Two dimensional ball balancing system - A real time control system and image processing

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Abstract

This project aims to relating theoretical concepts in control theory that students learn in the control system design course with real world. This is achieved by implementing two digital PID controllers that dominate the action of two servo-motors inside the domain of Simulink-Matlab. These servo-motors regulate the position of a ball to track a desired path. A camera captures the ball position and feedbacks the position for the controllers. Students can implement their controller inside Matlab and can observe the results immediately which gives them a direct impact of their design. The control system consists of two servo-motors that work as the main actuators, a web camera that is adopted for detecting the position of the ball and a PC that manipulates the feedback and gives a control action. A somehow complicated image processing is used to subtract ball position from camera data. Inside the PC also can be found two digital PID controllers. Obtaining a proper transfer function between the actuator actions and ball position is outside the scope of the work. Therefore, the tuning of the two PID gains are accomplished by trial and error. This is done by changing the gains and observing the performance of the control system. The following figures illustrate the function of the control systems as well as the real system components.

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Table of Contents

Chapter one

1. Introduction:

A control system is a system of devices or set of devices, that manages, commands, directs or regulates the behavior of other devices or systems to achieve desired results. In other words, the definition of a control system can be simplified as a system, which controls other systems. In general, there are two common classes of control actions, open loops, which operate with human input, and closed loops, which are fully autonomous.
Furthermore, we can the control systems in nature too as there are myriads of dynamical systems and processes in nature that make use of automatic control. Plants and animals rely on complex chemical reactions for nourishment and life. In turn, these chemical reactions require the control of parameters such as temperature, pH and enzyme concentrations so that they are kept within certain ranges.

The human body temperature regulation also works like a control system which is controlled by a feedback process causing the person to either shiver or sweat to keep body temperature fixed to the desired Set point.

Feedback control has a long history which began with the early desire of humans to harness the materials and forces of nature to their advantage. The first applications of feedback control appeared in the development of float regulator mechanisms in Greece in the period 300 to 1 B.C, An oil lamp devised by Philon in approximately 250 B.C. used a float regulator in an oil lamp for maintaining a constant level of fuel oil, At that time, machines were developed which greatly enhanced the capacity to turn raw materials into products of benefit to society. However, the associated machines, specifically steam engines, involved large amounts of power and it was soon realized that this power needed to be *controlled* in an organized fashion if the systems were to operate safely and efficiently .

the first automatic feedback controller used in industrial process was made by James watt making the fly ball governor in 1769 for controlling the speed of a steam engine.

In the 20^{th} century, the world has opened to a new level of control systems with Henry Ford's assembly machine and it was the start of automobile assembly. With the beginning of 21th century Advances in micro- and nanotechnology. First intelligent micro machines are developed and functioning Nano machines are created.

Control system engineers are concerned with understanding and controlling segments of their environment, often called systems, to provide useful economic products for society.

The twin goals of understanding and controlling are complementary because effective systems control requires that the systems be understood and modeled.

In Control System Analysis, engineers use tools to carry out examination to understand the characteristics and identify the properties of a plant, before designing a feedback controller to make a plant behave in a desired manner (meeting a set of performance specifications). In technical words, the control goal is to make a plant stable that operates in a predictable way, either by eliminating the error or by regulating the error bounded within the tolerance band, which ultimately leads to SAFETY (for users & environments), RELIABILITY (for operators).

Control systems is to be found in almost every aspect of our daily environment, In the home, The house thermostat is a system of feedback and information control. When the house temperature falls below the preset level, an electric message is sent to the heating system, which is then activated. When the temperature increases and reaches the set level, another message shut off the heater.

The continual measurement and turning on and off the heater keeps the house at the desired temperature. Driving an automobile is a pleasant task when the auto responds rapidly to the driver's commands. Many cars have power steering and brakes, which utilize hydraulic amplifiers for amplification of the force to the brakes or the steering wheel.

Feedback control systems are used extensively in industrial applications Thousands of industrial and laboratory robots are currently in use and there has been considerable interest recently in applying the feedback control concepts to automatic warehousing and inventory control. Furthermore, automatic control of agricultural systems (farms) is meeting increased interest .Automatically controlled silos and tractors have been developed and tested. Automatic control of wind turbine generators, solar heating and cooling, and automobile engine performance are important modern examples.

Chapter two

Two dimensional ball balancing system – A real time control and image processing

2.1 Introduction:

Digital image processing is now widely popular and growing field where its used in medicine, military, video production, security, tracking objects, and remote sensing. the goal of this project is to develop a ball-plate balancing system where the ball is sensed using camera and not a resistive touch screen which is expensive

The ball-plate system is a nonlinear and unstable open-loop system. This system has 2 degree of freedom (DOF). The objective is to balance the ball in a predefined coordinate or to follow a specific center with falling of the horizontal plate. The ball position will be controlled indirectly by tilting the angle of the plate in a 2D direction, x-axis and y-axis, and its controlled by two DC servo motors. Studying the mathematical modeling of this system in order to find the transfer function of the system and thus design a good controller to make sure getting the perfect control of the ball's position. The vision system (camera) will capture continuous frames that will be processed using Processing in order to get the coordinates of the ball. The servo motors will be controlled 2 using ARDUINO which controlled by a software developed using Processing which is cable of image processing, designing a controller and with a position feedback.

Characterizing ball-plate system specifications is difficult since the controller is not directly affecting ball and thus the designing of the controller and calculating its numerical value will be difficult. Nowadays the ball and plate system has been controlled by many control methods such as PID control, fuzzy control and so on. However, the Proportional Integral Derivative (PID) controller proved its efficiency in the world of controls and in the industrial field. The feedback controller (PID) will decrease the errors in controlling the ball's position and trajectory. It will also control the overshoot resulted from the jump in the reference signal and thus controlling the large input to the servo motors in order to keep the ball on the plate. In this thesis, an optimal PID controller will be designed with quick rise time, rapid settling, and negligible steady-state error.

2.2 Hardware parts:

- **Arduino Uno**

Arduinos an open-source electronics platform based on easy-to-use hardware and software. Arduino boards are able to read inputs - light on a sensor, a finger on a button, or a Twitter message - and turn it into an output - activating a motor, turning on an LED, publishing something online. You can tell your board what to do by sending a set of instructions to the microcontroller on the board. To do so you use the Arduino programming language (based on Wiring), and the Arduino Software (IDE), based on Processing the Arduino Due is the first Arduino board based on a 32-bit ARM core microcontroller. It is suitable for large scale projects and it differ from other Arduino kits as it runs at 3.3V as the maximum voltage r. It operates at a maximum speed of 84 MHz and up to 512 Kbytes of Flash memory and up to 100 Kbytes of SRAM. Fig. 2.1 shows a typical Arduino Uno board with some details.

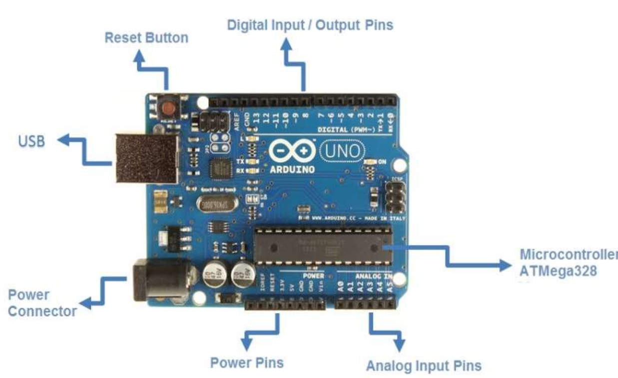

Fig 2.1: Arduino Uno board

- **Servo motor**

Tiny and lightweight with high output power. Servo can rotate approximately 180 degrees (90 in each direction), and works just like the standard kinds but smaller. Position "0" (1.5 ms pulse) is middle, "90" (~2 ms pulse) is all the way to the left. ms pulse) is middle, "90" (~2 ms pulse) is all the way to the right, " the left.

Fig 2.2: A micro servo motor

specifications:

Weight: 9 g.

Dimension: 22.2 x 11.8 x 31 mm approx.

Stall torque: 1.8 kgf·cm.

Operating speed: 0.1 s/60 degree.

Operating voltage: 4.8 V (~5V).

Dead band width: 10 µs.

Temperature range: 0 – 55 ºC.

- **Camera:**

Logitech® HD Webcam C270 webcam has been chosen because it has ability to recording at 30 fps for high resolutions and 60 fps for low resolution. It is a 1920×1080p full HD camera and the image resolution is up to 16 megapixels.

Fig 2.3: AC270 webcam used for ball position detection

2.3 System Overview:

In this project we use PID controller. A proportional integral derivative (PID) controller is a control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through use of a manipulated variable. The acronym PID stands for Proportional-Integral-Differential control. Each of these, the P, the I and the D are terms in a control algorithm, and each has a special purpose. Sometimes certain of the terms are left out because they are not needed in the control design. This is possible to have a PI, PD or just a P control .It is very rare to have an ID control.

The standard PID control configuration as shown Fig 2.4. In this configuration, the control signal u (t) is the sum of three terms. Each of these terms is a function of the tracking error e (t).The term Kp indicates that this term is proportional to the error. The term Ki /s an integral term, and 7 the term Kds a derivative term. Each of the terms works "independently"1 of the other

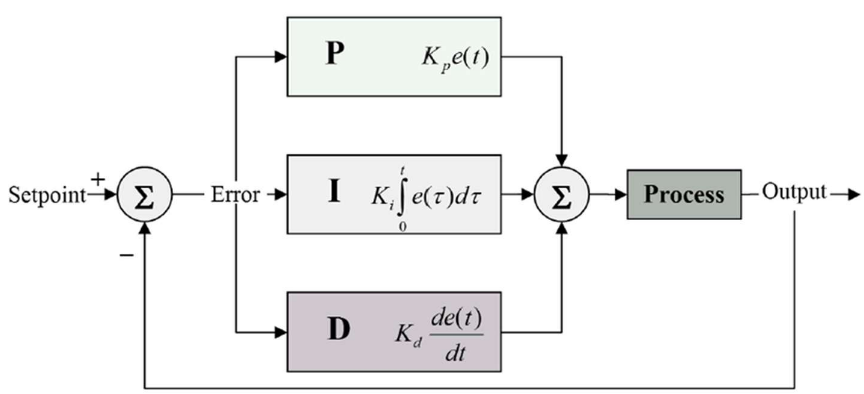

Fig 2.4: The general structure of a PID controller

One can summarize the effects of proportional, integral and derivative action in the following points:

- **proportional controller**

In the P controller algorithm, the controller output is proportional to the error signal, which is the difference between the set point and the process variable. In P controller the actuating signal for the control action in a control system is proportional to the error signal. The error signal being the difference between the reference input signal and feedback signal obtained from the output. The proportional response can be adjusted by multiplying the error by a constant Kp, called the proportional gain constant. The proportional term is given by: $P = K_p\, e(t)$.

- **Proportional integral controller**

At present, the PI controller is most widely adopted in industrial application due to its simple structure, easy to design and low cost. Despite these advantages, the PI controller fails when the controlled object is highly nonlinear and uncertain. PI controller will eliminate forced oscillations and steady state error resulting in operation of on-off controller and P controller respectively. However, introducing integral mode has a negative effect on speed of the response and overall stability of the system. Thus, PI controller will not increase the speed of response. It can be expected since PI controller does not have means to predict what will happen with the error in near future. This problem can be solved by introducing derivative mode which has ability to predict what will happen with the error in near future and thus to decrease a reaction time of the controller. PI controllers are very often used in industry, especially when speed of the response is not an issue. $PI = K_p\, e(t) + K_i \int e(t)\, dt$.

- **Proportional integral derivative controller**

Many industrial controllers employ a proportional, integral plus differential PID regulator arrangement that can be tailored to optimize a particular control system. PID controller is most commonly used algorithm for controller design and it is most widely used controller in industry. The controllers used in industry are either PID controller or its improved version. The basic types of PID controller are parallel controller, serial controller, and mixed controller. The PID controller algorithm utilized for is design velocity algorithm, it is also called incremental algorithm. In the industry, PID controllers are the most common control methodology to use in real applications. PID controller has all the necessary dynamics: fast reaction on change of the controller input (D mode), increase in control signal to lead error towards zero (I mode) and suitable action inside control error area to eliminate oscillations (P mode). Derivative mode improves stability of the system and enables increase in gain K and decrease in integral time constant Ti, which increases speed of the controller response .PID controllers are the most often used controllers in the process industry. The majority of control systems in the world are operated PID controllers. It has been reported that 98% of the control loops in the pulp and paper industries are controlled by single-input single output PI controllers and that in process control applications, more than 95% of the controllers are of the PID type controller. PID controller combines the advantage of proportional, derivative and integral control action. $PID(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt}(e(t))$.

2.4 Digital images:

As described before one of the requirements was to be able to detect different kinds of balls. This means that no assumptions about the color of the ball can be made for instance. Therefore, all frames from the web-camera are saved as black-and-white images. If simplified, digital images are represented by a matrix for each dimension of the image. Since black-and-white images can be represented in only one dimension, this makes the image processing easier. The elements in the matrix represents the value of the pixel, one element for each pixel. The values of the elements for a black-and-white image matrix are between 0 - 255, depending on the relation between black and white in the pixel. In the software the resolution of the captured frames are set to 640x480 pixels, but can of course be changed if required.

2.5 The outer controller:

To control the position of the ball a PID controller is used as an outer control loop The PID controller is the most used controller in the industry by far .A PID controller consists of three parts a Proportional, a Integral and a Derivative part. The proportional and integral part are the same as for the PI controller, because a PID controller with the derivative part set to zero works like a PI control, this is common setting in the industry. Eq.s for the PID controller

$$u(t) = K \cdot (e(t) + 1\ Ti \cdot Z\ t\ e(\tau) \cdot d\tau + Td \cdot de(t)\ dt\ )$$

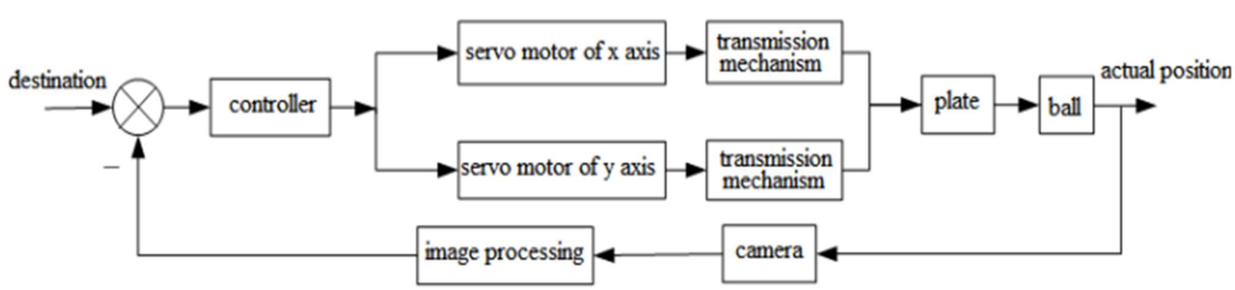

Fig 2.5: The final ball-plate balancing control

2.6 The Derivative part:

The equation for the PID controller is the same as the PI controller except with the derivative part added. The derivative part tries to calculate future control signals. One advantage of divide the PID controller into three different parts is that it becomes relative easy for humans to understand how the controller works. Also the PID controller has high performance if it is well-tuned and is an old and well tested controller. To limit the effects from noise the derivative part should not be implemented as a in Eq

$s \cdot Td \approx s \cdot Td \ 1+s \cdot Td/N$

where N limit the gain at high frequencies. N is usually set to 10 - 20 and is called the maximum derivative gain. In the real world it is a good idea to be able to modify the influence of the set point ysp. This is made by adding a factor γ to the derivative part in Eq

$D(s) = s \cdot Td \ 1+s \cdot Td/N \ (\gamma \cdot Ysp(s) - Y(s))$

Often is the factor γ set to zero because when the derivative part does not care about the set point.

Chapter Three

System Modeling and Design

3.1 Matlab Simulink code:

In this Simulink diagram we set our controlling action on constant points we choose on the plate (Output the constant specified by the 'Constant value' parameter). This will transform action to the servo motors via Arduino

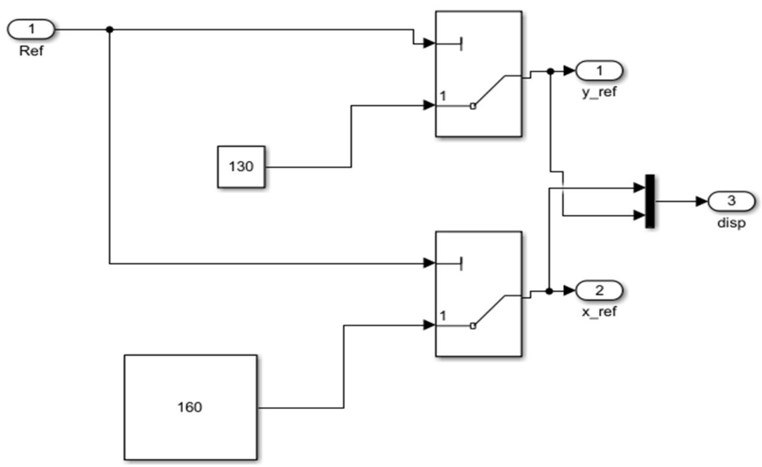

Fig 3.1: Simulink block diagram for desired reference

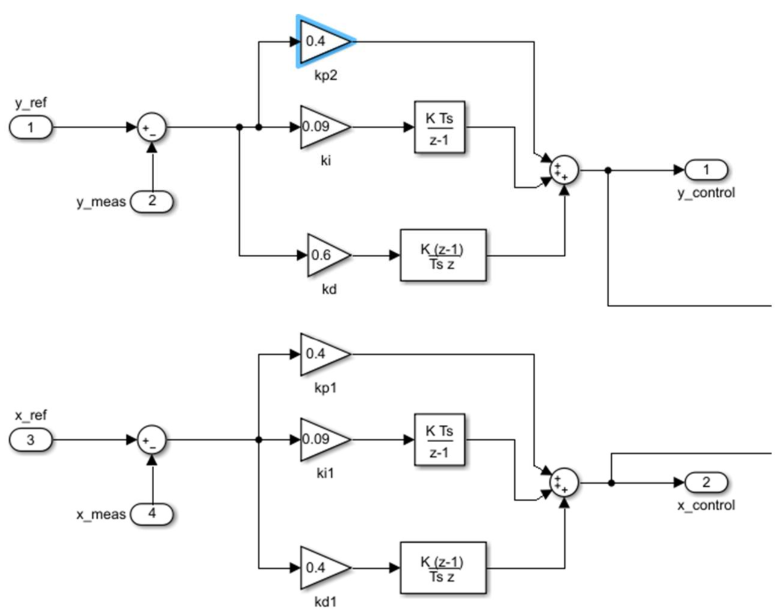

Fig 3.2: Simulink block diagram for user defined controller

Fig 3.2 shows the PID parameters after tuning, the control action tries to adjust the servo motors to the settled points. during this model continue looking at the position as the output. The position has been obtained by integrating the speed,

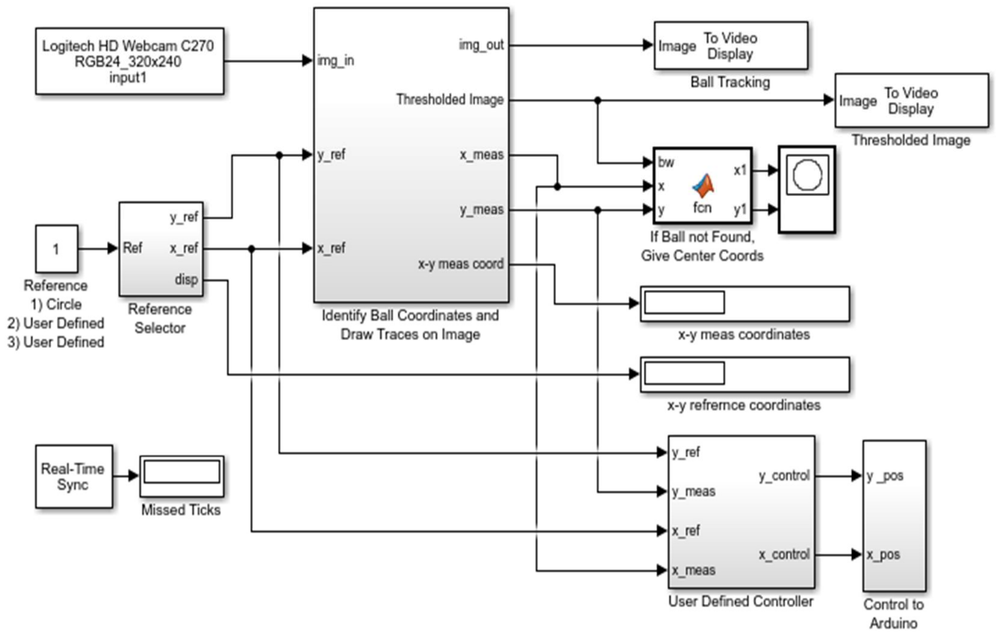

Fig 3.3: Simulink block diagram for complete control structure

Fig 3.3 shows the complete Simulink code. The objective of this project is to keep a ball on a platform within a predetermined boundary. The cameras function is to monitor a ball’s position. When the ball moves outside the boundary, the camera will detect the motion of the ball and send signals to the controller to determine the coordinates needed to stabilize the ball to its designated location. The controller and the servos will simultaneously control the plate’s pitch and roll to center the ball within the boundary.

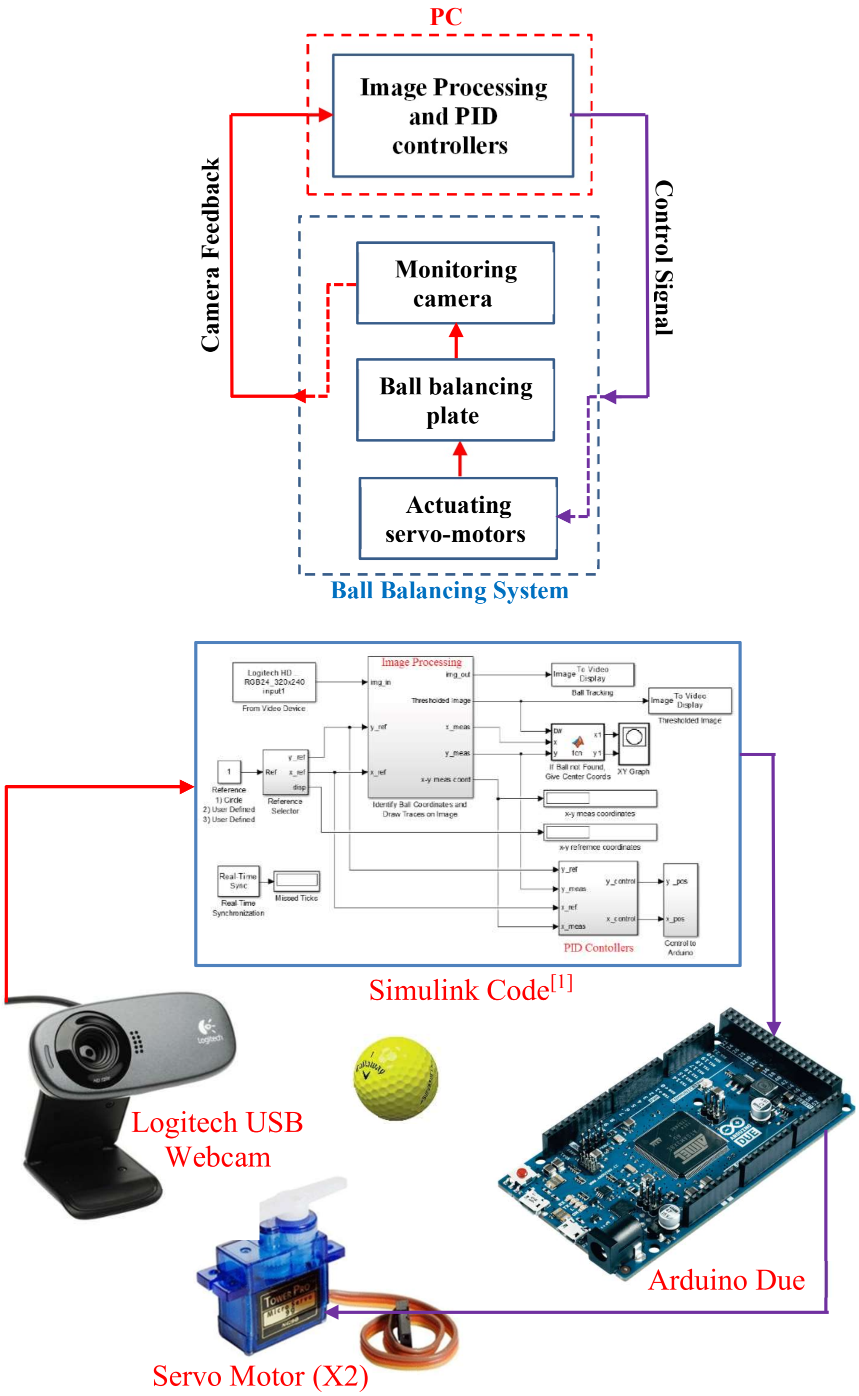

Fig 3.4: A diagram for the physical interfacing between software and hardware

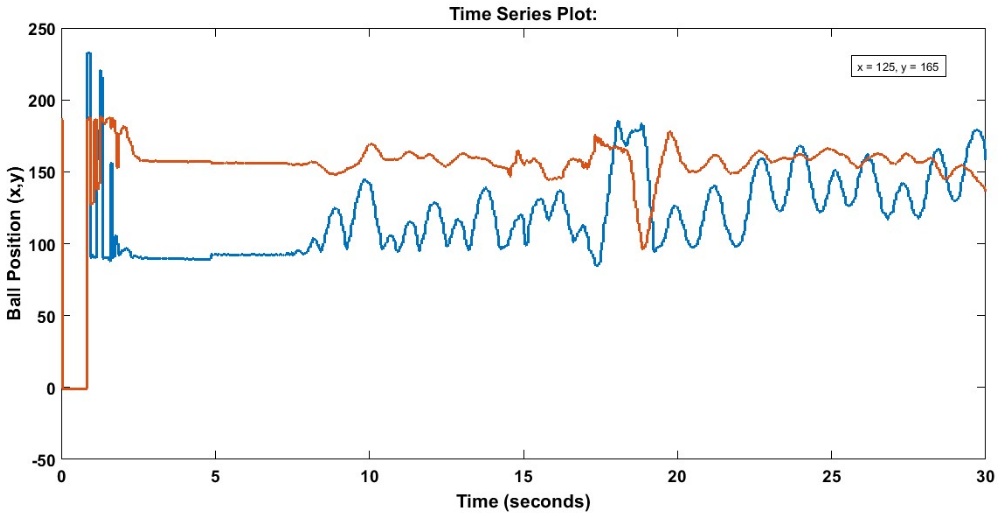

Fig 3.5: Response for fixed reference ball position

Chapter Four

Conclusion

Conclusion:

In conclusion, overall the system can be considered a success. The objective of the project was to control the position of the ball on the plate for constant positions, as well as have the system capable of correcting for disturbances in ball position. In general these goals were accomplished, especially constant position balancing and disturbance rejection. The ball can be centered on the plate or another coordinate location, and will quickly correct for disturbances to the ball position with fast response time, small overshoot, and with a small steady state error ; however in hindsight this may have been extremely fast target for settling a large disturbance. From an observers point of view the system definitely responds well. As for path following, the more advanced possible objective for this system, there was also a good deal of success. One apparent issue is related to image processing as the camera cannot detect the ball in a room with high brightness and we can minimize that by adjusting the camera sittings. A simplified mathematical model was derived by system parameters. The controller parameters values (Kp, Ki and Kd) were obtained by using manual tuning method from practical model so as to perform best system response. From experimental results, it is found that the best controller parameters which gave the best response of the system are: Kpx= 0.4, Kix= 0.4, Kdx= 0.6, Kpy= 0,6, Kiy= 0.09, Kdy= 0.09. The accuracy of the system is tested adjusting the position of the ball at three different points

References:

[1] Bay C. and Rasmussen B. "Exploring Controls Education: A Re-configurable Ball and Plate Platform Kit," American Control Conference (ACC) Boston, MS, pp 6652-6657, 2016.

[2] Ahmed Itani, "Ball Plate Balancing System Using Image Processing", MSc. thesis, Department of Information Systems Engineering, NEU, 2017.

[3] G. Andrews, C. Colasuonno and A. Herrmann, "Ball On Plate Balancing System" Rensselaer Polytechnic Institute, 2004

Appendix A

Arduino code (receiving data and directing servo motors)

```
#include <Servo.h>
const int SERVO1_BA  = 90;
const int SERVO2_BA  = 90;
const int SERVO1_PIN = 9;
const int SERVO2_PIN = 10;
Servo servo1;
Servo servo2;
int servo1_angle = 0;
int servo2_angle = 0;
void setup()
{

 Serial.begin(250000);
  servo1.attach(SERVO1_PIN);
  servo2.attach(SERVO2_PIN);
  servo1.write(SERVO1_BA);  // Here must
SERVOx_BALANCE_ANGLE,
  servo2.write(SERVO2_BA);
}
void loop()
{
  if (Serial.available() > 1)
  {
    servo1_angle = Serial.read(); // Reading angle of the servo1
    servo2_angle = 180 - Serial.read(); // Reading angle of the servo2
    // Mapping real angles to servs' range of angles
    servo1_angle = map(servo1_angle, -125, 125, 30, 105);
 servo2_angle = map(servo2_angle, -125, 125, 30, 105);

      // Writing mapped angles to servos
      servo1.write(servo1_angle);
      delay(1);
      servo2.write(servo2_angle);
      delay(1);
  }
  }
```