Development of a Stewart platform

PROJECT REPORT

for the module

MTE 380 Mechatronics Engineering Design Workshop

from the Course of Studies Mechatronics

at the University of Waterloo

by

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LEARN Group	Group 2
Course	MTE 380

Letter of Transmittal

Professor Sanjeev Bedi
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03. December 2024

Dear Prof. Bedi,

The report "Development of a Stewart platform" was written in whole by the group members of Group 2: Marvin Bullinger, Luke Johnston, Leo Xing, Gavin Grimm, and Aidan Landry. It has not been submitted for any previous academic credits at this university or any others.

This report is being submitted for the course MTE380 as required for completion of the course as requested by yourself.

The subject of this report is the Ball Balancing Robot project worked on by Group 2 throughout the three months between September 2024 and November 2024. The project spanned multiple disciplines including Software, Mechanical, and Electrical design. In the completion of this project, a platform was developed that could balance under disturbance and move a ping pong ball and golf ball along a set path.

We would like to thank the teaching staff for their assistance and support during this project.

Sincerely,

Group 2
Marvin Bullinger,
Luke Johnston,
Leo Xing,
Gavin Grimm,
Aidan Landry

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Acronyms

PLA	polylactide
PETG	polyethylene terephthalate glycol
HSV	Hue Saturation Value
RGB	Red Green Blue
CAD	Computer-aided design
RPi	Raspberry Pi

Contents

1 Introduction

1.1 Background

Stewart platforms are parallel actuators which provide high levels of load capacity and positioning precision [1]. The Stewart platform was invented in 1949 as a universal tire tester, but is best known for its use in flight and driving simulators as well as space telescopes [1]. These platforms consist of four major components, a moving top plate, a fixed baseplate, several actuated legs, and a control system [1]. In this project, a small Stewart platform is designed for balancing a ball based on its position and trajectory as determined by a computer vision system.

1.2 Needs Assessment, Problem formulation, constraints, criteria

The given problem for this project is to design a Stewart platform that can move a ball to a fixed point on top of the platform and automatically balance the ball on the platform even when disturbances are introduced for at least 10 seconds. Furthermore, the platform must be able to move the ball in a discernible, repeatable pattern for 10 seconds, and there are bonuses for being able to balance different types of balls as well as being able to bounce the ball in a controlled manner. These problems have all been solved before with existing Stewart platforms, and the platform which solve these specific problems tend to be smaller platforms designed for educational and demonstration purposes.

With the given problem for this project, the goal for the specific Stewart platform presented in this report is to balance balls of varying weight, namely a ping pong ball, a golf ball and a steel ball bearing, for at least 15 seconds, while also being able to guide said balls along a circular trajectory. Furthermore, the platform must maintain the balance of the balls after the introduction of physical disturbances.

From the problem assessment and needs analysis above, the following constraints were developed. The first constraint for our design is the platform must be able to balance balls for at least 10 seconds, even when under physical disturbances. The second constraint is the platform must have the mechanical strength to balance balls of various weights to balance both a ping pong ball and a golf ball. The third constraint is the dimensions of the platform must fall within 30 by 30 cm plus or minus 5 cm. The fourth constraint is the platform must be able to move balls along a fixed path. The fifth and final constraint is the total cost of the components of the platform must be under 150 C$.

In addition to the constraints which the platform must adhere to, there are several criteria which serve to optimize the design of our platform and improve how effectively it functions. The first criterion is ease of construction, which allows for more frequent design iterations as individual parts can be changed without the need for a lengthy takedown and rebuild process. The second criterion is cost optimization, which again allows for more design iterations and ensures the budget is well managed and well-used. The third criterion is a high range of motion, where range of motion describes the maximum angle the platform can tilt, because the ability for the platform to use steep angles to control the ball improves its capabilities of responding to disturbances. The fourth criterion is a fast control speed, which further improves the ability for the platform to react to sudden disturbances, and it improves the precision with which the platform can control the ball. The final criterion is being able to bounce the ball in a controlled manner, which is a goal set to stretch the scope of this project and improve the quality of the design in pursuit of that goal.

1.3 Patentability

The design developed during this project is most likely not patentable. The government of Canada states that for something to be patentable, it needs to be novel in the sense that it has not been done before, useful, and not common knowledge or trivial [2]. It is safe to say that the while the design may meet the usefulness and non-obvious criteria, it is not novel. Not only are there multitudes of existing Stewart/ball balancing platforms available, but the actual mechanical and software designs have been done already as well.

2 Proposed Solution

In this chapter, the team's decisions during the conceptualization phase are presented and justified.

2.1 Abstraction

The primary goal of the Stewart platform project is, as its name suggests, to design a fully functional Stewart platform system. The system must be capable of balancing balls of various weights (ping pong ball, ball bearing etc.) for 15 seconds. In addition to simply balancing the ball, the Stewart platform must also be able to direct said balls into specific patterns such as circles or lines, and it must be able to continuously balance the ball even after physical disturbances were introduced. Several design solutions were proposed for the Stewart platform. The baseline for each proposed design is that it must be capable of achieving the primary design goal and the design constraints outlined above. In addition to that, each proposed solution also took into account the different design criteria discussed above to varying degrees of significance.

Each proposed solution consists of seven key design parameters. These design parameters are then used to evaluate how successful the proposed solution will be at achieving the design criteria. To summarize the design selection process, each proposed solution must first be theoretically capable of achieving the design constraints and the design goals, since they are serving as the baseline for each design. In the end, a Stewart platform design will be selected based off on how well it can achieve the design criteria. The selection process for the proposed solutions will be discussed in more detail below.

2.2 Decision Matrices

A decision matrix was created to determine how significant and relevant each design criteria will be for the Stewart platform. In order to decide this, each design criteria would receive a score from 1 to 5 from each of the group members. The average score for each of the criteria were then calculated.

The design matrix used for criteria evaluation is showcased in figure 2.1.

Criteria	Aidan's Weight	Leo's Weight	Luke's Weight	Marvin's Weight	Gavin's Weight	Avg. Weight
Bounce Ball	2	2	5	4	1	2.8
Optimize Cost/	4	4	2	4	3	3.4
Ease of assembly/disassembly	4	5	3	2	5	3.8
Reaction speed/control	4	3	4	5	2	3.6
Range of motion	4	2	1	3	4	2.8

Figure 2.1: Decision matrix for the design criteria

As shown in figure 2.1, the group has decided that ease of assembly should be the most important criterion to consider when designing the Stewart platform. On the other hand, the range of motion and the ability to bounce the ball are both considered to be the least significant criterion for the design.

Four different designs for the Stewart platform were then created based on the seven design parameters that were mentioned above.

Parameters	Configurations			
Number of Motors	2	3	4	6
Motor Type	Stepper	Servo	-	-
Material	PLA	ABS	Aluminium	Aluminium / ABS
Size of the platform [cm]	25 by 25	27.5 by 27.5	30 by 30	35 by 35
Joint type (for connection to platform)	Ball	Hinge	Ball (Magnet)	Universal
Microcontrollers	RPi	Arduino + RPi	-	-
Ball detection	Camera (CV) Above	Proximity Sensor (3)	Camera (CV) Below	-

Figure 2.2: Design analysis matrix

As shown above in figure 2.2, the seven parameters to consider when designing the Stewart platform were the number of motors, the type of motor, the type of material used, the size of the platform, the type of joint used for the legs, the microcontroller used and how the Stewart platform will be detecting the balls it is balancing. The fourth proposed design was quickly dismissed because it requires six motors. The group decided that this design would be too overcomplicated and over-engineered for it to be feasible. Engineering judgement was then performed to determine how well each of the remaining three proposed solution would be able to satisfy the design criteria.

The results of the proposed solution analysis are shown in figure 2.3 below:

Criteria	Weight	Scores (0 - 5)		
		Design 1	**Design 2**	**Design 3**
Ability to Bounce Ball	2.8	4	0	2
Optimize Cost	3.4	4	5	1
Ease of Assembly / Disassembly	3.8	4	5	1
Reaction Speed & Control	3.6	5	3	2
Range of Motion	2.8	4	3	2
Weighted Total:	-	**70.2**	55.2	25.6

Figure 2.3: Proposed solution design analysis

Based on the design analysis shown in figure 2.3, the group decided design 1 would be the most successful at achieving the design criteria for the Stewart platform. Its primary advantage being it is relatively easy and cheap to construct since it will be 3D printed. In addition, it also offers much faster reaction speeds than the other designs. It has great range of motion and leaves the window open for additional features such as the ability to bounce the ball. As such, design one is selected as the initial design for the Stewart platform. One important thing to note is the design shown in figure 2.2 is only a preliminary design, and it received multiple modifications and adjustments throughout the project. For instance, the number of motors used in the design was increased from two to three in order to improve its static and dynamic stability. In addition, the stepper motor was switched in favor of the servo motors and the balancing platform was expanded.

3 Design of the proposed solution

In this chapter, the procedure for the design of the platform will be presented and problems during development will be highlighted.

3.1 Subsystem Design

For the development of the overall platform, the primary tasks were split into three subsystems: Mechanical Design, Electrical Design and Software.

3.1.1 Mechanical Design

For the joints, three different concepts were tested, each of which was prototyped and evaluated to determine the most suitable design. The initial goal was to use joints that relied solely on the 3D printed structure for functionality, avoiding the use of screws. This approach is illustrated in Figure 3.1.

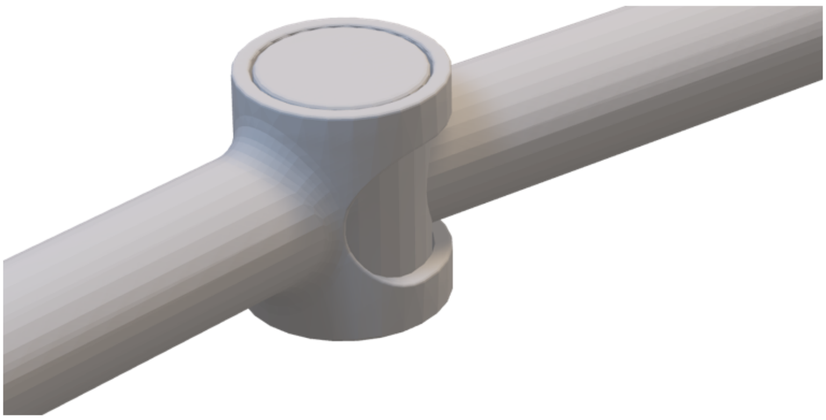

Figure 3.1: Initial joint system

The primary drawback of the initial design was the limited range of motion, which only reached a maximum of +45 degrees. This limitation was caused by geometric constraints of the printed structure. Additionally, the play inherent in the design, caused by manufacturing tolerances, could not be completely eliminated without compromising the ability of the layers to move independently.

To address these issues, a second joint concept was developed, as shown in Figure 3.2. This design aimed to increase the range of motion and reduce the play in the joints. While it showed some improvements, challenges remained with achieving sufficient stability and precision solely through the printed components.

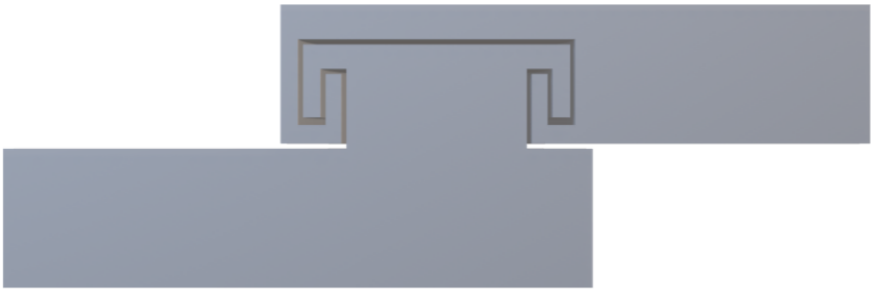

Figure 3.2: Second joint system

The final joint design, shown in Figure 3.3, incorporated a central screw as a connecting element. This solution allowed for a significant improvement in both stability and range of motion. To minimize radial play, two concentric circular components were integrated into the structure. These elements stabilized the joint while retaining the necessary flexibility for movement. Furthermore, the use of screws was kept to a minimum to maintain simplicity.

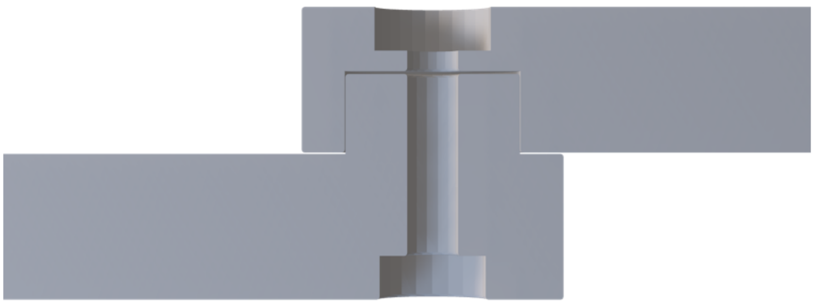

Figure 3.3: Final joint system

This final solution successfully balanced the competing requirements of range of motion, stability, and manufacturing constraints, providing a robust and functional joint system.

3.1.2 Electrical Design

Stepper Motors

From an electrical system perspective, the most important component of the Stewart platform is the motors. They play an essential role in the functionality of the Stewart platform since they are responsible for controlling the movements of the legs as discussed above. Two primary criteria that were considered when selecting the motors is their signal response and their strength.

Both criteria are equally important for the proper operation of the Stewart platform. Firstly, the ability for the motor to quickly and accurately respond to external signals is a very important feature to have and the motor will need to be able to dynamically adjust the legs in response to the ball position. This is because the ball being balanced will be in constant motion on the top plate. In addition, the strength of the motor is another criteria to consider. In this project, the strength of the motors is defined as the amount of torque that the motor is capable of supplying. Since the arcylic top plate that the motors will be supporting has a non-negligible weight, the motors must be capable of supporting it both statically and dynamically.

Two types of motors were initially considered during the preliminary stages of this project, stepper and servo motors. Stepper motors function by discrete steps whereas servo motors use feedback loops [3]. From a performance perspective, a stepper motor performs exceptionally well at low-speed, capable of achieving high torque and accuracy [4]. In contrast, servo motors generally perform better at high speed conditions where they are capable of greater speeds and torques than stepper motors [3]. In addition, servo motors are able to perform more reliably and consistently than stepper motors, allowing it to achieve greater accuracies [3]. A stepper motor was initially considered for the stewart platform design. However, after comparing and analyzing the different charactersitics of these motors, it was concluded that servo motors are better suited for the Stewart platform. This is primarily because of servo motors' better performance at higher speeds which is a key criteria for motors. Therefore, it is important to select a motor that is not only capable of reaching higher speeds, but also perform consistently and accurately at high speed conditions. In addition, servo motors are capable of delivering higher torques than the stepper motors at higher speeds, which means they are able to support the arcylic plate much better during motion. As a result, servo motors were selected over the stepper motors due to their better performance at high speeds.

Another reason why servo motors were selected over stepper motors is they have better control than stepper motors. Servo motors allow for highly accurate and precise controls for its parameters such as angular precision and speed [5]. This is highly beneifical for the stewart platform project since it makes testing the motor much easier. In addition, this means the servo motors can be controlled more precisely, allowing them to perform more accurately.

After making the decision to use servo motors, the specific motor that was implemented into the stewart platform was then decided. The most important factor in that decision was the motor's ability to supply sufficient torque to manipulate the arcylic top plate.

An approximate estimation of the torque that the arcylic balancing is applying is first determined. This is illustrated by the free body diagram in figure 3.4.

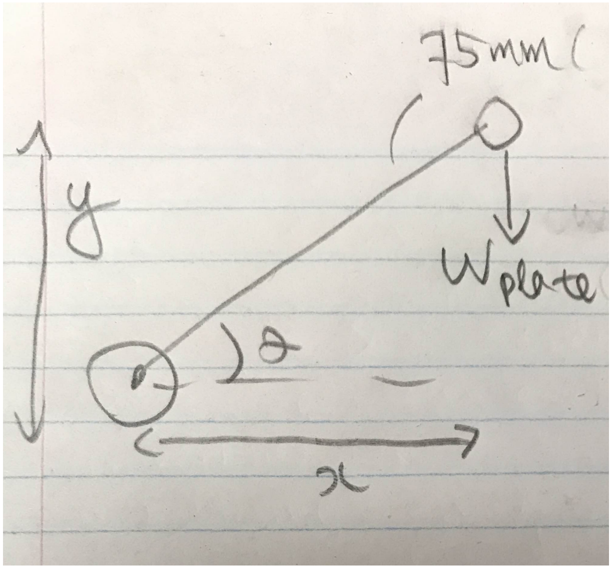

Figure 3.4: Free Body Diagram of a motor and plate

Calculations were then performed to determine the amount of torque being applied to the motors:

$$w_p = volume \times density \times gravity \tag{3.1}$$

Using this equation, the weight of the acrylic top plate can then be determined which is 5.15 N

Moment force that plate is applying on the motor:

$$T = 5.15 \times 0.075 \times cos(45) = 0.273Nm = 2.784kg/cm \tag{3.2}$$

Note: The torque calculated above represents the torque that the acrylic plate is applying to all three motors. Using the results from the torque calculations, a servo motor can then be selected. The initial choice of servo motor is the MG 995 servo motor obtained from the MTE design studio. The motor is shown in figure 3.5.

Figure 3.5: MG995 Servo Motor [6]

According to the data sheet for this motor, it is capable of delivering a torque of 9.4 kg/cm at 4.8V and a torque of 11 kg/cm at 6V [6]. This would theoretically allow the MG995 servo motor to supply enough torque to control the top plate. Shown in figure 3.6 is a more detailed data sheet of the MG955 servo motor. However, it was quickly discovered

Speed (4.8V/6.0V):	0.20 / 0.16 sec @ 60 deg
Torque kg/cm (4.8V/6.0V):	9.4 / 11
Max. Voltage:	6.0V
Current (Idle/No Load/Stall):	10mA / 170mA / 1200mA
Size (mm):	40.7 x 19.7 x 42.9
Mass (g):	55g
Gear Type:	Metal

Figure 3.6: Data sheet of the MG955 motor [6]

that the MG995 motor is unable to supply sufficient torque to move the acrylic top plate in practice. The most plausible reason for this was friction produced by the leg joints, especially the ball joint used to connect the legs to the platform. Friction produced by the leg joints will then translate into torque, which meant the actual torque required to move the plate was much higher than the calculations suggested.

A new servo motor was selected to replace the MG995 servo motors. The motor selected was the Stemedu 40K digital servo motor as shown in figure 3.7.

The data sheet for this motor is displayed in figure 3.8.

Figure 3.7: Stemedu 40k digital motor [7]

Control Angle	270 degree
Stall Torque (at 5V)	36 kg/cm
Stall Torque (at 6.8V)	45 kg/cm
Speed	0.20 sec/60°(5V) / 0.17 sec/60°(6.8V)
Operating Voltage	4.8 ~ 6.8V
Working frequence	1520μs / 334hz
Control System	PWM(Pulse width modification)
Pulse width range	500 ~ 2500μsec
Rotating direction	Counterclockwise (when 500 ~ 2500 μsec)
Neutral position	1500μsec
Running degree	270° (When from 500 - 2500μsec)
Dead band width	3 μsec
Motor Type	DC Motor
Gear Type	Copper & Aluminum
Shell Material	CNC Aluminum

Figure 3.8: Stemedu 40k digital motor technical specification [7]

The Stemedu 40k motor was selected because it can supply significantly greater of torque compared to the MG995 motor, which can be determined by analyzing their respective data sheets in figures 3.6 and 3.8. In addition, its other specifications such as its speed and its dimensions are nearly identical to the MG995 motor. This gives it a major advantage to some of the others designs that were being considered since it can be directly implemented into the design without requiring any adjustments. Testing was performed on this new motor and it was capable of delivering enough torque to not only drive the stewart platform, but also manipulate it quickly and accurately. This motor was therefore selected to be used in the Stewart platform.

Power System Design

To select the power supply, the required voltage of the servos was first noted as 5V. This is within the range of voltages that drive the selected servos and is a common voltage for power supplies to provide.

Next, a representative current draw had to be determined. Since the servos do not have their typical current draw documented, an experimental setup was created to test for it. A variable DC power supply was connected in series with a multimeter and the servos. By executing move commands on all three servos simultaneously, a maximum current draw of 6.18 A was recorded. This translates to an approximate 2 A typical current draw for each servo.

With both the voltage and current requirements for the servos understood, a 5 V and 10 A laptop charger was selected to power the servos. This charger was easily available from the MME workshop and exceeded our current requirements as a safeguard against sudden current spikes such as startup or stall current draws.

Summary Electrical Layout

With all the electrical components selected and fully understood, a summary electrical diagram could be created, as seen in 3.9:

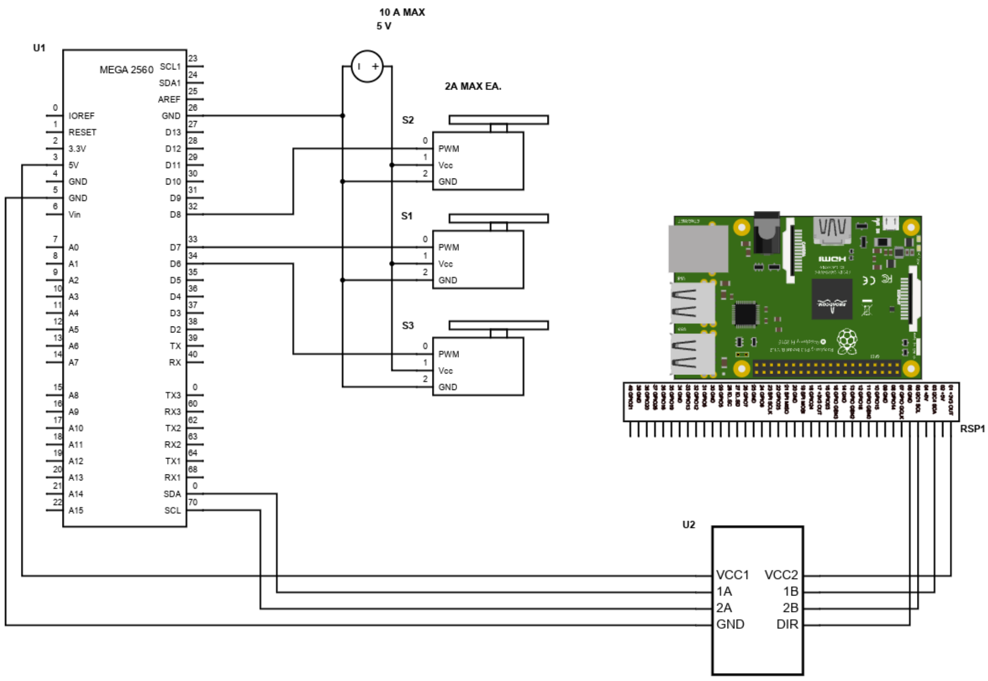

Figure 3.9: The electrical diagram showing power and signal wiring.

3.1.3 Software

Kinematic Calculations

Inverse kinematics were used to determine the necessary motor angles pertaining to tilts of the platform. To effectively control the motors, the calculation of the resultant platform tilt was paramount.

A reference axis was placed at the centre of the platform, aligning the connection of motor one with the positive x axis. This placed motor two and motor three 120° and 240° respectively from the positive x axis. With this reference, equations for the line that each connection lied on were found.

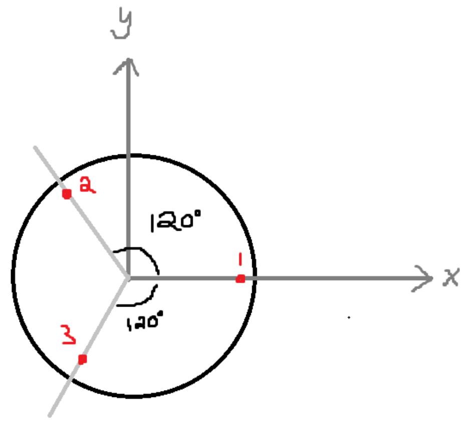

Figure 3.10: Reference Circle

$$\begin{aligned} y_1 &= 0 \\ y_2 &= -\sqrt{3}x_2 \\ y_3 &= \sqrt{3}x_3 \end{aligned} \tag{3.3}$$

Another assumption made that was key to the system set up was the centre of the platform, (0,0,h) where h was the height of the platform, would remain static during the balancing process. This allowed for the development of the equation of the plane corresponding to the surface of the platform.

$$n_x(x) + n_y(y) + n_z(z-h) = 0 \tag{3.4}$$

Where $< n_x, n_y, n_z >$ was the normal unit vector of the platform surface. The last set of equations were for relating the distance of the connections to the centre of the platform to the changes in their x, y, and z coordinates. As motor one's connection lied along the x axis, there were not any possible changes in its y coordinate. For motor two and three, this was not the case, so the distance perpendicular to the z axis would be a function of both the x and y coordinate. The differences between x and y coordinates could be grouped together as the radial distance r. As such, the following equations were made.

$$L^2 = (x_1)^2 + (h - z_1)^2 \tag{3.5}$$

$$L^2 = (x_2^2 + y_2^2) + (h - z_2)^2 \tag{3.6}$$

$$L^2 = (x_3^2 + y_3^2) + (h - z_3)^2 \tag{3.7}$$

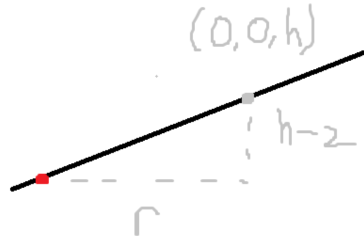

Figure 3.11: Distance Triangle

Where L was the predefined distance along the surface between the centre of the platform and each connection.

By combining the line and distance equations of each motor with the surface equation, a set of equations for each motor connection was created.

$$\begin{array}{rl} n_x(x_1) + n_z(z_1 - h) = 0 & L^2 = (x_1)^2 + (h - z_1)^2 \\ \left(n_x - \sqrt{3}n_y\right)(x_2) + n_z(z_2 - h) = 0 & L^2 = (4x_2^2) + (h - z_2)^2 \\ \left(n_x + \sqrt{3}n_y\right)(x_3) + n_z(z_3 - h) = 0 & L^2 = (4x_3^2) + (h - z_3)^2 \end{array} \tag{3.8}$$

By passing each set of equations through an equation solver, the x and z coordinate of each motor's connection could be found, with the y coordinate coming from the line equations.

Once the position of each connection was determined, the corresponding motor angle had to be found. By using L_1 and L_2, being the lengths of the links, and the cosine law, the inner angle α for each set of links could be calculated. The total angle γ could be found by using the difference in z coordinates and the radial distance between the location of the motor and the connection. By subtracting α from γ, the motor angle θ could be determined.

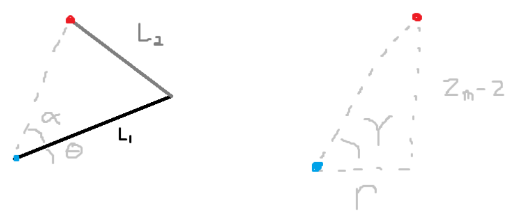

Figure 3.12: Angle Triangles

With this, by taking a unit normal, the required motor angles to get the platform to that position could be calculated.

Kinematic Implementations

The kinematic calculations were originally fully integrated into the main program, using the sympy library's equation solver functions to find the x and z coordinates via the defined equations. During initial testing of the accuracy, it was noted that angles the program calculated were correct. At the time, any testing of the processing time was ignored, and the calculations were left as they were.

After the rest of the programs systems were implemented, the response time of the system was observed to be incredibly slow, taking upwards of a second to respond to changes in the tracked position. The program was debugged, with timers put in place around major functions to highlight what was slowing everything down. It was found that each equation solution took around 110 milliseconds, which stacked up and was further slowed by the remaining calculations.

The solution developed was to move all the calculations to a separate program, which would then run through a set of possible positions of the platform. In result, a table containing the corresponding inputs and required motor angles was produced. This table replaced the calculations in the program, such that the program would simply reference the table for any motor angles. The input was initially the x and y position of the ball as read by the CV system, but this was later adjusted to instead be α and β (the tilts along x and y) as the PID controller was implemented.

Controller Design

For the design, the desired output of the controller was a unit normal that dictated the tilt and direction of the platform. This is due to how the kinematic equations are set up, as they take a normal vector and a platform height to generate the required motor angles.

Initially, an attempt was made to use the position of the ball directly to compute a normal vector. This was achieved by generating a "ghost point" opposite of the ball around the goal position. This point then became the head of a vector with a base at the origin. By scaling the z component of this vector before normalization, it was thought effective ball control could be achieved. The diagram below shows how the normal vector was constructed with this method.

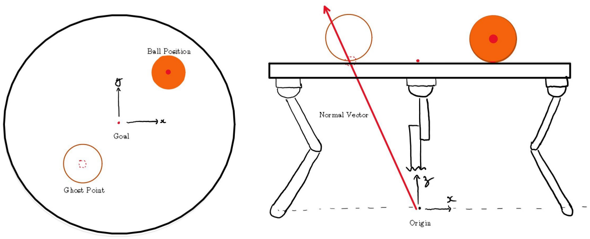

Figure 3.13: Diagram showing how the normal vector is determined from the ghost point.

Unfortunately, this method had two main issues. The first issue involved finding the correct scaling factor used on the z-component of the normal vector before normalization. This was done to indirectly achieve control over the magnitude of the tilt of the platform. Another issue involved correctly accounting for the momentum of the ball. Due to how the normal vector is constructed, it was impossible to account for the motion of the ball, since a ball at the goal will result in a flat platform.

The second controller design explored was a PID controller. Instead, the ball position and the goal position are fed directly into the controller. It would then use the controller constants set for the proportional, derivative and integral components of the error to compute an angle along the x-z and y-z planes. These angles could be turned into a normal vector using the following equations:

$$\begin{aligned} \hat{u_1} &= \cos(\alpha)\hat{\imath} + \sin(\alpha)\hat{k} \\ \hat{u_2} &= \cos(\beta)\hat{\jmath} + \sin(\beta)\hat{k} \\ \hat{n} &= \frac{\hat{u_1} \times \hat{u_2}}{\|\hat{u_1} \times \hat{u_2}\|} \end{aligned} \tag{3.9}$$

Where α and β are the tilt angles from the PID in the x-z and y-z plane, $\hat{u_1}$ and $\hat{u_2}$ were the unit vectors constructed from the tilt angles, and $\hat{n}$ is the unit normal vector.

This controller design allowed more control over the tilt angles by varying the controller constants. In addition, due to the derivative component of the controller, there was now a way to account for the momentum of the ball. Finally, the controller could now be tuned multiple times for the different balls to be balanced.

Ball Detection

OpenCV was used in this project to track the position of the ping pong and golf balls being balanced by the platform. The code followed a similar process to the one outline in the workshops provided at the beginning of the course. Upper and lower ranges for each ball were found, with the range for the golf ball using HSV and the range for the ping pong ball using RGB. This was because the color of the golf ball lined up perfectly with the one used in the workshop. But when varying values in attempt to find the range for the ping pong ball, it was determined to be too difficult to do so freely as the ping pong ball had a much wider spectrum. So in place of using the HSV method, reading the RGB values from the CV camera view proved to be more accurate.

With the ranges for each ball, the next step was to set a minimum radius. As the CV was very sensitive, it could find miniscule appearances of the color ranges. To work around this, setting a minimum size of said appearances limited the detection to useful data. The CV would create a circle around whatever it found, and if the radius of that circle was not large enough, it was disregarded. Once the CV found something that matched the colors and was large enough, the x,y position of the centre of the circle would be determined and have half the width and height of the camera view removed from it. This would make it so that the centre would be the point 0,0.

This x,y coordinate of the centre would be used by other functions as the position of the ball on the platform. For some other calculations that worked in cm instead of the pixel scale of the camera, a function to convert from pixel to cm was created. This would multiply each coordinate by the radius of the platform and divided by half the width and height respectively.

In the latest iteration of the software, the centre of the ball during the start up of the sytem was used as a reference for the centre of the platform. As the camera mount used was unreliable, setting a reference for the centre of the platform was useful to account for any misalignments. Finding this reference point used the same functions to find the ball.

Driving the Actuators

To drive the selected servo, the Arduino MEGA 2560 board was selected. This board was readily available in the kit provided and allowed sending PWM signals directly to the servos for control. This presented the added challenge of sending the motor angles from the Raspberry Pi to another controller. I^2C communication was selected as both boards have dedicated pins for this protocol.

One implementation issue encountered was a library conflict between "Wire.h" and "Servo.h", the first servo library used. When I^2C communications took place, the "Wire.h" library could randomly disable the timer used for the PWM signals sent by the "Servo.h" library. This led to undefined behaviour while controlling the servos, such as jerky, random motion in the servos. To solve this issue, a different servo library called "Servo_Hardware_PWM.h" was used which utilized a different timer than the one disabled by "Wire.h". This ensured the PWM signals would not be interrupted and overall led to smoother servo control.

Control Loop

The following steps show how each of these software components came together to balance the ball. During each frame captured by the camera, the following occured:

1. The frame was taken from the camera's video buffer by the Raspberry Pi.
2. Open CV was used to pick out the ball from the image and return its position relative to the camera.
3. The ball position and the goal were fed into the PID controller. The controller then produced two angles for the platform, one along the x-z plane and another in the y-z plane.
4. The platform tilt angles generated by the PID controller were converted into motor angles using the lookup table generated prior to running the control algorithm.
5. The motor angles were transmitted via I^2C to the Arduino, where they were written to the servo motors.

3.2 Additive Manufacturing

For the manufacturing of the components, 3D printing was exclusively used due to its quick availability. With the right parameters, it is possible to achieve very high rigidity. The following describes how high rigidity was achieved by adjusting slicer parameters.

1. The material used had a higher elongation at break compared to standard PLA. For all mechanically stressed components, PETG was chosen because it offers higher elongation at break and better durability while maintaining similar strength to conventional PLA.

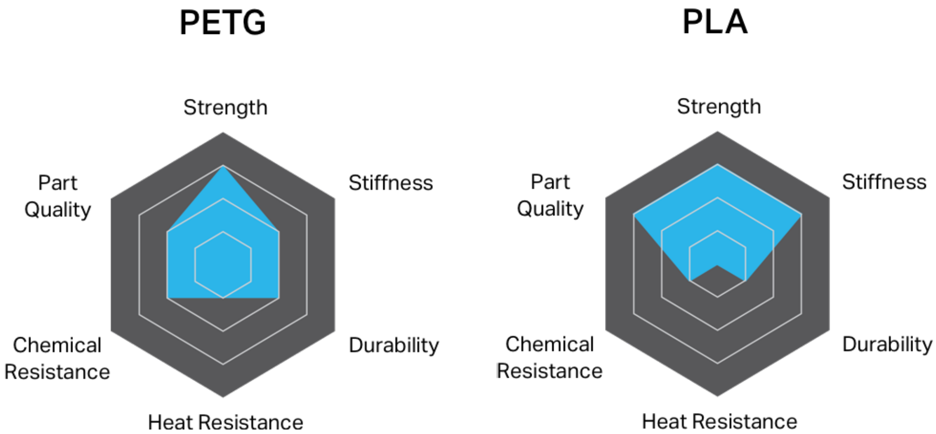

Figure 3.14: Comparison of PLA and PETG[8]

2. The infill value, which determines how much material is added between the outer layers, was set to 80% for mechanically stressed parts such as legs and joints. A higher infill value increases rigidity and durability but also adds weight.

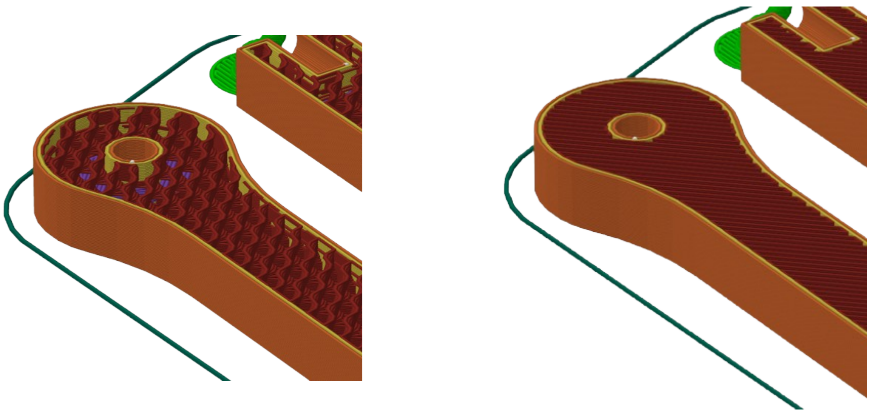

Figure 3.15: Left: Initial infill at 25%. Right: Adjusted infill at 80%.

3. The number of outer layers was increased, meaning more continuous layers were printed along the edges. This significantly enhances the rigidity of the components.

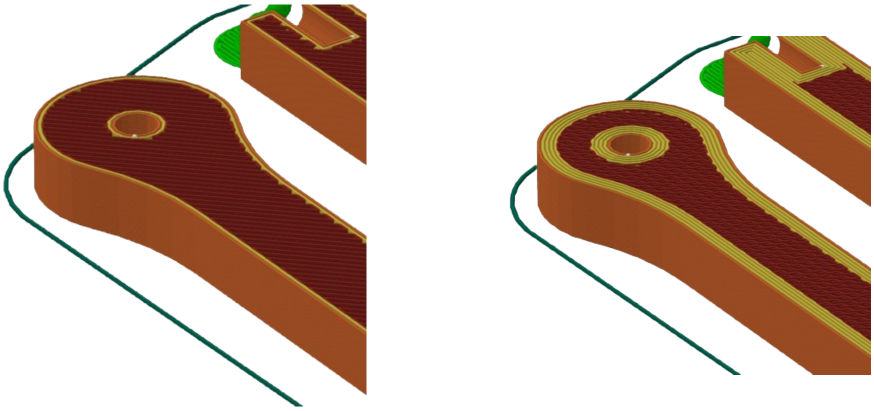

Figure 3.16: Left: Single wall loop. Right: Three wall loops for enhanced rigidity.

4. The alternate extra wall option was enabled in the slicer. This connects the infill to the inner layers of the outer wall on every second layer. This direct connection between the infill and the outer wall further increases stability.

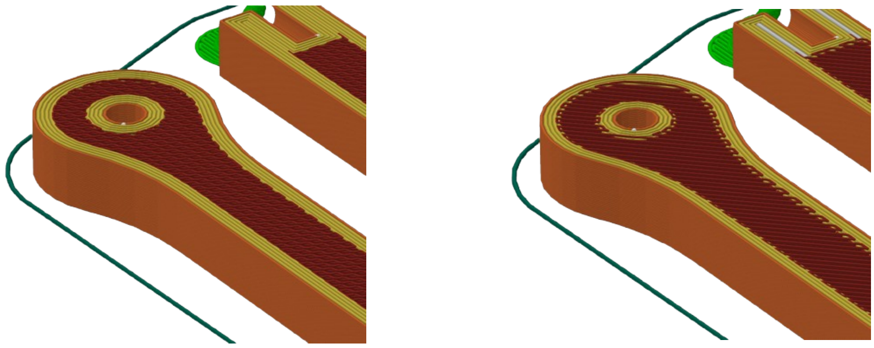

Figure 3.17: Left: Alternate extra wall disabled. Right: Alternate extra wall enabled.

The combination of material selection (PETG), increased infill, additional outer layers, and the alternate extra wall option provided very high rigidity with only moderate additional costs in 3D printing.

3.3 Cost Breakdown

To ensure the project fits within the allocated budget of 150 C$, a detailed cost analysis was conducted.

Mechanically, the project is relatively cost-effective compared to other solutions. Since 3D printing is inexpensive and the CAD design was already finalized, the costs can be accurately estimated based on the weight of the components as calculated in a slicer. With the RPC charging 0.1 C$ per gram, the cost for 3D printing was determined as follows:

$$\begin{aligned} \text{priceServo} &= (m_{\text{platform}} + m_{\text{legs}} + m_{\text{balljoints}}) \times \text{priceGramm} \\ &= (180\,\text{g} + 80\,\text{g} + 25\,\text{g}) \times 0.1\,\text{C\$} \\ &= 28.5\,\text{C\$} \end{aligned} \tag{3.10}$$

Additionally, a fixed cost of 30 C$ was incurred for laser-cutting the top plate.

Electrically, the project was more expensive than initially expected due to issues with the first set of servo motors, which led to the purchase of new high-torque servo motors. Each motor cost 24.50 C$, and as the design requires three motors, the total cost is:

$$\begin{aligned} \text{priceServo} &= 3 \times 24.50\,\text{C\$} \\ &= 73.50\,\text{C\$} \end{aligned} \tag{3.11}$$

Screws and a small circuit board required for the servo motors added another 10 C$.

The breakdown of costs is summarized in Table 3.1.

Table 3.1: Project Cost Breakdown

Component	**Cost per Unit**	**Quantity**	**Total Cost**
3D Printed Parts	0.1C$ per gram	285g	28.50C$
Laser-Cut Top Plate	Fixed cost	1	30.00C$
Servo Motors	24.50C$	3	73.50C$
Screws and Circuit Board	Fixed cost	-	10.00C$
Total			**142.00C$**

As shown in Table 3.1, the total project cost is 142 C$, leaving us with a remaining budget of 8 C$. Therefore, the project is financially feasible.

3.4 Design Review

Harkening back to the objectives outlined at the beginning of the project, almost all of them were met. The platform was able to balance a ping pong, and golf ball for more than a minute, and was able to move the ping pong ball on a set path. Where the design failed to meet objectives was with missing the balancing of the steel ball, and not being able to complete a circular path with the ping pong ball.

The platform remained within the dimension constraints of 30 by 30 cm plus or minus 5 cm, with the final design having a radius of 15 cm. The mechanical strength of each of the components were sufficient to withstand the various loads applied to the system. The total cost of the design was $142 which fit within the budget of $150.

It was expected that the design would only just meet the requirements for balancing time, that being 15 seconds. However, some additional hours tuning the PID during the final week of developement pushed the balancing time to upwards of 4 minutes, outside of excessive force application to the ball. Even after extensive testing, there was no visible wear or damage to the mechanical components, outside of the camera mount which was damaged during transportation and assembly.

Overall, the design developed met most of the objectives and constraints, resulting in a mechanically strong, and long-balancing platform that exceeded expectations.

4 Conclusions

The goal for this project was to create a Stewart platform which balances balls of varying weight for at least 15 seconds while being able to guide said balls along a circular trajectory, and the platform must maintain the balance of the balls after the introduction of physical disturbances. The platform developed in this project used 3D printed PETG plastic and laser cut acrylic for its construction paired with servo motors. The control system leveraged a look-up table to improve the reaction speed of the platform paired with a PID controller to balance the ball based on the input from the computer vision system. As stated in the design review, the Stewart platform developed in this project far exceeded the goal for balancing time with both the ping pong ball and the golf ball. The platform could only create a line trajectory and was not able to balance a steel ball, but this project can nonetheless be considered highly successful because the only targets which were missed was a stretch goal and the most ambitious aspect of the primary goal for this project.

If given the opportunity to do this project again, there are several lessons learned which would alter the approach for designing the platform. The first lesson is to be skeptical of seemingly easy paths compared to the conventional method and applying this lesson during the project lifecycle would have prevented the control system from initially taking the wrong approach with the "ghost point" method. The second lesson is to expect to need multiple design iterations and embrace failing early and often instead of having a perfect solution right away. Embracing an iterative design process to a greater extent would have made the early stages of the project much more efficient and prevented overthinking key design decisions. Similarly, the final lesson is to always start sooner when the opportunity arises, even when other priorities feel urgent. Getting a more aggressive start to the project would have created a larger time window at the end of the project to potentially achieve the most ambitious goals for this project.

The recommendation for future years of this project would be to provide more information on good manufacturing practices with various methods such as machining and 3D printing. The reason for this recommendation is there was a clear distinction between groups where members were heavily involved in design teams and groups where members were not in terms of knowledge of manufacturing concepts going into the course. Providing additional instruction on manufacturing and mechanical design or a workshop which focused on those skills could help reduce that knowledge gap between the groups. This would allow groups without significant design team experience to get a similar running start at the project to groups who had more experience from design teams.

5 Division of Work

The following is a final list of who contributed what to the success of the project:

- **Aidan Landry** developed the kinematic model used to determine the motor angles required, implemented the CV, and put together the majority of the code utilized by the system during runtime and the data table generation.
- **Marvin Bullinger** developed the mechanical design, especially the legs, bearings, and joints of the system. He also took over the complete production of the system (3D printing and soldering tasks). Marvin always helped troubleshooting, for example with the final steps in the development of the PID controller or the idea to set up a lookup table.
- **Leo Xing** was involved in the mechanical design of the Stewart platform, such as the top and baseplates. He was also involved in creating CAD models for the components and creating the final CAD assembly.
- **Luke Johnston** performed project management duties for the group such as placing parts orders and creating the timeline for the project. Additionally, worked on the mechanical design as well as the CAD modelling and fabrication of components for the Stewart platform.
- **Gavin Grimm** developed the control code used by the Arduino and implemented the I^2C communication between the Raspberry Pi (RPi) and Arduino controllers.

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