified equation for \( x \)-axis.

\[
\ddot{x}_b \left[ m_b + \frac{J_b}{r^2} \right] + m_b g \phi_x = 0
\]  

The effect of actuation of the motor creates an angular tilt on the plate in both \( x \) and \( y \) axes and are given in equation (4) and equation (5).

\[
\phi_x = \frac{d}{L} \theta_x
\]  

\[
\phi_y = \frac{d}{L} \theta_y
\]  

Since the system is symmetric, the equation and the transfer function derived for \( x \) and \( y \) axes are the same. The transfer function is derived between the linear displacement of the ball to a point and the input motor angle which in turn controls the plate angle. Equation (6) shows the transfer function of the system.
\[
\frac{x_b(s)}{\theta_x(s)} = \frac{y_b(s)}{\theta_y(s)} = \frac{m_0 g d r^2}{L(m_0 r^2 + J_b)} s^2
\]  

(6)

The relationship between the motor angle and the plate angle is obtained using the figure 2 which shows the schematic representation of the ball and plate.

Figure 2. Schematic representation of the ball and plate.

2.3. Mechanical design

The Computer Aided Design (CAD) of the ball-plate balancing system is done using SolidWorks software. Figure 3 shows the CAD model of the ball-plate balancing system.

Figure 3. CAD model of the ball-plate balancing system.

A square plate made of cardboard of length 320 mm and thickness 3 mm is chosen. The plate is connected to the base with a centre support of height 123 mm from the base. The plate rests on the centre support through a ball swivel joint like arrangement. This helps in free movement of the plate about x and y axes for maintaining the position of the ball. The entire base platform is raised from the ground by 15 mm corner and centre bushes. The base stand for the camera is of height 200 mm with a hole of 10 mm diameter into which an aluminium rod is inserted. The aluminium rod connected to the camera holder is attached to the base stand with a 90° support block. This ensures that the camera is exactly focusing on the top surface of the plate for reading the ball position. A ping pong ball of weight 2.7 gm with a diameter of 40 mm is used. The two servo motors used to actuate the plate in x and y axes are mounted on the base platform and their shafts are attached to the plate with 20 mm links.
The parts to build the system were 3D printed as it is efficient in fabricating customized design of the parts. The 3D printed components of the system include corner and centre bush of the base platform, centre support of the plate, plate hook of the servo motor, servo motor mount, holder for the camera, stand base for the camera, ninety-degree support block for the camera and camera weight support of the plate. Ender 3 pro 3D printer is used to 3D print the components specified. All the 3D printed parts and components are assembled to form the physical system setup. Figure 4 shows the 3D printed components and the assembled system.

**Figure 4.** 3D printed components and assembled physical setup of the ball-plate balancing system.

### 2.4. Electrical components

Two DC servo motors are used to control the roll and pitch of the plate to balance the ball in the desired position. MG995 servo motors of operating voltage 4.8 V ~ 6.6 V, stall torque 9.4 kg-cm (4.8 V) and 11 kg-cm (6.0 V) and operating speed 0.20 s/60° (4.8 V) and 0.16 s/60° (6.0 V) is used. Logitech C270 webcam that has a resolution of 1280 x 720 pixels and 30 frames per second frame rate is used. An Arduino UNO board is used for issuing the desired actuating signals to the servo motors. A 5 V switched mode power supply is used to provide input to the motors. Implementation of image processing algorithm to read the position of the ball and implementation of control algorithm to actuate the servo motors to position the ball at the desired location are carried out in a personal computer.

### 3. System integration and control

The physical system thus fabricated and assembled is integrated with image processing algorithm to read the position of the ball in real time and control algorithm to adjust the plate movement so as to balance the ball at the desired position. The control of the entire ball-plate balancing system is enabled with a smart phone HMI for which a customized mobile application is developed.

#### 3.1. Mobile application development

Using Hyper Text Mark-up Language (HTML), Cascading Style Sheets (CSS) and JavaScript, an application is developed to control and operate the ball-plate balancing system through the smart phone. Thus, a smart phone with a dedicated mobile app can be used as an HMI. The user interface or front-end of the app is developed using HTML and CSS. The back-end containing the functioning of the operation on the input given by the user interface is built using JavaScript.
The mobile app is designed to have a home page which displays three modes of operation of the system namely User Tab, Live Tab and Both Tab. The user input to locate the ball to a desired location on the plate can be given through the User Tab. If no input is given by the user, the ball is balanced in the centre of the plate by default. The ball’s current position on the plate can be viewed in real time using Live Tab and user input cannot be given here. Both Tab can be used for both giving user input and to view the ball’s current position. Figure 5 shows the mobile app developed and its different operating modes in working. The HTML canvas element is used for the touch area. The user input is given by selecting a desired point within the touch area in either User Tab or Both Tab.

![Figure 5](image)

**Figure 5.** (a) Home page of mobile app developed, (b) User tab, (c) Live tab and (d) Both tab.

When the user touches at a particular point on the square display, the coordinates of the point are mapped with pixel values of the camera. The pixel values are then sent to the main python program through web sockets. The process involved in designing the mobile app and its working in three operating modes are shown in the figure 6. The main program calculates the error between the current position and the desired position of the ball, to implement a PID algorithm to control the motor angle to position and balance the ball in the desired location.

![Figure 6](image)

**Figure 6.** Flowchart of working of mobile application.
3.2. Image processing and control

The image processing task is carried out with python programming in OpenCV which is an open-source platform for computer vision. Once the camera is connected and feed is obtained, the size and centre of the frame is defined. The Red-Green-Blue (RGB) feed of the video captured using the webcam is converted into Hue-Saturation-Value (HSV) to identify the object, in this case the ball. The variation of HSV values provides different shades of colours which upon thresholding provides an efficient method of object detection. Then dilation operation is performed on the image with a structuring element or kernel to expand the object of interest i.e., the ball on the image. This is followed by erosion or closing which helps in reducing the noise present in the image. The image is then smoothened by merging the sharp features by introducing a Gaussian blur achieved through a Gaussian filter or kernel. This helps in reducing the high frequency components and in reducing the noise in the image. Then on the detected ball, a contour is drawn to identify it and its location is obtained.

Next, based on the user input for desired position, a line is drawn between the current position of the ball and the desired position or centre of the plate (default position – if no input is given). The error between the current ball position and the desired or centre position is calculated. A closed loop PID control algorithm is implemented to reduce this error and to compute the servo motor angle required to actuate the plate. The control signal corresponding to the computed motor angle values are sent to Arduino board through serial communication which in turn issues pulse width modulated (PWM) signal to the servo motor. The actuation of the servo motor causes roll and pitch of the plate to position the ball at the desired location. Figure 7 shows the flowchart of steps involved in image processing and system control.

![Flowchart of image processing and control algorithm.](image-url)

**Figure 7.** Flowchart of image processing and control algorithm.
4. Result and discussion
The complete physical setup of the ball-plate balancing system is integrated with the mobile app for reading user input and for visualizing the position of the ball on the plate. Image processing algorithm to read the real time ball position and PID control algorithm to position the ball at the desired location are also integrated. The complete setup of ball-plate balancing system is shown in the figure 8.

Figure 8. Complete setup of ball-plate balancing system.

For a sample desired input location of (x, y) pixel coordinates (410, 300), the movement of the ball in x and y axes respectively are shown in the figure 9. The vertical axis represents the coordinate value in pixels and the horizontal axis represents the time in seconds.

Figure 9. Output ball movement in (a) X-coordinate and (b) Y-coordinate.

The PID controller is tuned by trial-and-error method to achieve the desired response. The gain values for the system (K_p, K_i and K_d) are so chosen that leads to reduced oscillation so as to maintain stability and lesser settling time. The tuned PID controller gain values for both x and y axes are shown in the table 1.

| Axis   | K_p value | K_i value | K_d value |
|--------|-----------|-----------|-----------|
| X – axis | 0.04      | 0.16      | 0.06      |
| Y – axis | 0.06      | 0.17      | 0.07      |
On experimenting with the above values, there is a variation of ±3 pixels in the output. The system has an error of $1 - 1.29\%$. The number of oscillations for the duration of five seconds is approximately four and hence the frequency of oscillation is 0.8 Hz. The time taken to reach the desired location, that is, the settling time is found to be around 26.4 seconds. Use of separate PID controllers for x and y-axes, helps in achieving accurate control of plate angle in that axes. This produces an interaction effect on controlling the overall angle of the plate, and the higher value of the settling time is attributed to it. Implementation with two independent controller hardware is sidestepped, as it makes tuning of PID controller parameters and synchronization of the controller outputs with their corresponding servomotors difficult and ensuring stability becomes complex for a common objective of controlling the plate angle.

5. Conclusion
A highly non-linear ball-plate balancing system is controlled for accurate positioning of the ball on the desired location of the plate. From the mathematical model developed, the system’s performance could be evaluated before designing the physical system. The design and fabrication of components that are 3D printed consumed more time but accurate physical dimensions of components helped in mitigating fabrication related errors and its impact on system behavior. The image processing algorithm implemented is efficient in real time. The mobile application developed provides a very convenient and intuitive human machine interface for communicating with the ball-plate balancing system. The PID control algorithm implemented is simple and efficient enough for achieving the intended response from the system. Further, the physical setup developed can be used as a test bed to understand and evaluate the performance of various other control algorithms. It can also be used for demonstration of proof of concept related to closed loop control of dynamic non-linear systems. Study on effect of disturbances and its compensation with different control algorithms are some of the works reserved for future.

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