**Abstract:**

A “Ball Balancing Platform” is a dynamic control system that is designed to stabilize a ball by adjusting the orientation of the platform. A 4-wire resistive touchpad is used as the platform to obtain position feedback. The platform is mounted on a 3RRS (Revolute-Revolute-Spherical) parallel manipulator to control the orientation of the platform. A PID (Proportional-Integral-Derivative) controller is used to maintain the ball at a target position by constantly adjusting the platform’s angle based on the displacement. The main objective of the thesis is to study control strategies, electronics, inverse kinematics, sensor integration and system modelling.

**Streszczenie:**

“Platforma do balansowania kulką” to dynamiczny system sterowania, który ma za zadanie stabilizować kulkę poprzez dostosowywanie orientacji platformy. Do uzyskania informacji o pozycji wykorzystuje się 4-przewodową rezystancyjną nakładkę dotykową. Platforma jest zamontowana na równoległym manipulatorze o 3 stopniach swobody (3 DOF), który kontroluje jej orientację. Regulator PID (proporcjonalno-całkująco-różniczkujący) jest używany do utrzymania kulki w wybranej pozycji, stale dostosowując kąt platformy na podstawie przemieszczenia kulki. Głównym celem pracy jest zbadanie strategii sterowania, elektroniki, kinematyki odwrotnej, integracji czujników oraz modelowania systemu.

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# Introduction

“Ball balancing platform” is a unique engineering problem that requires combining mechanical design, electronics, and advanced control algorithms. The aim of the project is to design and build a platform that can balance a spherical metal ball at a pre-defined point by tilting the platform to counteract external forces.

The interdisciplinary nature of this project inspired me to pursue it. The integration of mechanics, electronics, and control theory makes it an ideal dissertation topic for Mechatronics. Traditionally a stereo camera is used to capture images and use image processing techniques to obtain position feedback. However, in this project a resistive touchpad is used to obtain position feedback. This is more versatile and accurate than the former method.

The practical applications of such a control algorithm extends to various fields, including but not limited to Robotics, Aerospace and Industrial Automation.

A blue and yellow robotic device

Description automatically generated

Figure 1.1 CAD Model of a ball balancing platform

In addition to building the physical prototype a MATLAB Simulink model will be used to simulate the same. This can be helpful in ensuring the validity of the inverse kinematics model and PID controller.

# Project objectives and requirements

This chapter outlines the objectives of the project in a systematic order of implementation. There are some research-oriented objectives as well for which the results cannot be anticipated in advance and thus may not have been defined in the list. Requirements for both hardware and software development are listed as well.

## Project Objectives

Due to the interdisciplinary nature of the project, the implementation has been divided into three sections:

## Requirements

### Electronics

1. [Maker Uno Microcontroller](https://www.amazon.com/PJRC-Cortex-M7-Processor-iMXRT1062-Without/dp/B088JY7P2H/ref=sr_1_4?crid=36CI81XOWM0Z0&keywords=teensy+4.1&qid=1677474562&s=electronics&sprefix=teensy+4.1%2Celectronics%2C139&sr=1-4)
2. [Nema 17 59 Ncm Stepper Motors (Bipolar)](https://www.amazon.com/dp/B00PNEQKC0?psc=1&ref=ppx_yo2ov_dt_b_product_details)
3. [TMC2209 V2.0 Stepper Motor Drivers](https://www.amazon.com/dp/B082LSQWZF?psc=1&ref=ppx_yo2ov_dt_b_product_details)
4. [CNC](https://www.amazon.com/gp/product/B08BWPGSSC/ref=ppx_yo_dt_b_search_asin_title?ie=UTF8&psc=1) shield
5. [100uF Capacitor 35V](https://www.amazon.com/dp/B07Y3F194W?psc=1&ref=ppx_yo2ov_dt_b_product_details)
6. [Male and Female Header Pins](https://www.amazon.com/Honbay-Single-Female-Connector-Arduino/dp/B06Y4S6G29/ref=sr_1_8?crid=1W7J1GV4G3XE3&keywords=header+pins&qid=1677475169&s=electronics&sprefix=header+pin%2Celectronics%2C144&sr=1-8)
7. [30V Bench Power Supply](https://www.amazon.com/gp/product/B082FV1PGP/ref=ppx_yo_dt_b_search_asin_title?ie=UTF8&psc=1) (or any 24V power supply)
8. [22 AWG Wire](https://www.amazon.com/gp/product/B01LH1FR6M/ref=ppx_yo_dt_b_search_asin_title?ie=UTF8&psc=1)
9. [5V Regulator](https://www.amazon.com/Weewooday-Regulator-Voltage-Converter-Transformer/dp/B08JZ5FVLC/ref=sr_1_2_sspa?crid=28M4EAWMIWBMT&keywords=5v+regulator&qid=1684300783&sprefix=5v+regulator%2Caps%2C198&sr=8-2-spons&psc=1&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUExSThTTFJLVFozQ0hKJmVuY3J5cHRlZElkPUExMDMyNTI2WEZWTUZFWkhZQVNNJmVuY3J5cHRlZEFkSWQ9QTAxNTE0MDUyUVZGRzBRTkxZMUpBJndpZGdldE5hbWU9c3BfYXRmJmFjdGlvbj1jbGlja1JlZGlyZWN0JmRvTm90TG9nQ2xpY2s9dHJ1ZQ==)

### General Parts

1. [8.4" 4 Wire Resistive Touch Panel](https://www.amazon.com/dp/B07TZGVY8K?psc=1&ref=ppx_yo2ov_dt_b_product_details)
2. [1" Steel Bearing Ball](https://www.amazon.com/dp/B07CHZ94W9?psc=1&ref=ppx_yo2ov_dt_b_product_details)
3. [22mm long m3 tie rod](https://www.amazon.com/dp/B09JLKLK73?psc=1&ref=ppx_yo2ov_dt_b_product_details)
4. [m3 x 6mm threaded inserts](https://www.amazon.com/dp/B07LBQRYR3?psc=1&ref=ppx_yo2ov_dt_b_product_details)
5. [M3 x 5mm Standoffs](https://www.amazon.com/dp/B07M7D9PRM?psc=1&ref=ppx_yo2ov_dt_b_product_details)
6. [M3 x 5mm Screws](https://www.amazon.com/Dahszhi-Phillips-Machine-Metric-Thread/dp/B099ZK3NK9/ref=sr_1_5?crid=18J5PGUV1ZTGU&keywords=m3%2Bx%2B5mm%2Bscrews&qid=1681514624&sprefix=m3%2Bx%2B5mm%2Bscrews%2Caps%2C110&sr=8-5&th=1)
7. [M3 x 8mm Screws](https://www.amazon.com/Socket-Screws-Metric-Stainless-Machine/dp/B07NSW9RBQ/ref=sr_1_6?crid=3EDVNS6LIQKI2&keywords=m3+x+8mm+screws&qid=1677476973&sprefix=m3+x+8mm+screw%2Caps%2C93&sr=8-6)
8. [M3 x 10mm Screws](https://www.amazon.com/Socket-Screws-Metric-Stainless-Machine/dp/B0BJ1V4FKY/ref=sr_1_6?crid=3EDVNS6LIQKI2&keywords=m3%2Bx%2B8mm%2Bscrews&qid=1677476973&sprefix=m3%2Bx%2B8mm%2Bscrew%2Caps%2C93&sr=8-6&th=1)
9. [M3 x 35mm Screws](https://www.amazon.com/M3-0-5x35mm-Stainless-Machine-Eastlo-Fastener/dp/B07X2Q33NW/ref=sr_1_19?crid=A5V6SF3S5SII&keywords=m3%2Bx%2B35mm%2Bscrews&qid=1681514731&sprefix=m3%2Bx%2B35mm%2Bscrews%2Caps%2C106&sr=8-19&th=1)
10. [M3 Nylon Locknuts](https://www.amazon.com/SpzcdZa-Stainless-Industrial-Construction-Fasteners/dp/B08LMQC765/ref=sr_1_1_sspa?crid=282O9LSLQ01JO&keywords=m3%2Block%2Bnuts&qid=1681514827&sprefix=m3%2Block%2Bnuts%2Caps%2C93&sr=8-1-spons&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEyTU1XQ09ESVpPWDFLJmVuY3J5cHRlZElkPUEwNzkyMTI5MUxaUlVaT1ZFVFdDRyZlbmNyeXB0ZWRBZElkPUExMDEzOTM5WURaQlZUUzNBV0k0JndpZGdldE5hbWU9c3BfYXRmJmFjdGlvbj1jbGlja1JlZGlyZWN0JmRvTm90TG9nQ2xpY2s9dHJ1ZQ&th=1)
11. [M4 x 20mm Screws](https://www.amazon.com/Socket-Screws-Metric-Stainless-Machine/dp/B07KRFQJK1/ref=sr_1_6?crid=3EDVNS6LIQKI2&keywords=m3%2Bx%2B8mm%2Bscrews&qid=1677476973&sprefix=m3%2Bx%2B8mm%2Bscrew%2Caps%2C93&sr=8-6&th=1)
12. [M4 x 25mm Screws](https://www.amazon.com/Socket-Screws-Metric-Stainless-Machine/dp/B07KRS36P2/ref=sr_1_6?crid=3EDVNS6LIQKI2&keywords=m3%2Bx%2B8mm%2Bscrews&qid=1677476973&sprefix=m3%2Bx%2B8mm%2Bscrew%2Caps%2C93&sr=8-6&th=1)
13. [M4 Nylon Locknuts](https://www.amazon.com/SpzcdZa-Stainless-Industrial-Construction-Fasteners/dp/B08LMNFS5P/ref=sr_1_1_sspa?keywords=m4%2Blocknuts&qid=1681514944&sr=8-1-spons&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEzRU5YVFhHV09QRFJUJmVuY3J5cHRlZElkPUEwMTIzODg3QlQ4SjVKVUcwVDFUJmVuY3J5cHRlZEFkSWQ9QTAzMTgzMDlGQUdMUDM5Vzc4TjImd2lkZ2V0TmFtZT1zcF9hdGYmYWN0aW9uPWNsaWNrUmVkaXJlY3QmZG9Ob3RMb2dDbGljaz10cnVl&th=1)

### Tools

1. needle nose pliers
2. wire cutters
3. wire strippers
4. 2.5mm allen wrench
5. soldering iron
6. exacto knife
7. hot glue gun

## Assumptions

This chapter constitutes the detailed list of assumptions made in work. As the Ball Balancing Platform is a demonstration built in a lab environment, the required assumptions are not very rigid. The following assumptions were made:

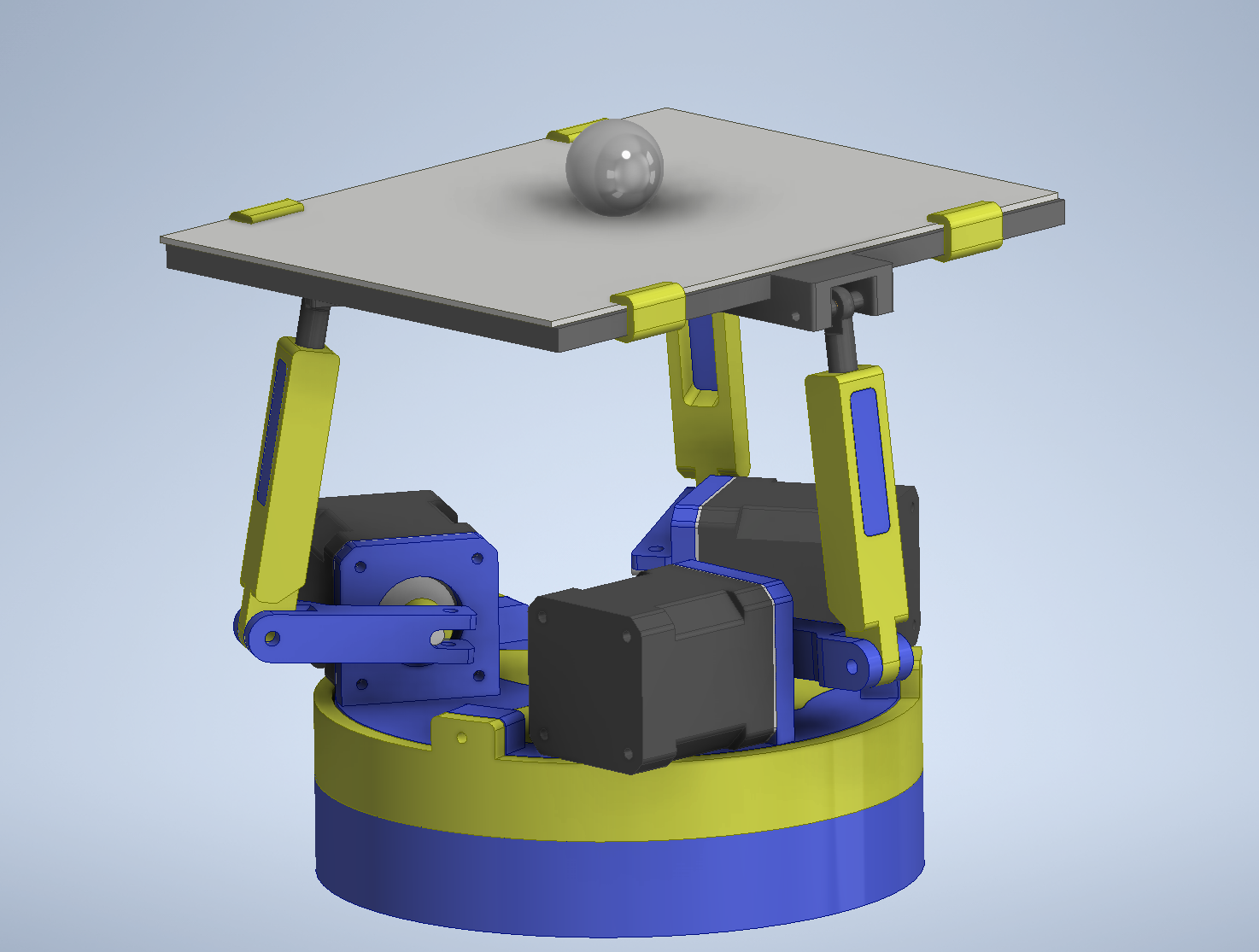
1. The platform’s operation is intended to be demonstrated in a lab environment.
2. A PID controller will be used primarily. Similar control strategies may be explored.
3. An Arduino UNO microcontroller will be used as the brain of the system. The selection was made due to its features like real time control, low latency and floating-point calculation.
4. Areas like control theory, microcontrollers, Mechanical design and kinematics were studied.

# Hardware - Mechanical

This section details the mechanical design, fabrication and testing of the 3RRS platform. The 3RRS platform has 3 degrees of freedom and 3 points of actuation. 3 stepper motors with TMC drives are used for precise actuation. Thanks to the KN-Humanoid club’s 3D printer - 3D printing was used to fabricate most of the structures.

## Mechanical Design

The chapter describes the mechanical design of the 3RRS parallel manipulator. The design is inspired by Aaed Musa’s Ball Balancing platform [[1]](#footnote-1) with modifications. The project is designed and fabricated as a demonstration and thus is not suitable for industrial applications.



4

2

3

5

6

1

Figure 3.1 Ball Balancer mechanical design (description below)

A metallic ball **1** is placed on a resistive touchpad **2** which outputs the position of the ball by detecting the contact point and returning it as a cartesian point. The platform is connected to the actuator legs with a spherical joint **3.** The actuator leg has two links connected by a revolute joint **5.** The lower leg is connected to the rotor of the stepper motor **6** with a revolute joint **4.**

## Inverse Kinematics

The inverse kinematics required to orient the platform according to the position of the ball is derived in this sub-chapter. The equations derived are then verified in MATLAB.

Given a unit normal vector of the platform plane, the IK equations than compute the required angles

A drawing of a triangle with lines and dots

Description automatically generated

Figure 3.2 Kinematic Diagram of the ball balancing platform

Table 3.1 Description of symbols in Figure 4.2

|  |  |  |
| --- | --- | --- |
| SYMBOL | DESCRIPTION | UNITS |
| O | Origin of the global co-ordinate system | [0,0,0] |
|  | The rotor angle that will be controlled | - |
|  | The revolute joint angles between the two links | radians |
| h | Distance between the platform plane and base plane | cm |
| l | Perpendicular distance between the steppers | cm |
|  | Length of the first link | cm |
|  | Length of the second link | cm |
|  | Unit normal vector of the top platform plane | - |
|  | The distance between the origin and steppers | cm |

### Deriving IK equations.

The system is divided into three separate kinematic chains. The origin for the global frame (O) is marked at the mid-point of the base plane. The mid-point of the platform plane is represented by .The required rotor angles is calculated as a function of tilt of the platform plane represented by and the height between the platforms represented by h.

|  |  |  |
| --- | --- | --- |
|  |  | () |

A diagram of a triangle with lines and points

Description automatically generated

Figure 3.3 Kinematic diagram for a single chain

Figure 4.2.2 represents one kinematic chain out of three. While the other chains are very similar, derivations will be performed individually. The derivation of the first chain is as follows.

**Equation for :**

|  |  |  |
| --- | --- | --- |
|  |  | () |

From the hypotenuse triangle marked blue in Fig 4.2.2,

|  |  |  |
| --- | --- | --- |
|  |  | () |

We have 2 equations (Eq. 2, Eq. 3) and 2 unknowns. Solving for we get:

|  |  |  |
| --- | --- | --- |
|  |  | () |
|  |  | () |

Equation 4 and Equation 5 describe the ball joints in terms of the Normal Vector and the height h. Next, the Link 1 will be described in terms of the ball joint’s position.

A diagram of a circle with lines and circles

Description automatically generated

Figure 3.4 Kinematics of Link 1 and Link 2

Let denote the position of the revolute joint of Link 1, The spherical joint and the revolute joint constitute a sphere of the equation:

|  |  |  |
| --- | --- | --- |
|  |  | () |

Where is the length of the Link 1.

Similarly let denote the position of the rotor. constitute a sphere of the following equation.

Where is the length of the Link 2. As the chain lies in the plane, . Also

Solving Equation 7:

|  |  |  |
| --- | --- | --- |
|  |  | () |

Solving Equation 6:

# Hardware – Electrical

The following chapter describes the electrical configuration of the project. The pinout diagrams and the general schematics are also described.

## Circuit Boards

### Arduino UNO

Maker UNO will be used instead of Arduino UNO. It has an identical pinout configuration as compared to Arduino UNO. The ease of use, versatile connectivity with ample IO ports and analogue ports, native programming IDE and real time control with low latency make it an ideal choice.

A blue circuit board with many wires

Description automatically generated

Figure 4.1 Arduino UNO pinout diagram. Maker UNO has an identical configuration.

Table 4.1 Maker UNO technical specification.

|  |  |
| --- | --- |
| **Category** | **Specification** |
| Microcontroller | ATmega328P |
| Operating Voltage | 5V |
| Input Voltage (Recommended) | 7V - 12V |
| Input Voltage (Limits) | 6V - 20V |
| Digital I/O Pins | 14 (of which 6 can be used as PWM outputs) |
| Analog Input Pins | 6 |
| DC Current per I/O Pin | 40 mA (recommended) |
| DC Current for 3.3V Pin | 50 mA |
| Flash Memory | 32 KB (ATmega328P) |
| SRAM | 2 KB |
| EEPROM | 1 KB |
| Clock Speed | 16 MHz |
| UART | 1 (Universal Asynchronous Receiver/Transmitter) |
| SPI | Yes |
| I2C | Yes |

### TMC2209 V2.0

The TMC2209 is known for its silent operation. Low noise levels, different micro stepping options, current control and low heat generation makes it an ideal choice to control the stepper motors. The is set using a potentiometer screw.

From the stepper documentation,

A black circuit board with many small screws and many small screws

Description automatically generated

Figure 4.2 TMC2209 stepper driver pinout diagram.

Table 4.2 TMC2209 Microstepping Configuration.

|  |  |  |
| --- | --- | --- |
| **MS1** | **MS2** | **Microstepping Mode** |
| Low | Low | Full Step (1x) |
| High | Low | Half Step (2x) |
| Low | High | Quarter Step (4x) |
| High | High | Eighth Step (8x) |

Table 4.3 TMC2209 technical specifications.

|  |  |
| --- | --- |
| **Specification** | **Value** |
| Operating Voltage (VM) | 4.75V to 29V DC |
| Output Current | 2.0A RMS, 2.4A Peak (per phase) |
| Microstepping Resolution | Full, Half, Quarter, Eighth, Sixteenth steps |
| PWM Frequency | Up to 28 kHz |
| Control Interface | UART (for advanced configuration) |
| Operating Temperature | -40°C to +150°C |

### CNC Shield

A CNC shield will be used instead of manually connecting the jumpers through a breadboard. The CNC shield has built in decoupling capacitors and integrates with Maker UNO seamlessly. Addition of CNC shield makes electrical management easy.

Micro stepping can be configured by

A circuit board with many components

Description automatically generated

Figure 4.3 CNC shield pinout diagram

Table 4.4 Cross-referencing of Arduino pins

|  |  |  |
| --- | --- | --- |
| Arduino Pin | CNC Shield Pin | Function |
| Pin 2 | X Step | Step signal for X-axis motor |
| Pin 3 | Y Step | Step signal for Y-axis motor |
| Pin 4 | Z Step | Step signal for Z-axis motor |
| Pin 5 | X Dir | Direction signal for X-axis motor |
| Pin 6 | Y Dir | Direction signal for Y-axis motor |
| Pin 7 | Z Dir | Direction signal for Z-axis motor |
| Pin 8 | Enable | Enable signal for X-axis motor |

In addition to the digital pins, analogue pins are also used. The resistive touchpad is connected to A0, A1, A2 and A3 pins shown in the schematics.

## Stepper Motor

NEMA 17 bi-polar stepper motors from STEPPERONLINE were used for the project. Cost-efficient, precise control, open-loop control and low noise makes it an ideal choice.

A black and silver square device

Description automatically generated

Figure 4.4 Nema 17 Bi-polar stepper motor.

A diagram of a wire

Description automatically generated

Figure 4.5 Nema 17 Stepper motor dimensions

Table 4.5 Nema 17 technical specifications

|  |  |
| --- | --- |
| **Property** | **Value** |
| Inductance (mH) | 4.0 |
| Phase Resistance (ohms) | 2.3 |
| Rated Current (A) | 1.5 |
| Step Angle (deg.) | 1.8 |
| Bipolar/Unipolar | Bipolar |
| Holding Torque (Ncm) | 42 |
| Holding Torque (oz.in) | 59.49 |
| Frame Size (mm) | Nema 17 (42 x 42) |
| IP Rating | 40 |
| Output Shaft Type | D |
| Shaft Diameter (mm) | 5 |
| Shaft Length (mm) | 23.5 |
| Product Series | E |
| Body Length (mm) | 38 |
| Single Shaft/Dual Shaft | Single Shaft |
| No. of Lead | 4 |
| Lead Length (mm) | 1000 |

## Resistive touchpad

1. https://www.youtube.com/watch?v=v4F-cGDGiEw [↑](#footnote-ref-1)