Ball and Plate Controlling, applications and methods

***Abstract* — Control theory is a broad field with applications in various domains. Temperature and speed control, robotic and autonomous, and telecommunication systems are some examples. There are some typical examples in control theory that hold fundamental concepts of the whole field. An inverted pendulum on a cart, motor speed control, and ball and plate balanced system are some basic examples. Additive complex features can be added to the basic models. In a recent project, the focus is on a ball on a plate and keeping it balanced. Stabilizing and controlling objects in robotics is one application for this example. And it helps for a better elaboration on the car suspension system and getting its concept. The problem can be solved in various methods like PID controller or reinforcement learning.**

***Index Terms*—Ball and Plate, Stabilizing, Control Theory**

INTRODUCTION

The ball and plate system is a complex, nonlinear, and multivariable system, and various types of control systems can be applied to address the challenges it presents. The ultimate goal is to keep the ball on a plate that can tilt in two dimensions without falling the ball.

The project has some different aspects like basic concepts, requirements, software modeling, controlling strategies, physical components that we may encounter and use, implementation, and application. Physical implementation is out of the scope of this report.

MODELING

As the system could be complex in some aspects, some restrictions and boundaries are assumed for simplification. We can restrict the amount of plate tilt to prevent the ball from getting accelerated and falling from the edges. Also, we may assume that the plate cannot move along the z-axis (up and down) in this step, the initial step is not too far from the center and there is no noise.

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The most important information which is needed to be acquired is the ball position and this should be fast enough. In the simulation step, we can just assume that we already know the ball's position. In hardware implementation, some approaches are accessible to acquire ball position which we will discuss later.

CONTROL SOLUTIONS

Speaking of possible controlling theories, some common types of control systems are often used in solving the ball and plate problem which are not hard to simulate, fast enough, and easy to tune. Here we can name some of them below.

PID Control

Proportional-integral-derivative (PID) is a generic, classic, and widely used control strategy (difference between desired and actual ball position). Implementation of PID is used to gain the stability of any system.

State-Space Control
Linear Quadratic Regulator (LQR) is an example of a state-space control approach.

Nonlinear Control
Nonlinear control strategies like feedback linearization or sliding mode control can be used.

Adaptive Control
Adaptive control can be useful when dealing with uncertainties or variations in the ball and plate system.

Model Predictive Control (MPC)
Model Predictive Control (MPC) involves predicting the future behavior of the system and optimizing the control inputs over a finite time horizon.

Neural Network Control
Neural network-based control approaches, such as neural network controllers or reinforcement learning, can be applied to learn and optimize control policies for the ball and plate system smarter with the least human-needed tunings.

As it is proven from the equations and logically, the two controllers are independent and exactly similar. They can be designed and also work simultaneously. Based on the linear model, the schema is loop in loop.
Various approaches are available to conduct balancing problems. The PID controller is chosen as a loop-in-loop feedback control system to keep balancing.
As a recap for PID fundamentals, it is worth mentioning that there are some constraints for the K_p, proportional to the error, K_i, proportional to the integral of the error, and K_d, proportional to the deviation of the error, values as mentioned in figure 1.

	Rise time	Overshoot	Settling time
Increase k_p	↓	↑	↑
Increase k_i	↓	↑	↑
Increase k_d	↓	↓	↓

Fig. 1 – PID parameters basic relation

HARDWARE DESIGN

Hardware design includes sensor and actuator selection. As far as some existing solutions of ball-plate balancing systems are expensive and bulky, the focus is to offer a solution that is relatively cheap, easy to implement, and flexible with the least components needed. As was mentioned earlier, we need to know the ball position (x, y) to take action in time. For this purpose, some solutions are offered.

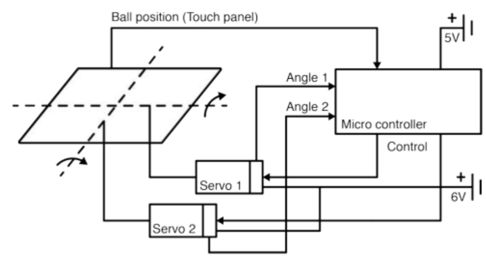

Fig. 2 – essential system elements [1]

Ball positioning
One of the main steps in modeling such a system is to estimate the ball position. There are some solutions for that as below:

1. Touch screens
2. Camera and video processing [2]
3. Gridding sensors
4. Sensors on ball

Each solution has plus points and drawbacks. Among them, the first solution is more compact, needs less machinery, is more affordable, and probably easier to implement. There are different types of touch screens with different specifications; though based on [1], the plate is recommended to be a resistive one, which is accurate with less than 2% error and also affordable. A resistive touch-sensitive glass screen consists of two layers, a glass sheet, and a flexible outer layer.

Actuator
The other parts of the system are actuators to control plate angle. There are also different assumptions for this aim.

1. Linear actuators
2. Gimbal ring

3. Cable and pulley
4. Joint parallelogram linkage

All the solutions provide the two desired degrees of freedom and can tilt the plate on two axes to overcome balancing.

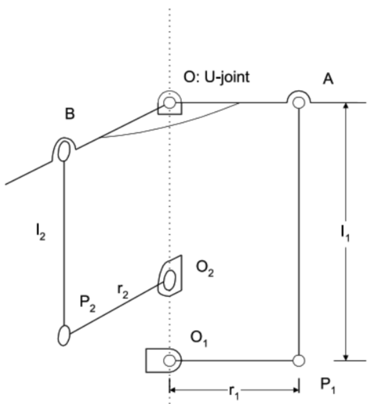

Fig. 3 – coordination of joint parallelogram linkage [3]

Figure 3 is one installation proposal. Other combination of components also can be practical [4]. There are also other parts for a flawless and smooth action. An optical encoder on the motor shaft to measure the angle, dual axis inclinometer on the plate, DC motors, and of course a processor, either a microprocessor like ATMEGA32 or just an Arduino. An amplifier also may be used to amplify the motor power.

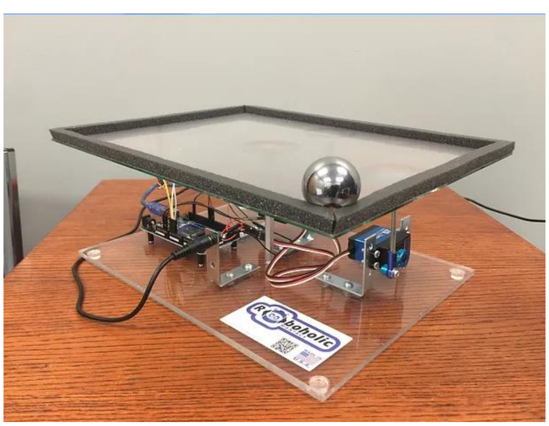

Fig. 4 – physical system sample [5]

SIMULATION RESULTS

To simplify the calculations, it is assumed that the sliding friction is high enough to prevent the ball from slipping, the rolling friction is negligible, the plate does not have vertical movement, and has two degrees of freedom and its movement is kept as small as it can be and the deviation from its balanced pose would be minimum. The geometry of the ball is perfectly spherical. Two degrees of freedom is equal to the number of inputs of the system, the two motor angles.
The simulation is done by virtual control lab on MatLab [6] via Simulink.

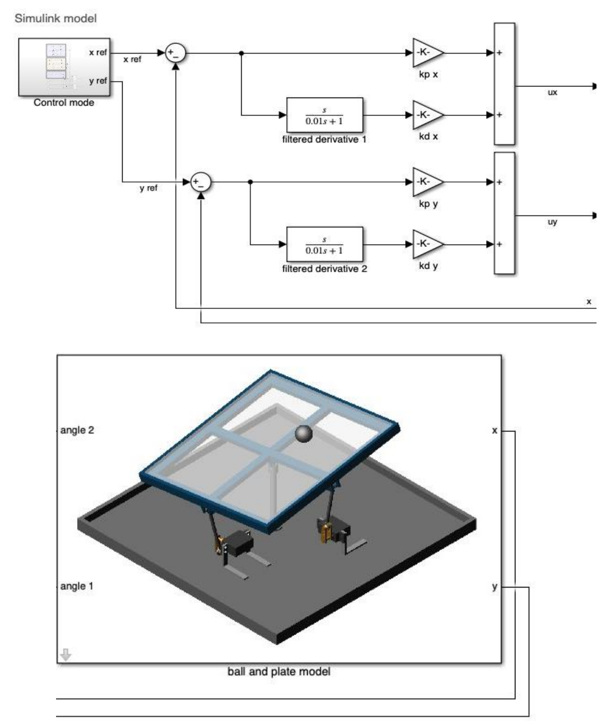

Fig. 5 – simulation on MatLab – a) Simulink and b) schematic

Here we have one use case of the GUI of a virtual control laboratory. The plots show that the system operates well and oscillates without falling the ball. The second image is a short video of the movement of the ball on the plate from lateral views.

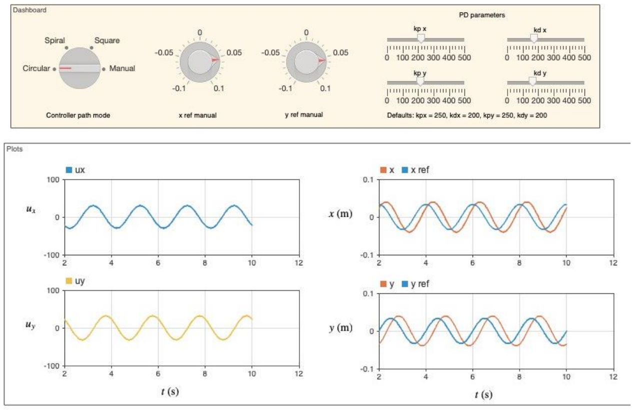

Fig. 6 – a) setting panel and b) sample plots

Figure 7 is a short video of the movement of the ball on the plate from lateral views.

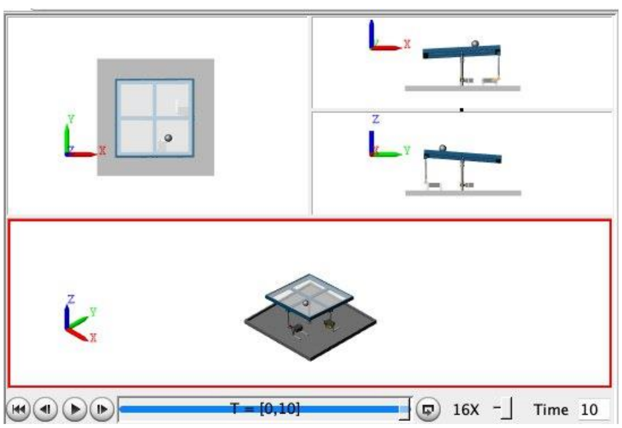

Fig. 7 – lateral views of movement

APPLICATIONS

The ball and plate balancing problem is a classic control problem that involves stabilizing a ball on a flat plate by controlling the tilt of the plate. This problem has various real-world applications, particularly in the field of control theory and robotics. Some of these applications include:

Control System Design, education, and research
The ball and plate system serves as a challenging yet illustrative platform for testing and developing control algorithms. The challenge is nonlinear dynamics and the need for precise control to keep the ball balanced on the plate. It is often used as a benchmark problem to test the performance of different control algorithms. It is also widely used in educational settings to teach control theory concepts such as feedback control, stability analysis, and system identification. It also serves as a valuable research platform for studying nonlinear control systems and advanced control algorithms. Ball on beam [7], which is actually pretty similar to the current research, just in one dimension is an easier example. A more complex one is the ball on a sphere [8], still in a similar context.

Robotics
The principles behind ball and plate balancing apply to the stabilization of objects on surfaces in robotics to design robotic arms carrying objects while keeping the balance like camera stabilizers.

Gyroscopes and Inertial Measurement Units (IMUs)
The concept of balancing a ball on a plate can be extended to the stabilization of gyroscopes and IMUs used in navigation systems.

Flight Control Systems
The principles of ball and plate balancing can be adapted to stabilize aircraft during flight. Aircraft autopilot systems use similar control algorithms to maintain stability and control orientation based on sensor feedback.

CONCLUSION AND DISCUSSION

This report was meant to cover basic concepts, MatLab modeling, simplifications and assumptions, control design of dynamic systems, and applications of ball and plate balancing challenge. The mathematical formulation and calculation are neglected in this step.
The major concerns in implementing and simulating such dynamic systems are accuracy, response time, cost, performance, functionality, and extendibility. We tried to find the best practical choices from simulation to mechanical components to get ready for physical implementation. There are plenty of documented sources of construction of physical model and simulation [9], worth to study deeper to get better insight.

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