Høgskulen på Vestlandet

Bacheloroppgave

ELE350

Predefinert informasjon

Startdato:	08-05-2023 09:00 CEST	**Termin:**	2023 VÅR
Sluttdato:	22-05-2023 14:00 CEST	**Vurderingsform:**	Norsk 6-trinns skala (A-F)
Eksamensform:	Bacheloroppgave		
Flowkode:	203 ELE350 1 O 2023 VÅR		
Intern sensor:	Knut Øvsthus		

Deltaker

Navn:	Marte Utkilen
Kandidatnr.:	306
HVL-id:	586624@hvl.no

Informasjon fra deltaker

Egenerklæring *:	Ja
Inneholder besvarelsen konfidensielt materiale?:	Nei
Jeg bekrefter at jeg har registrert oppgavetittelen på norsk og engelsk i StudentWeb og vet at denne vil stå på vitnemålet mitt *:	Ja

Gruppe

Gruppenavn:	BO23EB-16
Gruppenummer:	52
Andre medlemmer i gruppen:	Sondre Espeland

Jeg godkjenner avtalen om publisering av bacheloroppgaven min *

Ja

Er bacheloroppgaven skrevet som del av et større forskningsprosjekt ved HVL? *

Nei

BACHELOR’S THESIS

Stewart Platform Control

Marte Utkilen
Sondre Espeland

Bachelor’s thesis in Software Engineering at

Department of Computer science, Electrical engineering and Mathematical sciences,
Western Norway University of Applied Sciences

May 22, 2023

Preface

This report is written in connection with our final bachelor's thesis at Western Norway University of Applied Science (HVL), Bergen Campus, in the spring of 2023. The project involved modifying a Stewart Platform and further developing the software code. The platform will be used in a PhD project at the Department of Mechanical and Marine Engineering at HVL.

We would like to thank Torstein R Rykkje for providing an exciting task and valuable assistance, as well as Knut Øvsthus for providing helpful advice and guidance. Furthermore, we would like to thank everyone who has assisted us along the way.

Summary

Summary	Sammendrag
This bachelor project consisted of programming and modifying a Stewart platform for use in a PhD project at HVL. The platform is intended to function as a wave simulator for testing a scaled-down model of Palfinger's new product, OPTS (Offshore Passenger Transfer System). The Stewart platform project involved various improvements, including mechanical design enhancements, mounting and connecting electrical equipment, as well as further development of the software code. The platform consists of six electric cylinders, each with a built-in stepper motor. These motors are utilized to position the top plate of the platform. A Raspberry Pi functions as the main controller (master) to manage the system. It sends signals to the Arduinos, which controls the stepper motors. Most of the goals of the project were achieved, except for one specific goal: the implementation of a feedback system that would provide the lengths of each cylinder. These lengths were intended to be transmitted to a digital twin to ensure synchronized movements between the model and the twin. Although the code for this system has been developed, it has not been possible to test it due to the lack of necessary components and power supply. Therefore, we cannot confirm that this functions as expected. The model cannot be considered a finished product. Suggestions for improvements and opportunities for further development are included in Chapter 7.1	Dette bachelorprosjektet har gått ut på å programmere og modifisere en Stewart plattform som skal brukes i et doktorgrad prosjekt på HVL. Plattformen skal brukes som en bølgesimulator for å teste en nedskalert modell av Palfinger sitt nye produkt OPTS (Offshore Passenger Transfer System). Stewart-plattformprosjektet har omfattet en rekke forbedringer, blant annet innen mekanisk utforming, montering og tilkobling av elektrisk utstyr, samt videreutvikling av programkode. Plattformen er sammensatt av seks elektriske sylindere som hver har innebygde steppermotorer. Motorene brukes til å posisjonere plattformens topp-plate. For å styre systemet er en Raspberry Pi brukt som hovedenhet (master). Den sender signaler til Arduinoene som igjen styrer steppermotorene. De fleste målene i oppgaven ble oppnådd, med unntak av ett spesifikt mål: implementeringen av et tilbakemeldingssystem som skulle gi ut lengdene til hver sylinder. Disse lengdene skulle deretter sendes til en digital tvilling for å oppnå samsvarende bevegelser mellom modellen og tvillingen. Selv om koden for dette systemet er utviklet, har det ikke vært mulig å teste det på grunn av manglende deler og strømforsyning til viktige komponenter. Derfor kan vi ikke bekrefte at denne funksjonaliteten virker som forventet. Modellen kan ikke betraktes som et ferdig produkt. Mangler og muligheter for videreutvikling er derfor vedlagt i kapittel 7.1.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Contracting entity

Western Norway University of Applied Sciences (HVL) is one of the largest educational institutions in the country and stretches over five campuses; Bergen, Førde, Haugesund, Sogndal and Stord.

Combined, the campuses have about 17,000 students and offer education programs at Bachelor's, Master's, and Ph.D. levels within health- and social sciences, engineering, teacher education, maritime sciences, nature sciences, culture and sports, social sciences, economics, and management [1].

This bachelor's thesis will be written for the Faculty of Engineering and Science, from the field of study, Automation, and Robotics. From the University there will be two supervisors, Thorstein Ravneberg Rykkje and Knut Øvsthus.

1.2 Problem description

This project is part of the ongoing Ph.D. project of Thorstein R Rykkje in computer science with the working title "Wave compensated ship cranes an integrated, physics-based simulation and control system". The project researches physics-based digital twins in order to control and simulate motion and deformation in structures. In real-time and as a data engine for machine learning tools. The Ph.D. project is in cooperation with Palfinger and is focused on their new product, the Offshore Passenger Transfer System (OPTS). As part of the project, a scaled prototype of the system is built. In order to test the wave compensation capabilities of the OPTS model, a wave-simulating platform is needed as the model is too big to test in the wave tank at HVL. Therefore, a Stewart Platform was built by mechanical engineering students during the spring of 2022.

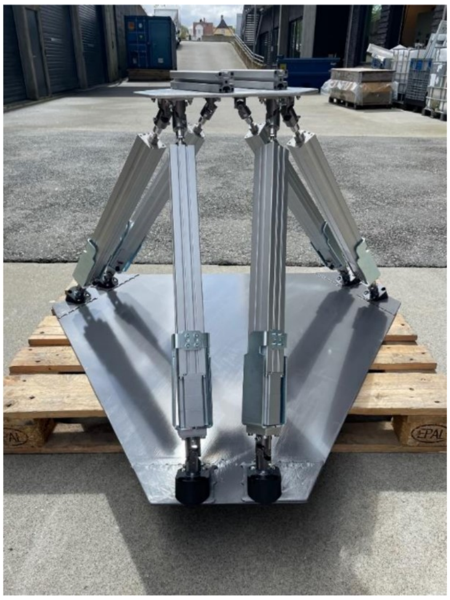


Figure 1.1: Stewart Platform built by mechanical engineering students at HVL in 2022.

The OPTS model is a passenger and cargo transfer system designed for marine applications to facilitate a safe and efficient transfer of persons between a moving vessel and a static offshore structure, such as a wind turbine or a platform [24]. The Stewart Platform must therefore be programmed to perform scaled movements of offshore wave data so that the model can be tested in the conditions it will be exposed to. Feedback from the platform must be sent onwards to Thorstein's digital twin with information about the stepper cylinder movements.

1.3 Goals

The goal of this project is to accomplish the following objectives in relation to the Stewart platform:

Hardware: All components should be connected and mounted in a junction box. The layout should be organized and designed in a way that allows others to easily understand and be able to work with the system.

Mechanical improvements: Evaluate the mechanical structure and modify the design of the platform to strengthen the construction and make it easier to transport.

Communication Method Selection: Select and implement an appropriate communication method for the system.

Code Modification: Modify the code provided by the Ph.D. student to meet the requirements of the Stewart platform. While the given code was capable of controlling a single stepper cylinder, adaption is necessary to control all six cylinders simultaneously.

Feedback system: Implement a feedback system that retrieves the lengths of each cylinder. The results should be able to be transmitted to a digital twin.

Chapter 2

The Stewart Platform

2.1 Mechanical Design

Stewart Platform is a parallel manipulator originating from a mechanism designed to simulate flight conditions by Stewart [9] in 1965 [10]. The Platform consists of two parallel plates, one static plate attached to the floor or other surfaces, and one moving top plate [35]. They are combined with six adjustable legs, each with spherical joints at both ends or with spherical joints at one end and universal joints at the other end. The legs are prismatic actuators, often electric linear actuators or hydraulic jacks, attached in pairs to three different positions on each plate. This gives the platform the possibility to move in six degrees of freedom.

The Platform in this assignment was designed by mechanical engineering students at IMM/HVL in the spring of 2022. This platform has six electric linear stepper-motor actuators as the prismatic joint legs with universal joints at both ends. The universal joints connected to the bottom plate is attached with bearings making the characteristic similar to a spherical joint.

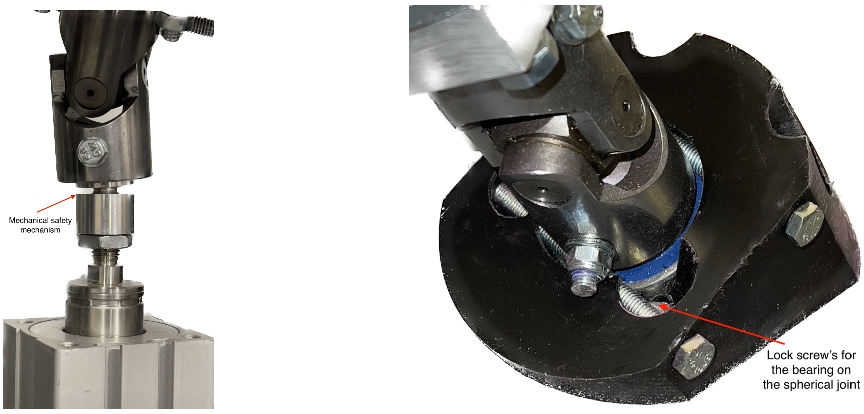


Figure 2.1: Mechanical safety mechanism

As shown in the right photo of Figure 2.1, the bearing is fastened with two screws to mechanically lock the bearing in place. This prevents the legs from detaching from the base plate while maintaining full mobility of the spherical joint. The photo on the left depicts a mechanical safety mechanism intentionally designed to bear the brunt of any malfunction or failure, ensuring that other parts remain protected from damage. This precautionary measure prevents further breakage or harm to other components.

The top and bottom plate is both shaped as hexagonal geometric figures, with each leg connected to a corner on the same flat circular trajectory. The top plate is rotated 180 degrees in relation to the base plate, creating an assembly angle between the hinges of the base to $15,07^o$ and $90,38^o$ for the top plate. The schematic diagrams of a Stewart Platform is shown in the figures 2.2 and 2.3.

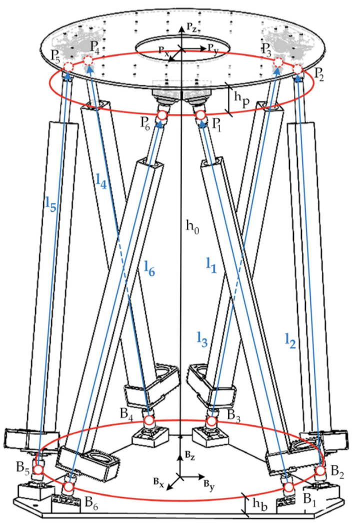


Figure 2.2: Geometrical description of the Stewart Platform.

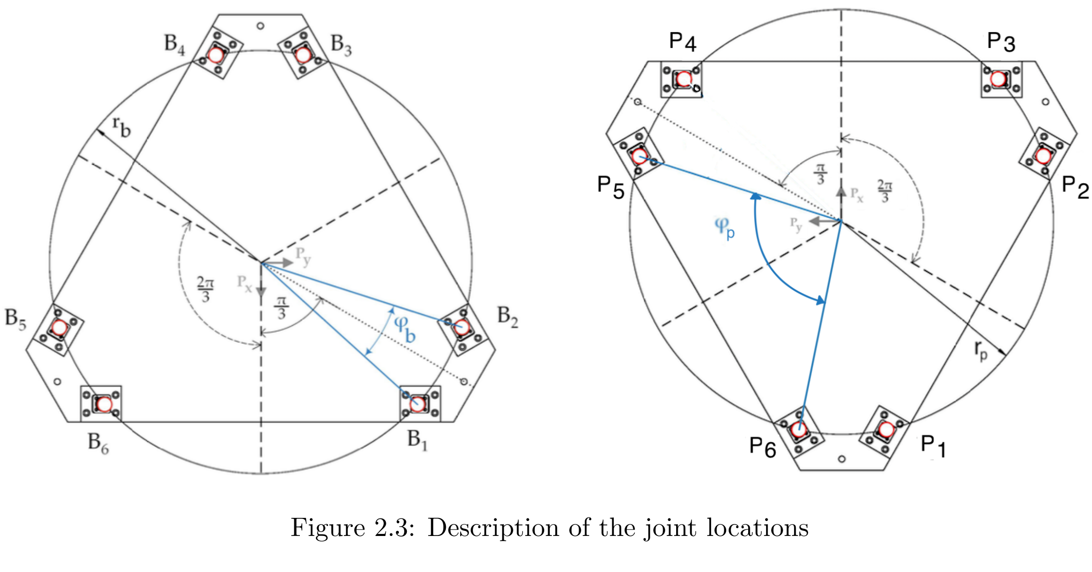


Figure 2.3: Description of the joint locations

From the platform configurations the extends and retracts of the linear electrical actuators enable for control of the position and orientation. The workspace of the Stewart Platform is constrained by the mechanical limitations of the maximum extraction of the cylinders and will operate in the radius of the base plate in the xy-plane, with a height from 70cm to a maximum of 115cm in the z-direction. Table 2.1 below shows lengths of the Platform with the cylinders fully retracted.

Definition	***Variable***	***Value***
Radius base platform	r_b	557mm
Radius top platform	r_p	148mm
Initial height platform	h_0	700mm
Initial length cylinder	l_0	836mm
Angle between the hinges of the base	φ_b	$15,07^o$
Angle between the hinges of the top plate	φ_p	$90,38^o$

Table 2.1: Specifications of the Stewart Platform

2.1.1 Degrees of Freedom

The Stewart platform has a configuration of six degrees of freedom (DOF) of a rigid body. It is connected with fourteen links, where each of the six legs contains two parts (twelve links), that are connected together with the base- (thirteen links) and top plate (fourteen links). With six prismatic joints, twelve universal joints, and six bearings the total degrees of freedom can be calculated using Grübler's formula. On each leg, one of the universal joints is connected to a rotatably base in the form of a bearing to make it function as a spherical joint with three DOF [20].

Grübler's formula: $F = \lambda(l - j - 1) + \sum_i^j f_i - I_d$

From the formula, F represents the effective degrees of freedom of the mechanism, λ is the spatial degrees of freedom, l is the number of links, j is the number of joints, f_i represent the number of freedoms of the i^{th} joint, and I_d is the passive DOF. The calculation is made in the following equation:

$$F = \lambda(l - j - 1) + \sum_i^j f_i - I_d$$

$$F = 6(14 - 18 - 1) + \sum_i^j 6(1) \cdot 6(2) \cdot 6(3)$$

$$F = 6\ dof$$

As the formula shows, there are six degrees of freedom, and therefore enables the platform to move in all three axes of movement (x, y, z) and rotation (α, β, γ).

2.2 Kinematics

2.2.1 Inverse Kinematics

Finding the inverse kinematics involves determining the joint positions required to achieve a desired end-effector configuration. In comparison to forward kinematics, the inverse kinematics of open-chain robots can be more complex, while closed-chain parallel robots, like the Stewart Platform, tend to be more straightforward. While a given set of joint positions corresponds to a unique end-effector position and orientation, a particular end-effector configuration may have multiple solutions for joint positions or none at all.

The inverse kinematics problem for a Stewart platform involves determining the length of each leg required to position the platform at a desired location and orientation in space.

Due to the complexity of the Stewart platform's kinematics, analytical solutions for the inverse kinematics problem are often difficult to derive. Instead, numerical methods such as gradient descent and Newton's method are commonly used to solve for the leg lengths.

One approach is to use the Jacobian matrix to map changes in the leg lengths to changes in the position and orientation of the platform. By iteratively adjusting the leg lengths based on the desired changes in the platform position and orientation, a solution can be found that minimizes the error between the desired and actual platform configuration.

Another approach is to use optimization algorithms such as genetic algorithms or particle swarm optimization to search for the optimal set of leg lengths that achieve the desired platform configuration. These methods can be computationally expensive but are often more robust and effective in finding solutions for highly complex systems.

The output values of the inverse kinematics can be used to determine the position and orientation in space of the top plate for the Stewart Platform. The values are calculated into six leg lengths, and further processed in a feedback control system to move the platform to the desired orientation. Calculations made in this report are based on the information in [32].

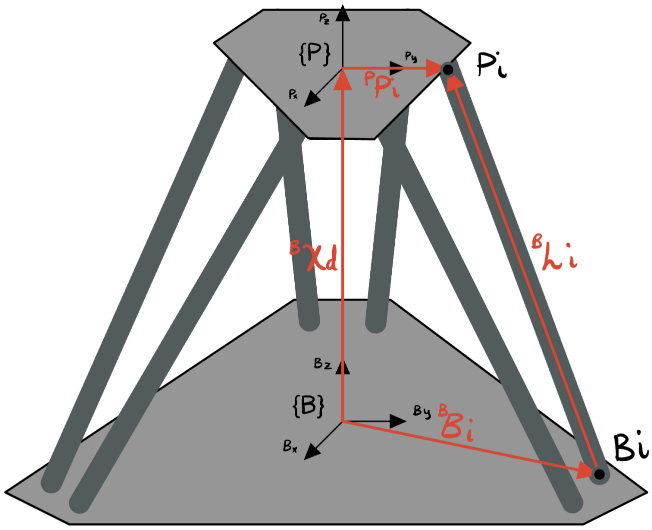


Figure 2.4: Closed loop schematic of one the Stewart Platform leg

From figure 2.4 the closed-loop vector approach is considered to determine the inverse kinematics of the Stewart Platform. It's placed in two Cartesian axes based on the center of the base plate {B} and the center of the moving top plate {P} of the platform. The base plate could be considered at the origin of the coordinate system with {B} represented in point [0, 0, 0]. The length of the cylinder is denoted by L_i, it's connected to the spherical joint on the base plate with an anchor point in B_i, and the universal joint on the top plate in point P_i. The vector notations $B_i = [B_{ix}, B_{iy}, B_{iz}]$ and $P_i = [P_{ix}, P_{iy}, P_{iz}]$ represent the connection points to the origin on the base and top plate. Vector $X_d = [x, y, z]$ establishes a connection between the coordinate system {P}'s desired position and the coordinate system {B} forming a translation vector. With the vector relationship for each of the six legs of the platform, the equation is given:

$$^{B}L_i =^{B} P_i +^{B} X_d -^{B} B_i \tag{2.1}$$

Vector $^{B}P_i$ who's connecting the top plate joints, to the B coordinate system, can be found using the equation 2.6. For this equation, it's necessary to apply a Roll-Pitch-Yaw matrix ($^{B}R_P$) to the vector $^{P}P_i$. The rotation matrix has the rotation angles θ_1 for the x-axis, θ_2 for the y-axis and θ_3 for the z-axis.

The rotation matrices standard notation for the axes $[x, y, z]$. Shorten the notation with "c" for cosine and "s" for sine:

$$R_x(\theta_1) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c(\theta_1) & -s(\theta_1) \\ 0 & s(\theta_1) & c(\theta_1) \end{bmatrix}, R_y(\theta_2) = \begin{bmatrix} c(\theta_2) & 0 & s(\theta_2) \\ 0 & 1 & 0 \\ -s(\theta_2) & 0 & c(\theta_2) \end{bmatrix}, R_z(\theta_3) = \begin{bmatrix} c(\theta_3) & -s(\theta_3) & 0 \\ s(\theta_3) & c(\theta_3) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The Stewart Platform rotation matrix relative to the Base, is obtained by using matrix multiplication for the axes.

$$^{B}R_P = R_x(\theta_1) \cdot R_y(\theta_2) \cdot R_z(\theta_3) \tag{2.2}$$

$$^{B}R_P = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_1) & -\sin(\theta_1) \\ 0 & \sin(\theta_1) & \cos(\theta_1) \end{bmatrix} \cdot \begin{bmatrix} \cos(\theta_2) & 0 & \sin(\theta_2) \\ 0 & 1 & 0 \\ -\sin(\theta_2) & 0 & cos(\theta_2) \end{bmatrix} \cdot \begin{bmatrix} \cos(\theta_3) & -\sin(\theta_3) & 0 \\ \sin(\theta_3) & cos(\theta_3) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.3}$$

$$^{B}R_P = \begin{bmatrix} c(\theta_1)c(\theta_2) & c(\theta_1)s(\theta_2)s(\theta_3) - s(\theta_1)c(\theta_3) & c(\theta_1)s(\theta_2)c(\theta_3) + s(\theta_1)s(\theta_3) \\ s(\theta_1)c(\theta_2) & s(\theta_1)s(\theta_2)s(\theta_3) + c(\theta_1)c(\theta_3) & s(\theta_1)s(\theta_2)c(\theta_3) - c(\theta_1)c(\theta_3) \\ -s(\theta_2) & c(\theta_2)s(\theta_3) & c(\theta_2)c(\theta_3) \end{bmatrix} \tag{2.4}$$

Simplifies the rotation matrix with abbreviations for the elements to use in equation (2.5).

$$^{B}R_P = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \tag{2.5}$$

$$ {}^{B}P_i = {}^{B}R_P \cdot {}^{P}P_i = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \begin{bmatrix} P_{ix} \\ P_{iy} \\ P_{iz} \end{bmatrix} = \begin{bmatrix} u_i \\ v_i \\ w_i \end{bmatrix}, i = 1..,6 \tag{2.6} $$

The displaced auxiliary vector ${}^{B}d_i$ can be used to group the vector subtraction between the end-effector positioning vector and the vector of the base member platform attachments.

$$ {}^{B}d_i = {}^{B}X_d - {}^{B}B_i = \begin{bmatrix} x - B_{ix} \\ y - B_{iy} \\ z + h_0 - B_{iz} \end{bmatrix} = \begin{bmatrix} \bar{u_i} \\ \bar{v_i} \\ \bar{w_i} \end{bmatrix} \tag{2.7} $$

The height h_0 is the distance between the platforms base- and top-center when its in home position.

The equation 2.8 is obtained by combining equations 2.6 and 2.7. The translation vector ${}^{B}X_d$ represents the linear displacement of the origin of the Platform frame in relation to the Base reference framework, while vector ${}^{P}P_i$ defines the coordinates of the anchor point relative to the Platform top framework, and ${}^{B}B_i$ is the vector that defines the coordinates of the lower anchor point. The length of each leg can be calculated using the equation 2.9.

$$ {}^{B}L_i = {}^{B}X_d + {}^{B}R_P \cdot {}^{P}P_i - {}^{B}B_i \iff {}^{B}L_i = {}^{B}P_i + {}^{B}d_i \tag{2.8} $$

By using this equation for i^{th} leg, the lengths of the six legs can be determined to achieve the desired position and attitude of the platform.

Using geometric inverse kinematics, the elongation value of the prismatic joint l_i can be obtained by calculating the norm of the $||{}^{B}L_{,i}||$ vector, as shown in equation 2.9.

$$ l_i = ||{}^{B}L_{,i}|| = \sqrt{L_{ix}^2 + L_{iy}^2 + L_{iz}^2} = \sqrt{(\bar{x_i} + u_i)^2 + (\bar{y_i} + v_i)^2 + (\bar{z_i} + w_i)^2}, i = 1..,6 \tag{2.9} $$

The inverse kinematic matrix computed on the Raspberry Pi emits six joint angles that are required to achieve the desired position and orientation of the platform in space. These joint angles correspond to the necessary lengths of each of the six legs of the platform. By implementing these joint angles into the Arduino code, it can control the length of each leg by driving the stepper motors, to precisely position the platform.

Example of inverse kinematics

Using the inverse kinematics calculations in the Juptyter notebook [12] a plotted visualization of the Stewart Platform can be displayed. The coordinate of the platform is first calculated using $r_B = 55.7cm$ (Radius of base), $r_P = 14.8cm$ (Radius of top), $\gamma_B = 0.13148rad$ (Half angle between two anchors on the base), $\gamma_P = 0.2857rad$ (Half angle between two anchors on the top plate).

Using the values of γ_B and γ_P, we can derive $\psi_B \in R^{6\times1}$ and $\psi_P \in R^{6\times1}$. These represent the polar coordinates of the anchors located on a unit circle with a radius.

Furthermore, by considering the values of r_B and r_P, we can establish $B \in R^{6\times3}$ and $P \in R^{6\times3}$. These matrices represent the coordinates of the anchors in their respective local frames, using Cartesian coordinates. For instance, the anchor points on the base, denoted as B, are visually depicted below 2.5:

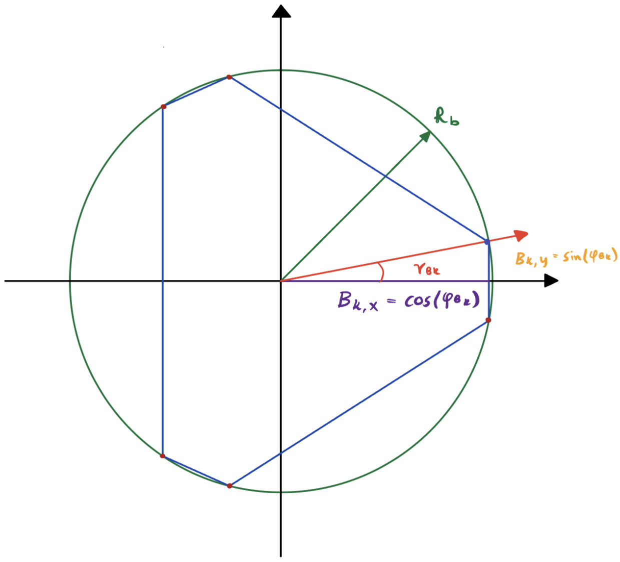


Figure 2.5: Basic parameters for mechanical configurations

With the calculating done in [12] we get the $R^{6\times3}$ array for the Base anchors and $R^{6\times3}$ for the top plate anchors shown in figure 2.6.

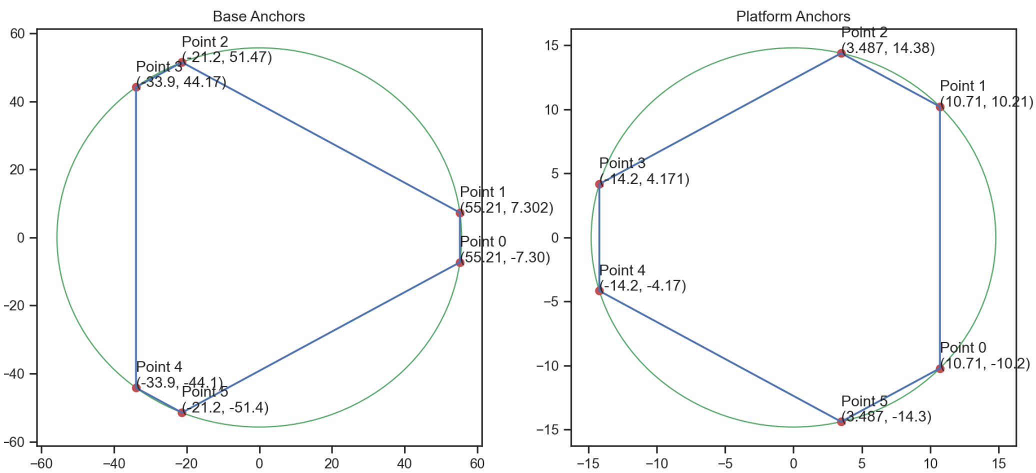


Figure 2.6: Anchor points for the base and top in home position

Next, we proceed to define the displacement between the base and the platform at the home position, denoted as h_0. This represents the length of the linear actuators when they are in their resting state. The height of the platform when all cylinders are fully retracted are 70cm, and therefore home position will be the array([0, 0, 70]). This indicates that the home position is located at coordinates (0, 0, 70) in a three-dimensional space.

Finally, we are at the stage of solving the inverse kinematics problem.

To determine the lengths of the legs, given the desired translation vectors $T = (t_x, t_y, t_z)^T$ and rotation vector $\theta = (\theta_x, \theta_y, \theta_z)^T$, we need to calculate the new coordinates of each anchor on the platform after applying the desired rotation and translation.

Since the purpose of each leg is to connect the anchor on the base to the anchor on the top plate, the desired vector for each leg (direction and length) corresponds to the position of the leg in 3D space relative to its respective base anchor.

By applying these values 2.10:

$$Trans = transpose \begin{bmatrix} 17 & 11 & 26 \end{bmatrix} \; and \; Rotation = transpose \begin{bmatrix} \pi/12 & \pi/6 & \pi/12 \end{bmatrix} \tag{2.10}$$

The translation vector T, and the rotation vector θ the visualization of the platform can be shown in figure 2.7. Length of each leg will then be 2.11:

$$l_i = [93.36142275, 105.155147, 110.85176023, 115.62026512, 115.32214022, 113.46285916] \tag{2.11}$$

This is approximately max extension of leg four and five with 115cm.

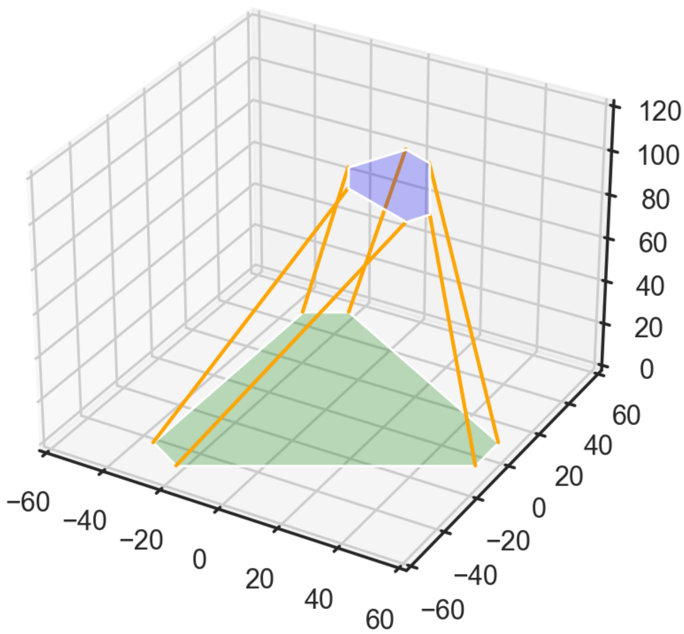


Figure 2.7: Representation inverse kinematics

2.2.2 Forward Kinematics

In an open chain, the joint positions determine the unique position and orientation of the end-effector. The forward kinematics problem involves finding the position and orientation of the reference frame attached to the end-effector based on the joint positions. The product of exponentials (PoE) formula is used to describe the forward kinematics of open chains. Derived from the exponential coordinate representation for rigid-body motions, the PoE formula provides an intuitive interpretation of the joint axes as twists while eliminating the need for link frames. Only the base frame and end-effector frame are required, which can be chosen arbitrarily [16].

The forward kinematics of a Stewart platform involves determining the position and orientation of the platform based on the lengths of its six legs. This is a critical task in controlling the motion of the platform and achieving a desired end-effector configuration.

To solve the forward kinematics problem for a Stewart platform, several methods can be used. One common approach is to use the geometric approach, which involves finding the intersection point of the six leg lengths using complex mathematical calculations. However, this method can be computationally expensive and prone to numerical errors.

An alternative method is to use matrix transformations and homogeneous coordinates. The Stewart platform can be modeled as a set of six linear equations, each representing the length constraint of each leg. These equations can then be transformed into matrix form using homogeneous coordinates, resulting in a 4x4 transformation matrix that maps the position and orientation of the platform [30].

The transformation matrix can be decomposed into a translation vector and a rotation matrix, which can be used to determine the position and orientation of the platform in 3D space. This approach is computationally efficient and can be easily extended to account for different platform configurations and leg geometries.

Overall, the forward kinematics of a Stewart platform is a critical task in controlling its motion and achieving a desired end-effector configuration. Matrix transformations and homogeneous coordinates provide an efficient and robust method for solving the forward kinematics problem of the Stewart platform.

2.3 Feedback Loop Control

A feedback control loop is a system where the output of a process is taken into consideration and fed back into the system to adjust its performance to meet a desired response or set-point value. The difference between the desired value and the measured value, known as the error signal, is used to adjust the input to the process. This creates a closed-loop system that continuously monitors and adjusts the output to maintain a desired level of performance or operation. The feedback loop can include one or more sensors to measure the output and a controller to adjust the input based on the feedback received. Feedback control loops are used in a wide range of applications, including process control, robotics, and automation.

The feedback loop of a Stewart Platform could be done in several ways. Depending on equipment and code, different variables are used to control the loop. In the case of this particular Stewart Platform, the feedback loop shown in Figure 2.8 is constructed using the following components. In the first block, the desired end-effector position is put into the Raspberry Pi, this could be in form of scaled offshore wave data or any other relevant source. Since the platform is able to move in all three axes of movement (x, y, z) and rotation (α, β, γ), calculations of the anchor points

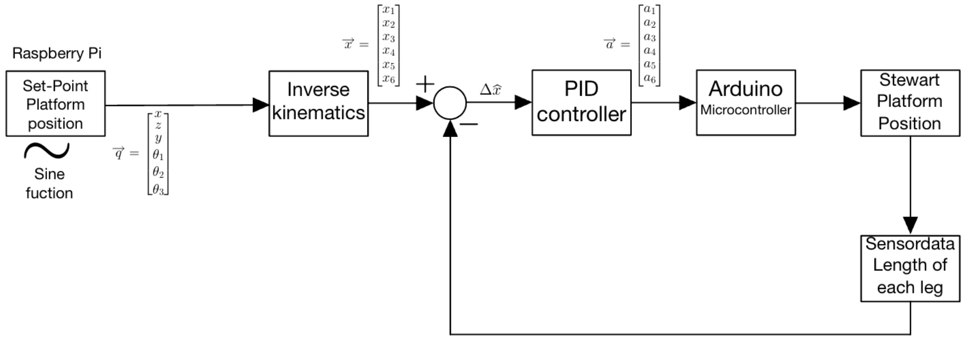


Figure 2.8: Feedback Loop Control of the Stewart Platform

are necessary to define the orientation of the end effector in 3D space. To solve this, the values is put into the inverse kinematics's calculations, which is located in the Raspberry Pi code. The length and direction of anchor points in then put together to find each length of the six legs. These values are put into the PID controller block which calculates the acceleration needed to achieve the desired end-effector position. The Arduino code receives the acceleration and activate the output to drive the stepper motors. When the cylinders are moving the encoders will send continuous feedback to calculate the length δx remaining to achieve the desired position of the platform. The controller will adjust the acceleration output accordingly to how close the desired position is.

2.4 Electrical Loop Diagrams

The electrical loop of the Stewart Platform is put together with a combination of various components and equipment. The electrical loop is put together in two separate junction boxes, to reduce the possibility of electrical interference on the signals and low-voltage components. The higher voltage components, such as the power supplies and micro step drivers are put together in one box, and the Arduino with RS485 modules and Raspberry Pi is in the second box. With this separation the 230V, 24V and 12V are in one box and the 5V and 3,3V in the other. A photo of the junction boxes is shown in Figure 2.9 and 2.10. Full sized drawing can be found in the appendix A.1

The loop diagrams shows how the I2C is connected together from the Raspberry Pi to the Six Arduino's, and also how one complete cylinder loop is connected together. The cylinder loop show the connection from from the encoder to the RS485 modules, and further wiring to the Arduino. From the Arduino digital output to the Geckodrive G201X stepperdriver, and also the connecting with the Raspberry pi trough the Sparkfun Logic Level converter. The power supplies is not included in the schematic loop diagrams. 2.11

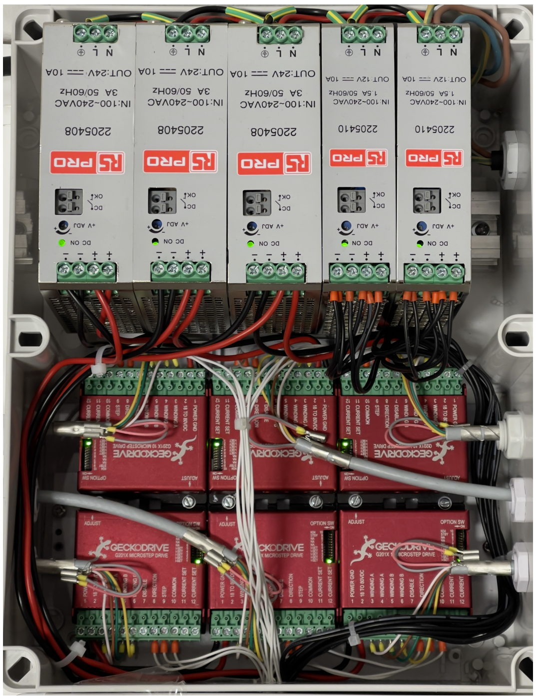


Figure 2.9: Voltage converter's and control circuit

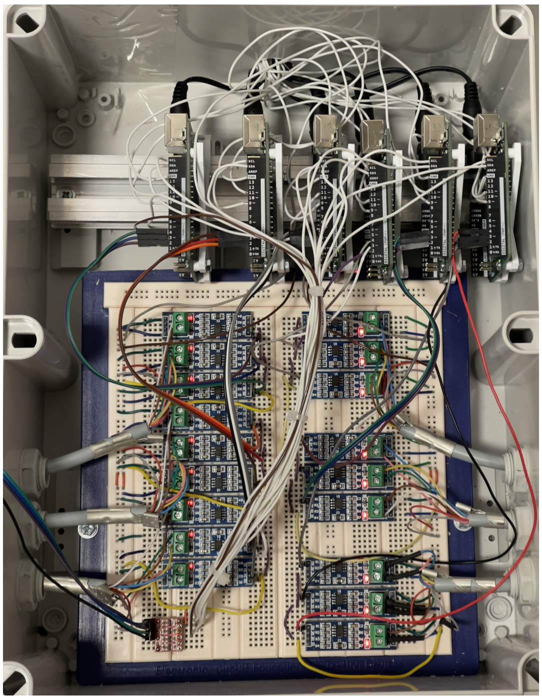


Figure 2.10: Signal connection box

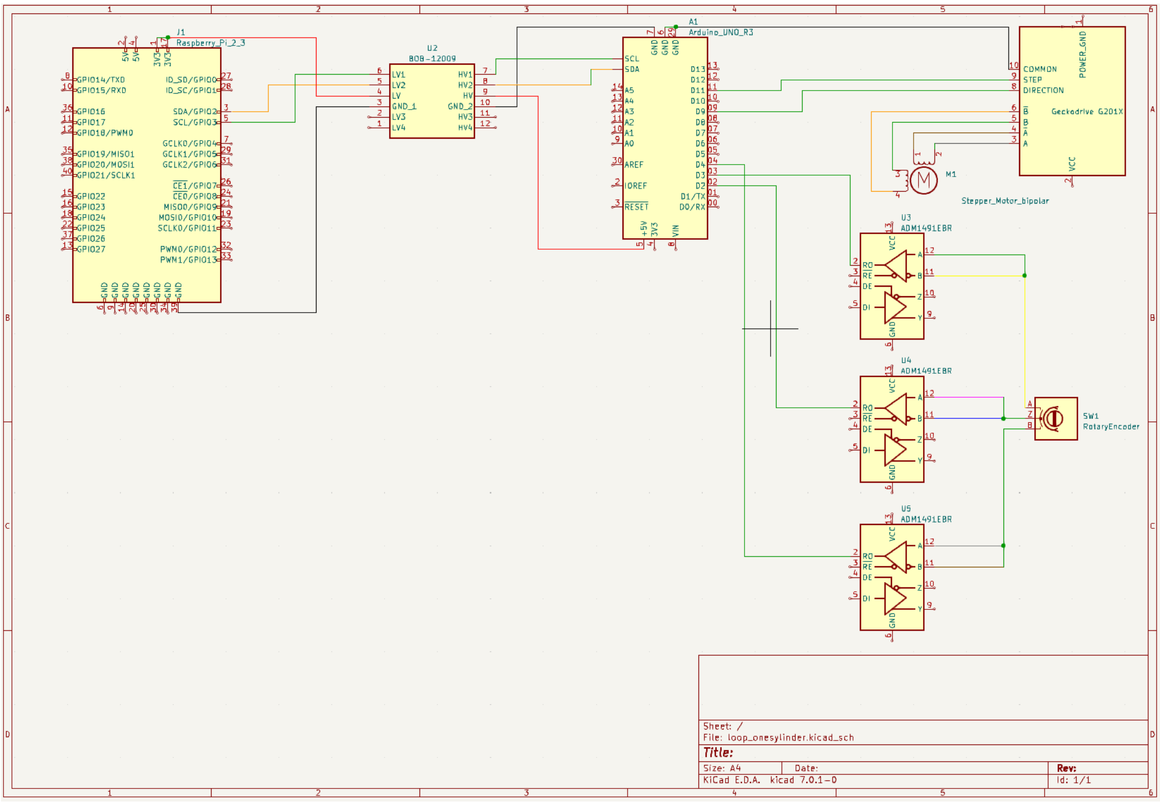


Figure 2.11: Cylinder electrical loop

Chapter 3

Selection of Solutions

There are various solutions to build a Stewart Platform, and it's possible to achieve our desired goal in different ways. Through literature search and guidance from our supervisors, we have come up with solutions that possibly would give us the final product we are aiming for. With Arduino Uno micro-controllers connected to each of the six Festo EPCO-40 stepper cylinders, we will collect and send signals with a feedback loop using Raspberry Pi 4 as a controller. The stepper motor cylinders are each connected to their own encoders for counting their movements. The system operates with various electric signals, and differences in voltage levels for the components may cause electromagnetic noise and must be considered. Communication can be sensitive to noise and therefore different communication methods must be reviewed to find a suitable solution.

3.1 Serial Communication Protocols

Serial communication is a method of transmitting data between two electronic devices over a communication channel. In this method, data is sent one bit at a time, in a sequential order, over a single communication line. This differs from parallel communication, where multiple bits are transmitted simultaneously over multiple lines.

Serial communication is commonly used in a variety of electronic devices, such as computers, microcontrollers, and sensors, as in our situation between Arduino's and Raspberry Pi. It allows for efficient and reliable transfer of data.

There are several types of serial communication protocols that are widely used. In this project there are three protocols that's going to be closely looked into, including Universal Asynchronous Receiver/Transmitter (UART), Serial Peripheral Interface (SPI), and Inter-Integrated Circuit (I2C). Each protocol has its own specific set of rules and characteristics, but they all involve the transmission of data in a sequential manner.

Overall, serial communication plays a crucial role in the field of electronics, enabling devices to communicate with one another and transfer data efficiently and effectively.

Since there are several ways to connect an Arduino to a Raspberry Pi it's important to find a suitable method for our project. The communication protocols offer different pros and cons that need to be considered when building the platform, e.g. the difference in voltage levels between the Arduino and Raspberry Pi.

3.1.1 UART

Universal Asynchronous Reception and Transmission (UART) is an asynchronous multi-master protocol based on Serial communication. Multi-master means that all connected devices seamlessly can send data when they want. Unlike master-slave protocols, where only the master device can initiate communication, UART allows all connected devices to freely send data whenever they desire. The Arduino Uno board provides a single UART that can be utilized either through a USB cable or by connecting to the RX/TX pins. However, it's important to note that simultaneous usage of both methods should be avoided due to potential conflicts and interference between the two communication channels. The raspberry pi is equipped with four USB ports for serial connecting devices and an additional UART on the GPIOs(RX/TX) pins. Since there are six Arduino's, the amount of UARTs would be a problem. There are only four available USBs on the Raspberry Pi and one additional one on the board. [11]

The UART interface could operate in three different ways:

- Simplex = Sends data transmission in one direction
- Half-duplex = Sends data transmission in either direction but not simultaneously
- Full-duplex = Sends data transmission simultaneously in both directions

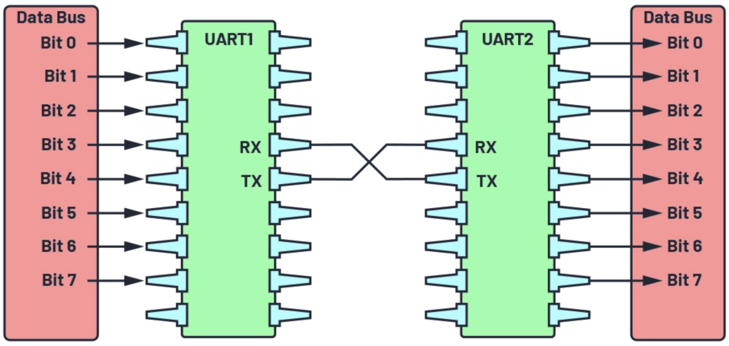


Figure 3.1: UART with databus

As shown in Figure 3.1, the signals flow from the transmitting port TX to the receiving port RX. The data bus is connected to the transmitting UART that sends data in parallel form. The Parallel data from the master device will be converted to a serial form in the transmitting UART and sent to the receiving UART, and then converted back into a parallel data pack. The received data from the data bus is processed by adding a start bit, a parity bit, and a stop bit to form a complete data packet, these are then checked and confirmed to see if the whole packet was received. The parity bit assures that there are no errors and lost data.

To ensure proper communication between devices using UART and other serial protocols, it is necessary to set the same baud rate on both the transmitting and receiving devices. The baud rate refers to the speed at which information is transferred over the communication channel, and it determines the maximum number of bits that can be sent per second in the serial port context.

Unlike synchronous communication methods that rely on clock signals to keep the transmitter and receiver in sync, UART is an asynchronous protocol that does not use a clock signal. Instead, the transmitter generates a bitstream based on its clock signal, while the receiver uses its internal clock signal to sample the incoming data. Synchronization between the two devices is achieved by maintaining the same baud rate.

Failing to set the same baud rate on both devices can lead to timing discrepancies during data handling, which can affect the accuracy of data transfer. The allowable difference in baud rate is typically up to 10%, beyond which the timing of bits becomes too far off. Therefore, it is essential to ensure that the baud rates are properly configured to enable reliable and efficient data transfer.

The received data from the data bus is processed by adding a start bit, a parity bit, and a stop bit to form a complete data packet. If the start bit is confirmed valid, the data bits are sampled every 16th cycle of Baud16, which is determined by the length of the data character. Additionally, if the parity mode is activated, the parity bit is also detected during this process [38].

The advantages of using this protocol are the simple hardware setup, full duplex communication, no clock needed, and error check with the parity bit. Disadvantages may result in the low data transmission speeds, the 9-bit limitation of a data frame, and the communication from one master (Raspberry Pi) to six slaves (Arduino) could result in a slow connection [19].

3.1.2 I2C

Inter-integrated-circuit (I2C) protocol is a serial communication protocol similar to UART, but it is primarily used for connecting modules and sensors rather than for PC-device communication. I2C is a simple, bidirectional two-wire synchronous serial bus, that only requires two wires to transmit and receive information between connected devices on the bus. This communication is particularly useful in projects that require many different components to work together and can connect up to 128 devices to the main board while maintaining clear communication pathways. This is achieved through I2C's address system and shared bus, allowing multiple devices to be connected using the same wires and transmitting all data on a single wire, resulting in a low pin count. However, I2C's simplified wiring comes with a tradeoff, as it is slower than SPI, and is limited to data sizes of 8 bits.[38]

I2C's data rate depends on factors such as wire quality and external noise. Nevertheless, the protocol is commonly used as a two-wire interface to connect low-speed devices such as micro-controllers, EEPROMs, A/D and D/A converters, I/O interfaces, and other similar peripherals in embedded systems

Using I2C we can connect multiple slaves to a single master, or multiple masters to control single, or multiple slaves. This feature is useful when several micro-controllers read data to a single memory card or display text. This connection only requires two signal wires that will be connected through the converter and onto the breadboard. The connections are SDA (Serial Data) and SCL (Serial clock). While the SDA transfer bit by bit, sending and receiving data from the master and slave the SCL carries the clock signal see Figure 3.2. The protocol is known to be flexible and is a well-known and used protocol.

The I2C protocol may have limitations in its resistance to electromagnetic noise. The platform has multiple voltage sources with different voltage levels that can cause electromagnetic noise and therefore it is important to carefully route the communication levels. To address this, the components are divided into two junction boxes. One box contains the power supplies and stepper drivers, while the other box contains the 5V devices. Figure 3.1.2, is a loop drawing showing the connection between six Arduino Uno boards and a Raspberry Pi, along with a voltage level converter. Full sized drawing can be found in the appendix A.2.

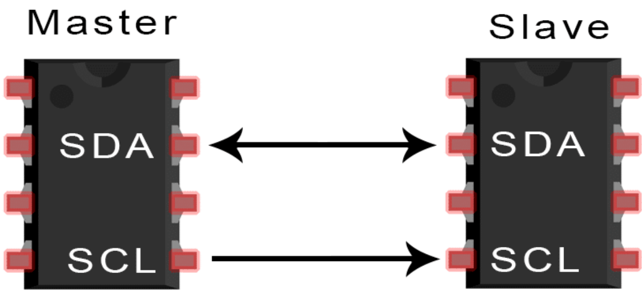


Figure 3.2: I2C Master and Slave connection

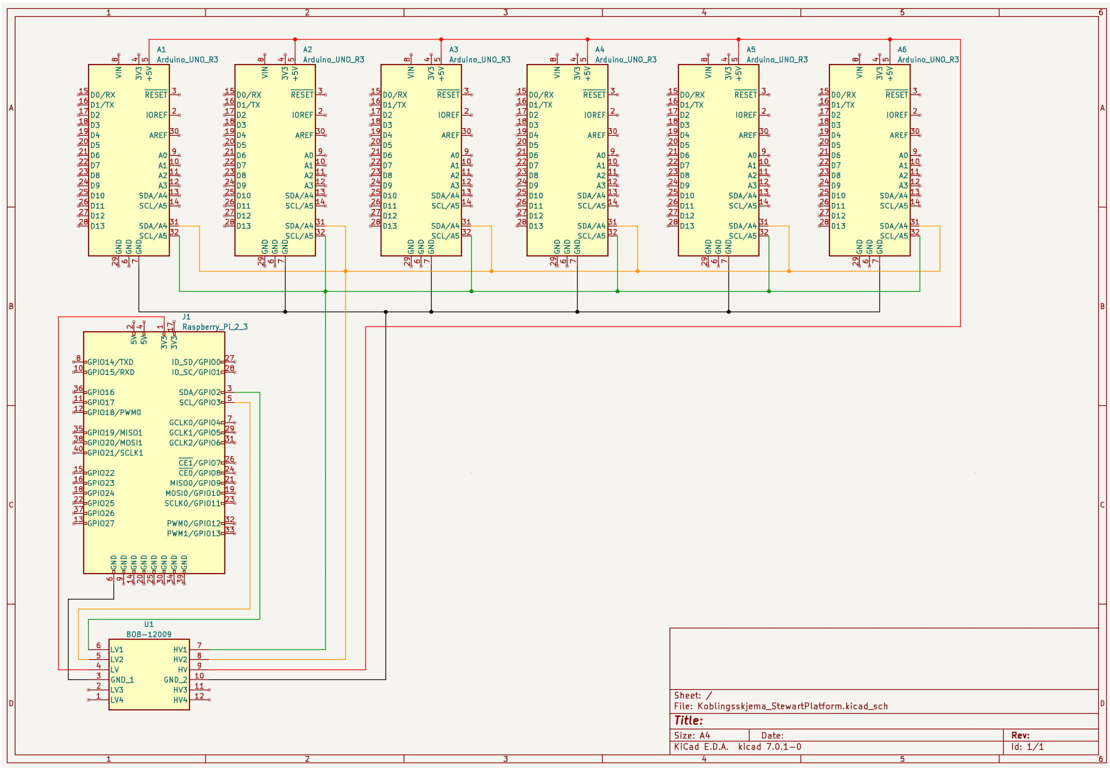


Figure 3.3: I2C loop connection of six Arduino and Raspberry Pi

3.1.3 SPI

Serial Peripheral Interface (SPI) is a commonly used synchronous serial communication protocol with micro-controllers. One advantage of SPI over I2C and UART is its ability to transfer data continuously without interruption. Unlike I2C and UART, where data is transmitted in packets of a fixed number of bits with start and stop conditions defining the beginning and end of each packet, SPI streams data continuously.

SPI communication between devices is based on a master-slave relationship (Figure 3.4). The master device, usually a microcontroller, controls the communication and issues instructions to the slave device, which can be a sensor, display, or memory chip. While the simplest SPI configuration consists of a single master and single slave, one master device can control multiple slave devices. One of the main advantages of SPI is its speed. SPI operates at higher clock rates than I2C or UART, making it a preferred choice for high-speed communication, with data transfer of up to 8 Mbps between the Arduino and Raspberry Pi.

However, there are also some drawbacks to using SPI. SPI requires more pins than I2C, which can be a limitation for devices with a limited pin count. Another potential issue is that SPI does not have a standard addressing scheme, making it more difficult to connect multiple devices to a single bus. Finally, since SPI is based on a master-slave architecture, it may not be suitable for situations where multiple devices need to communicate with each other simultaneously.

While I2C and UART only require a two-wired connection, the SPI needs 3+n where n is the number of slave devices. For this project, the situation with six Arduino slaves would therefore require a connection of 3+6 wires.

In summary, SPI is a fast and efficient communication protocol for connecting multiple devices to a microcontroller, but its hardware requirements and lack of standard addressing can be limiting factors. It is important to consider the specific needs of the project when choosing a communication protocol. [31]

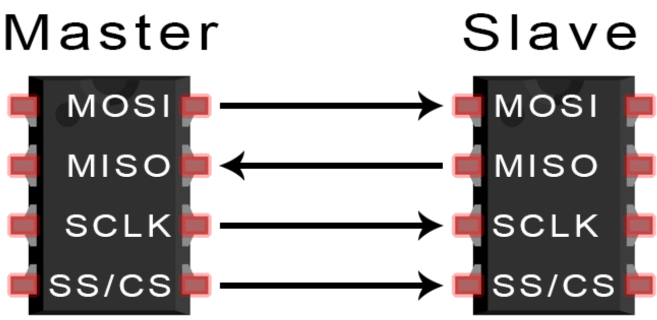


Figure 3.4: SPI Master and Slave connection

- MOSI (Master Output/Slave Input) – Line for the master to send data to the slave.
- MISO (Master Input/Slave Output) – Line for the slave to send data to the master.
- SCLK (Clock) – Line for the clock signal.
- SS/CS (Slave Select/Chip Select) – Line for the master to select which slave to send data to.

3.1.4 Choice of Protocol

When it comes to connecting a Raspberry Pi to multiple Arduinos, I2C communication stands out as the best choice in this scenario for several reasons.

Firstly, I2C only require two wires, making it easy to set up and use, especially when there are six Arduinos. This means that the wiring of this protocol will be much more straightforward and less complicated compared to SPI.

Secondly, I2C is capable of supporting multiple devices using a single bus, which means all six Arduino devices can be connected to the same I2C bus. This makes it easier to synchronize the information and control the devices without needing multiple interfaces.

Thirdly, I2C includes built-in error checking that ensures data integrity during transmission. This feature is particularly important when dealing with multiple devices and large amounts of data. This minimizes the possibility of data corruption or loss during transmission, making the protocol reliable.

Finally, I2C allows for simple addressing of each device on the bus, which makes it easy to identify and communicate with specific devices. This feature can be particularly important with scenarios like the Stewart Platform, where we have multiple devices and could avoid confusion and potential communication errors.

In conclusion, I2C seems like the best option for communication protocol to choose when connecting a Raspberry Pi to multiple Arduino devices. Its simplicity, support for multiple devices, built-in error checking, and easy addressing make it a reliable and efficient communication protocol for this scenario.

3.1.5 Encoder communication

From the encoder located on the electrical cylinders, there is used an RS485 serial communication module to make the encoders and Arduino able to communicate with each other. The RS485 converts the signals between the encoders and the Arduino so that the Arduino can both send commands and read the data from the encoders.

The RS485 standard defines the electrical interface and physical layer for point-to-point communication between electrical devices. It's commonly used to support multiple devices on the same bus and to transfer data over long distances in noisy environments.

The RS485 uses two signal lines, 'A' and 'B', which must be balanced and differential. These two lines share a pair in a twisted pair cable, with the same impedance on each line. Balanced cabling enables noise reduction when employing differential signals, where two signals named 'A' and 'B' form a differential pair. While one of the signals matches the original signal, the other signal is inverted, making it a complementary signal. From the encoder on the electrical cylinder, there is a twisted four-pair cable connected. This allows the Arduino connected to the RS485, to pick up the direction, clockwise or anti-clockwise, and full rotations of the stepper to calculate the length of extend from start. [28]

Chapter 4

Equipment

4.1 Stepper motor and driver

Stepper motor

Stepper motors are electromechanical motors that can move in small steps, within a millimetre range. They consist of multiple coils arranged in groups known as “phases”. By activating each phase in a specific sequence, the motor is able to rotate one step at a time [2].

Stepper motors are often used in applications that require accurate positioning, including 3D printers, CNC machines, and camera platforms. Additionally, because stepper motors can move in precise increments, they offer excellent control over rotational speed, which makes them a popular choice for process automation and robotics applications. Another advantage of these motors is their ability to provide high torque at low speeds, which makes them a good option for applications that require low speeds with high precision [2].

There are three basic types of stepper motors: permanent magnet(PM) stepper motor, variable reluctance(VR) stepper motor and hybrid(HY) stepper motor. The following information is based on this site [42].

Permanent magnet(PM) stepper motor

A PM stepper motor has a cylindrical permanent magnet rotor which is driven by the stator’s windings, as shown in Figure 4.1. The stator usually has two windings which create opposite polarity poles compared to the poles of the rotor and this propels the rotor [17].

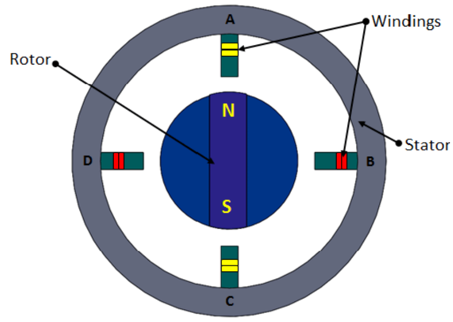


Figure 4.1: Permanent magnet stepper motor [14]

Figure 4.2 shows a diagram of a 2-phase winding PM rotor stepper motor. In Figure 1a phase A is energized with terminal ”A” positive, and the north-seeking pole of the rotor is at 0°. In Figure 1b phase B is energized with terminal ”B” positive, and the north-seeking pole has rotated 90° clockwise. The shaft completes one revolution for each complete revolution of the electromagnetic field.

Figure 2 shows the same stepper motor but with both windings energized. Here the field has rotated 45° from Figure 1. The main difference between these two Figures is that the resultant magnetic field in Figure 2 will be between two poles [42].

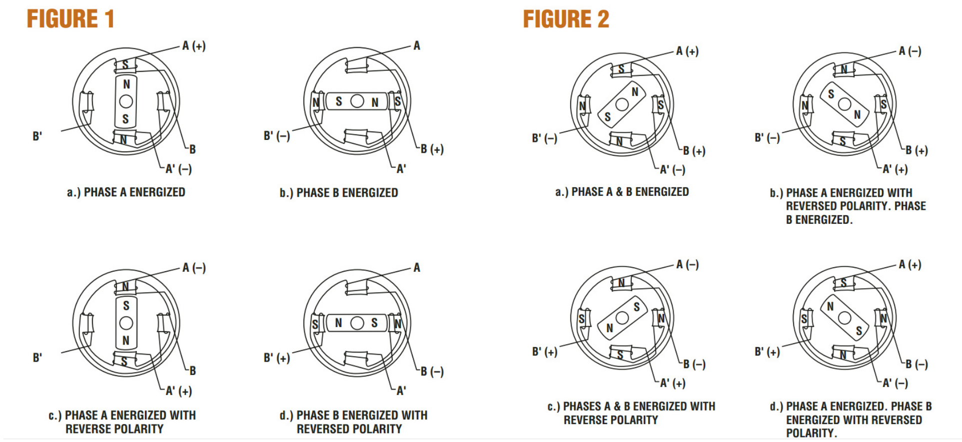


Figure 4.2: Two-phase permanent magnet rotor stepper motor [42]

This type of stepper motor can also step in smaller increments. By combining the energization from Figure 1 and Figure 2 the motor can perform a half-step rotor motion. In Figure 4.3, only phase A is energized, while in Figure 3b both phases A and B are energized. This leads to a 45° rotation of the north-seeking pole, instead of 90° as in Figures 1 and 2 [42].

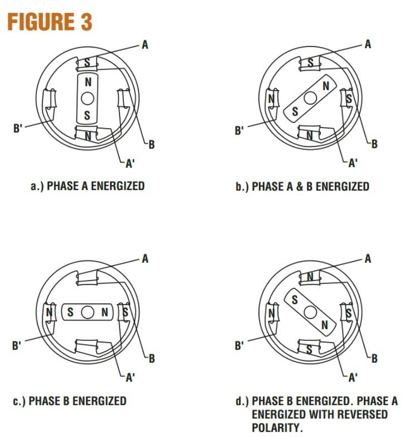


Figure 4.3: Permanent magnet stepper motor with half-step [42]

Variable reluctance(VR) stepper motor

A VR stepper motor uses a non-magnetised soft iron rotor. The rotor has teeth that are offset from the stator. The stator poles in each pair are located directly across from each other and connected in series, therefore they are energized at the same time but with different polarity. Magnetic flux lines flow between the poles through the rotor. Only the energized stator poles will line up with the teeth of the rotor as shown in Figure 4.4 where stator pole A is energized.

Magnetic flux lines pass more easily through the material with lower reluctance rather than material with higher reluctance. The rotor is made of soft iron which has a lower reluctance value than air. The difference in reluctance causes the rotor to turn so the flux lines can pass through the iron [37].

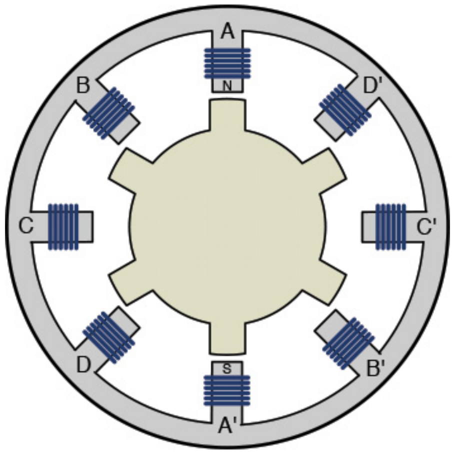


Figure 4.4: Variable reluctance stepper motor

Hybrid(HY) stepper motor

HY stepper motor is a combination of PM and VR stepper motors. The rotor is magnetized like the PM and has teeth like the VR. As shown in Figure 4.5, the rotor consists of two cups. The North and South rotor cup has different polarity and the teeth are offset by one tooth. To prevent the teeth from all aligning at the same time the stator and the rotor have a different number of teeth [36].

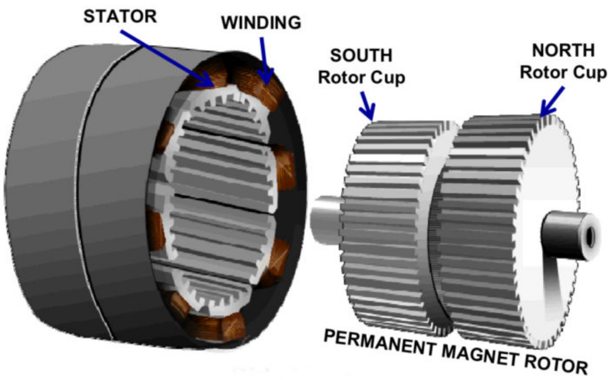


Figure 4.5: Hybrid stepper motor [6].

The HY can also half-step and micro-step. Half-step means that if the rotor is rotating 200 full steps per revolution, it will rotate 400 steps per revolution. First, one winding is energized, and then two windings are energized. This is shown in Figure 4.3 (3). Micro-stepping is full steps divided into smaller steps by changing the current ratio in two windings [25].

When the full step angle is $1,8°$, micro-stepping can divide the step angle 256 times. This equals a new step angle at $0,007°$ which is 51,200 steps/rev [7].

The Stewart Platform is built up by six EPCO-40-300-5p-st-e electrical cylinders. These have a built-in 2-phase hybrid stepper motor and operate on 24V, with a maximum current rating of 4,2A. It has a step angle of $1,8°$, 200 steps per revolution, feed constant at 5 mm/rev, and a maximum feed force fx 650N.

The hybrid stepper motor is a good choice for this project considering its possibility to move in micro-steps, making the movements smoother and more accurate. Micro-stepping also decreases mechanical noise and reduces resonance problems [23].

Figure 4.6: EPCO-40-300-5p-st-e electrical cylinder

Max.speed	180 [mm/s]
Max. acceleration	10 [m/s^2]
Feed constant	5 [mm/rev.]
Max.feed force Fx	650 [N]
Nominal Voltage	24 [V]
Nominal current	4,2 [A]
Stepper angle	$1,8 + -5\%$ [$\circ$]

Table 4.1: EPCO-40-300-5p-st-e specifications

Stepper motor drive

A stepper motor requires specialized drivers to provide the necessary power and electronic pulses to move the motor in steps. Geckodrive G201X will be used to control the motors correctly.

The Gecodrive G201X is a micro-stepping driver with a current range from 0,8A to 7,0A. Micro-stepping is steps divided into smaller steps and is typically used in applications that require a smooth motion, and an accurate position over a wide range of speeds [42]. This driver has a fixed 10 micro-step resolution and has ten DIP switches to tune to desired current.

The DIP switch setting as configured in Figure 4.8 below, is set to the maximum current rate at 4.0A.

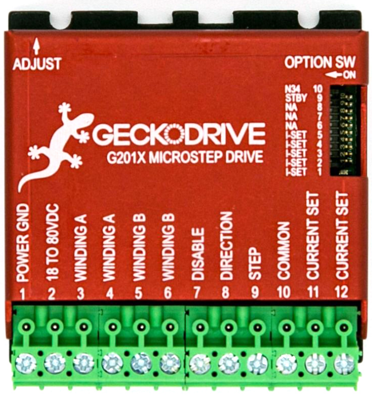


Figure 4.7: Geckodrive G201X Microstep Drive

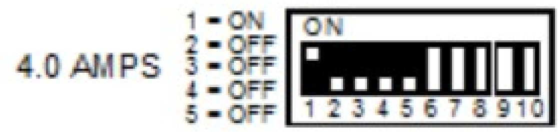


Figure 4.8: Geckodrive DIP Switch [15]

The driver has three input signals to control the stepper motors, these are controlled by an Arduino. The first input is STEP and it receives pulses from the Arduino. For each pulse the stepper motor will move one step forward. The second input is DIRECTION and controls the direction the stepper motor should turn when receiving a STEP signal. The last input signal is COMMON and can be connected to the controllers +3.3VDC, +5VDC or GND.

4.2 Encoder

An encoder is a sensor that converts motion to an electrical signal [8]. The encoder is used for the measurement of the position or rotation of a shaft or other moving parts in a machine. Typically the encoder consists of a sensor, either optical or magnetic, attached to the shaft and a processing unit that converts the sensor's output to an electrical signal. This signal can be used to provide feedback for monitoring and control purposes or to control the position or speed of the shaft.

In this project, optical encoders will be used. The optical encoder is widely used in machine tools and industrial robots as a high-precision position control sensor [26]. The advantage of this type of encoder is that they're more precise than magnetic encoders, as they're not affected by environmental factors such as temperature changes or magnetic interference [5]. Optical encoders also do not have moving parts, as they only use light to detect position, therefore these encoders suffer from less mechanical wear and tear, which leads to a longer lifetime.

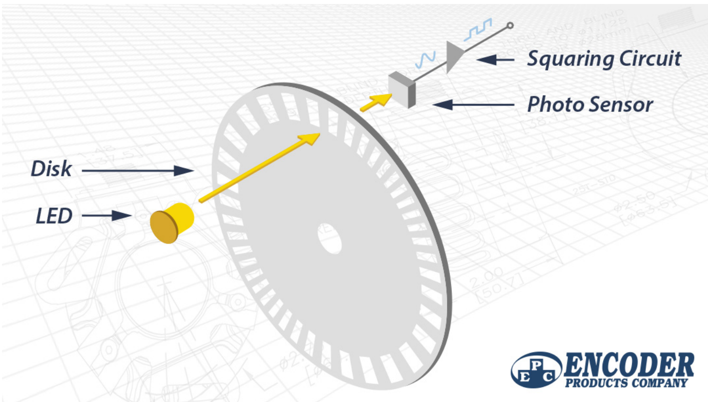


Figure 4.9: How optical encoders works [8]

As shown in Figure 4.9, the optical encoders use a LED to emit light, which passes through a transparent Code Disk with opaque lines. A photo sensor captures the light and converts it into a square wave or pulse train. This pulse signal, representing light on/off, is then sent to an electronics board and furthermore to a counter or controller. The counter or controller interprets the signal to initiate the desired action [8].

Encoders can be incremental or absolute, the difference is that incremental encoders can indicate that the position has changed but they don't give a specific position. Absolute encoders on the other hand can indicate both that the position has changed and the location of the position relative to shaft rotation [8].

The optical encoders built into the stepper cylinders are incremental and will be used to count how many steps the stepper motor has taken. The steps are then converted into a distance measured in centimetres using an Arduino code that we have developed to get an accurate position.

4.3 Microcontroller & Microcomputer

This project uses Arduino Uno and Raspberry Pi 4B. The difference between Arduino Uno and Raspberry Pi is that Arduino Uno is a microcontroller, while Raspberry Pi is a microcomputer/single-board computer (SBC). The Arduino board contains I/O connectivity, RAM, ROM, and CPU, while Raspberry Pi has all features of a computer with a processor, storage, memory, graphics driver, and connectors on the board. Unlike Arduino, the Raspberry needs an Operating System to run. Arduino only needs a compiled source code [34].

4.3.1 Arduino Uno

Six Arduino Uno micro-controllers are used to program each of the stepper cylinders to create a sine wave pattern. Each of the stepper cylinders has its own controller to reduce the workload on each Arduino. By having only one task to perform, the reading and transmission of signals will be faster, resulting in greater efficiency. Furthermore, in the event of a motor or controller failure, it will be less critical since the remaining five will continue to operate normally.

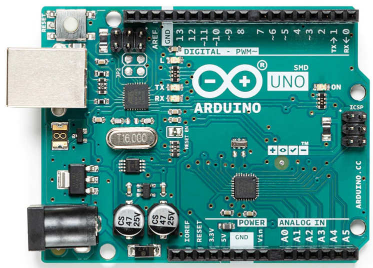


Figure 4.10: Arduino Uno Board [4]

Arduino is an open-source programmable circuit board based on the ATmega328P and has 14 digital input/output pins, 6 analog inputs, a USB connection and a power jack [39][3]. As a programming language, Arduino uses C++ with an addition of special methods and functions [13].

Microcontroller	ATmega328P
Operating Voltage	5 V
Input Voltage Recommended	7-12 V
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB
SRAM	2 KB
Clock Speed	16 MHz

Table 4.2: Arduino Uno specifications [4]

Due to its affordability and versatility, the Arduino microcontroller has become a popular option for individuals and maker spaces engaged in creating interactive hardware projects [3].

4.3.2 Raspberry Pi

Raspberry Pi is a low-cost computer built on Linux and can be programmed using languages such as Python, Scratch, Java and C/C++ [44]. This credit-card-sized computer is used worldwide to learn programming, build hardware projects, and is even used in industrial applications [41]. It has the capability to perform many tasks typically performed by a desktop computer and can be plugged into a computer monitor or Tv [40].

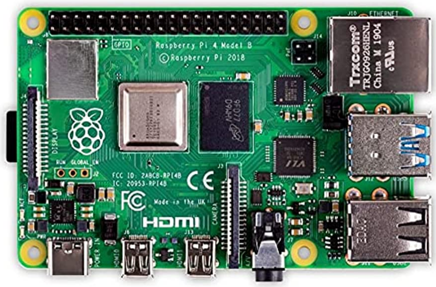


Figure 4.11: Raspberry Pi 4 Model B [27]

CPU	ARM Cortex A-72; 1,5 GHz, quad-core
RAM	2GB LPDDR4
GPU	Broadcom VideoCore VI @ 500 Hz
Video out	2 x micro-HDMI ports (up to 4K supported)
GPIO	40 pins
Display	DSI display port
Camera	CSI camera port
Power	USB-C; 5V,3A
USB	2 USB 3.0 ports; 2 USB 2.0 ports
External memory	Micro SD-card slot
Network	Gigabit Ethernet
Wireless	802.11ac 2,4/5 GHz; Bluetooth 5.0

Table 4.3: Raspberry Pi 4 Model B specifications [21]

4.4 Power Supply

There are used two different power supplies for this system. RS-PRO-2205408 is used to power the stepper motors. Each of the three power supplies are connected to two stepper motors. RS-PRO-2205410 is used to power the Arduino's and the Raspberry Pi.

Model		RS-PRO-2205408	RS-PRO-2205410
Output	DC Voltage	24V	12V
	Rated Current	10A	10A
	Rated Power	240W	120W
Input	Voltage Range	85-264 V	85-264 V
	Frequency Range	47-63Hz	47-63Hz
Other	MTBF	300 000h	300 000h

Table 4.4: Power supply specifications B

The power supplies are 230V to 24V/12V DC transformers designed to convert high voltage alternating current (AC) power at 230V to low voltage direct current (DC) power at 24V/12V.

Figure 4.12: RS-PRO Power Supplies

4.5 RS485

RS485 is a general communication standard and is commonly used as a communication method for data acquisition and control. It can enable multiple nodes to link to each other by putting multiple 485 devices on the same bus. In addition, the RS485 can link to the local network [43].

The encoders on the Stewart platform are connected to RS485. The stated protocol for the stepper motor cylinder is RS422 B but most of the equipment was already bought, including the RS485 so this will be used. The RS485 can be used in RS422 applications as it is a descendant of the RS422 and meets all the specifications B.

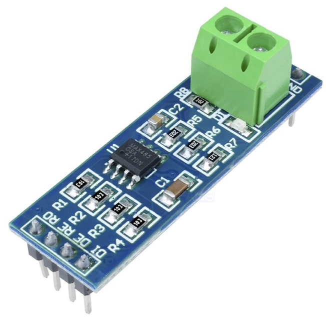


Figure 4.13: MAX485 TTL Converter [29]

The advantage of RS485 is its long transmission distance of 1200 meters, data rates of up to 10Mbps, differential transmission increases noise immunity and decreases noise emissions and the possibility of having multiple drivers and receivers on the same bus. Given the RS485 specifications, it has the ability to sustain up to 32 units while the RS422 on the other hand only allows for 1 controller and 10 receivers B.

The MAX485 TTL (transistor-transistor logic) converter makes it possible to send and receive data by using the RS485 network from micro-controllers such as Arduino. The TTL signal gets converted to RS485 for long-range and high data rates [22].

4.6 Logic Level Converter

Sparkfun Logic Level converter is a device that allows communication between digital circuits operating at different voltage levels. The converter steps down 5V signals to 3.3V and steps up 3.3V to 5V signals at the same unit. This voltage translation is needed to shift the voltage level between the Arduino (5V) and the Raspberry PI (3.3V) [33].

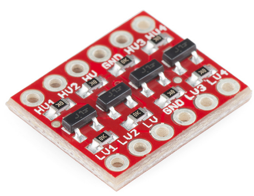


Figure 4.14: Sparkfun Voltage Converter [33]

The Sparkfun Logic Level converter prevents potential damage to components caused by different voltage levels. It utilizes a bidirectional circuit with high-voltage and low-voltage sides and uses a level-shifting mechanism with resistors and MOSFET transistors. When a signal is received

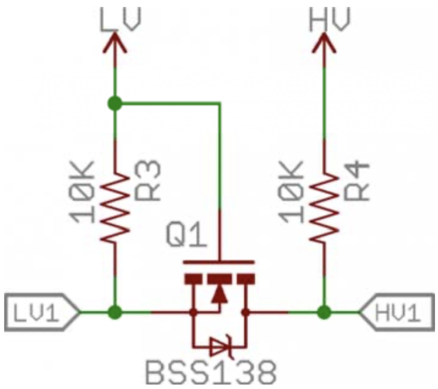


Figure 4.15: Schematic drawing of the bi-directional level-shifting used on the four channels of the Sparkfun Logic Level Converter [18]

from the high-voltage side, the MOSFET acts as a switch, allowing the signal to pass and shifting its voltage to the low-voltage side and vice versa. [18].

Chapter 5

Software Development

In order to develop the program code for this project, the tasks were divided into smaller sections.

Before starting to program the entire system, it is important to become familiar with each of the components and how they work.

5.1 Python

Python is a popular high-level programming language that is widely used for a variety of tasks such as web development, scientific computing, data analysis, artificial intelligence, and automation. It was created in the late 1980s by Guido van Rossum and has since grown to become one of the most popular programming languages in the world **??**.

One of the key strengths of Python is its simplicity and ease of use. It has a clear and concise syntax that is easy to read and understand, making it an excellent language for beginners to learn. Additionally, Python has a vast collection of libraries and frameworks that make it easy to perform complex tasks with minimal effort.

Python is an interpreted language, which means that code is executed line by line at runtime, making it very flexible and easy to debug. It is also a dynamically typed language, which means that variables do not need to be declared before they are used, making coding faster and more efficient.

Python's versatility and scalability make it an excellent choice for building complex applications, from web apps to machine learning algorithms. Its active and supportive community of developers has created many resources and tools that make learning and working with Python a breeze.

In conclusion, Python's simplicity, flexibility, and vast range of applications make it a top choice for developers of all skill levels.

5.2 Arduino C++

The Arduino platform is a popular open-source hardware and software platform that is widely used for building electronics projects. It features a microcontroller board that can be programmed using the Arduino C++ programming language, which is a variant of the C++ programming language with specific syntax and libraries designed for use with the Arduino board **??**.

Arduino C++ allows developers to write code that can interact with sensors, actuators, and other components connected to the board. The language provides a set of libraries and functions that simplify common tasks, such as reading analog and digital inputs, controlling LEDs and motors, and communicating with other devices.

Arduino C++ is easy to learn, even for beginners with little programming experience. Its syntax is similar to other C-like languages, and the Arduino IDE provides a user-friendly interface that allows developers to write, compile, and upload code to the board with ease.

One of the main advantages of Arduino C++ is its versatility. The language can be used to build a wide range of projects, from simple blinking LED projects to complex robotics and automation systems. It is also highly customizable, as developers can create their own libraries and functions to suit their specific needs.

In conclusion, Arduino C++ is a powerful and versatile programming language that allows developers to create a wide range of electronic projects using the Arduino platform. Its simplicity, versatility, and user-friendly interface make it an excellent choice for both beginners and experienced developers alike.

5.2.1 Platform Code

The code for the Stewart platform includes several libraries such as "Wire.h", "Arduino.h", "myAccelStepper.h", and "MyRotaryEncoder.h". These libraries include functions that can be implemented into the code making the arduino available to drive the stepper motors and retrieve the encoder pulses to measure the length of travel. Assigning global variables to the program its controlling the stepper motor and encoder from the Arduino microcontroller and micro stepper.

The code sets up the serial communication with the Arduino board and initializes the stepper motor, RotaryEncoder, and interrupts. The code also defines the functions for sending position and time over the I2C bus and receiving acceleration value from a connected device.

The main loop function of the code checks for the acceleration status of the stepper motor and runs it accordingly. The code also defines two interrupt service routines to read the signals from the encoder.

Overall, the code is designed to control the stepper motor using acceleration and receive positional information from a rotary encoder while communicating with the Raspberry Pi over the I2C bus.

The Raspberry Pi is the controller in the I2C network and is being set as master in the code. All logic, current state for every node in the network is handled by the code in the controller. From the controller the I2C communication/synchronization is made with the code below. The six calculated leg lengths are being send trough a "for" loop to the list of Arduino addresses.

```

//I2C Setup for the multiple nodes
    const int i2c_slaves[] = {0x08, 0x12, 0x16, 0x20, 0x24, 0x28};

//Initialize I2C master
    Pi2c rpi(0x00);

//Read information from the six Aduinos
```

```
    for (int i = 0; i < 6; i++){
        rpi.i2cChangeSlave(i2c_slaves[i]);
        rpi.i2cRead((char*)&floatsToReceive + length*i,length);
    }

//Write output/length to the six Arduinos
    for (int i = 0; i < 6; i++){
        rpi.i2cChangeSlave(i2c_slaves[i]);
        rpi.i2cWrite((char*)&floatsToSend + 4*i,4);
    }

```

I2C code for the Arduino:

```
void setup() {
  Wire.begin(0x08);
  Wire.onRequest(sendPositionAndTime);
  Wire.onReceive(recieveAccC0);
}

void sendPositionAndTime()
{
  long positionAndTime[2] = {0};
  char *char_ar = (char*)positionAndTime; //Create String

  encoder.getPositionAndTime(positionAndTime);// Get position and time of measurment
  Wire.write(char_ar,8); //Write two long to Pi.

}

void recieveAccC0(int numBytes){

//Set Up Vars
  float c0=0.0;
  char* c0Char = (char *)&c0;
  int count=0;

  //We'll recieve one byte at a time. Stop when none left
  while(Wire.available())
  {
    char c = Wire.read();    // receive a byte as character
    //Create float from the Byte Array
    *(c0Char+count) = c ;
    count++;
  }
}
```

All code files are available at: https://github.com/Sondreesp/bachelor-stewart-platform.git

Chapter 6

Results

This chapter delves into the testing procedure of the Stewart platform system. The primary objective of the test is to evaluate the system's overall performance in terms of functionality, speed, precision, and accuracy.

Mechanical testing will involve evaluating the system's physical components to identify any potential issues that may impact its functionality.

Electrical testing will focus on evaluating the electronic components of the system, such as the power supplies, drivers and controllers to ensure that they are functioning as intended.

6.1 Mechanical testing

A mechanical test of a Stewart platform is a process that involves evaluating the functionality of the platform, including its load-bearing capacity, precision and flexibility. Testing can be performed by applying various loads to the platform and performing precision movements.

Mechanical testing of the Stewart platform is important to evaluate the construction's performance and make sure the construction meets the requirements and will work as intended. By conducting a test, weaknesses, limitations, or deviations in the system can be identified. The result from the tests can be used to improve the design, optimize performance, and ensure that the platform meets the necessary specifications.

After conducting a mechanical test on the Stewart Platform, it was found that the mounting brackets securing the stepper cylinders were inadequate as they failed to hold the joints in place. To address this issue, new mounting brackets were created that allow the spherical joints to be locked in place using two screws, providing improved stability and security.

It was also found that the base plate lacked sufficient rigidity, causing the platform to sway. This will cause instability and pose a potential danger, particularly if the platform is carrying a heavy load and undergoing rapid movements. Therefore the base plate will need to be replaced and built with a stronger material. Additionally, modifications were made to the base plate to improve the platform's portability.

During the testing of two cylinders, an extra load was added to the platform to evaluate its load-bearing capacity. The platform was tested with an additional weight of 80kg without any struggles. The platform was designed to move loads up to 60kg and is therefore within good margin to the capability of the platform.

Testing of mechanical safety mechanism

A safety mechanism was installed between the stepper motor cylinders and the universal joints to prevent damage to the equipment in case of a malfunction, see Figure 2.1. The safety mechanism, made of aluminium with a small diameter, was designed to break first in the event of any issues. This was done to prevent damage to the expensive components.

When testing two stepper motor cylinders simultaneously, one of the cylinders got stuck. As a result, the safety mechanism broke when the other cylinder continued running and applied force to it. This worked exactly as intended.

However, the weakness of the safety mechanism is evident. During the testing of tree cylinders simultaneously, two additional safety mechanisms broke. These cylinders were positioned on the right side of the corners, and none of them experienced any obstructions. It appears that the safety mechanisms were not sufficiently robust and gradually bent with each program run until they eventually broke.

6.2 Electrical testing

Electrical testing of a Stewart platform is a process that involves evaluating electronic components in the system to ensure that they function as expected and interact correctly.

Testing can be performed by measuring the different voltages in the system and checking the electrical connection cables to ensure they are properly connected. By examining the electrical signals, errors, weaknesses, or incorrect connections in the system can be detected. It also ensures that the platform operates safely.

The electrical installation was controlled before testing the platform. The control was performed to secure that the wiring and connections were correct. Measurements were done with a multimeter at the connection points. The voltage supplied from the Arduino to RS485 was somewhat unstable, ranging between 3.8V and 5V depending on the quality of the connection.

The Microstep driver has a fixed 10 micro-step resolution, this may cause the driver to draw twice the power supply needed. In this specific scenario, a minimum of 8.0A is required because microstepping can result in both windings simultaneously drawing 4.0A. While testing the circuits with one electrical cylinder, the loop works fine. This may result in slower operation of the stepper cylinders.

The electrical circuits of the Stewart platform were tested using an oscilloscope. The oscilloscope was connected to the Arduino, allowing us to monitor the output of the code and ensure its proper functioning, even with delays as short as 1 microsecond.

When observing the stepper driver with the oscilloscope, the observations revealed a step period of 50 microseconds and a Vpp (Peak-to-peak voltage) of 38V as shown in Figure 6.1.

When changing the delayed time to 10ms the signals on the winding and stepper gets a lot of interference on the signal and the stepper cylinder is not moving, only making a screeching sound. The result on the winding is shown in the figure 6.2, and the step and direction is shown in figure 6.3.

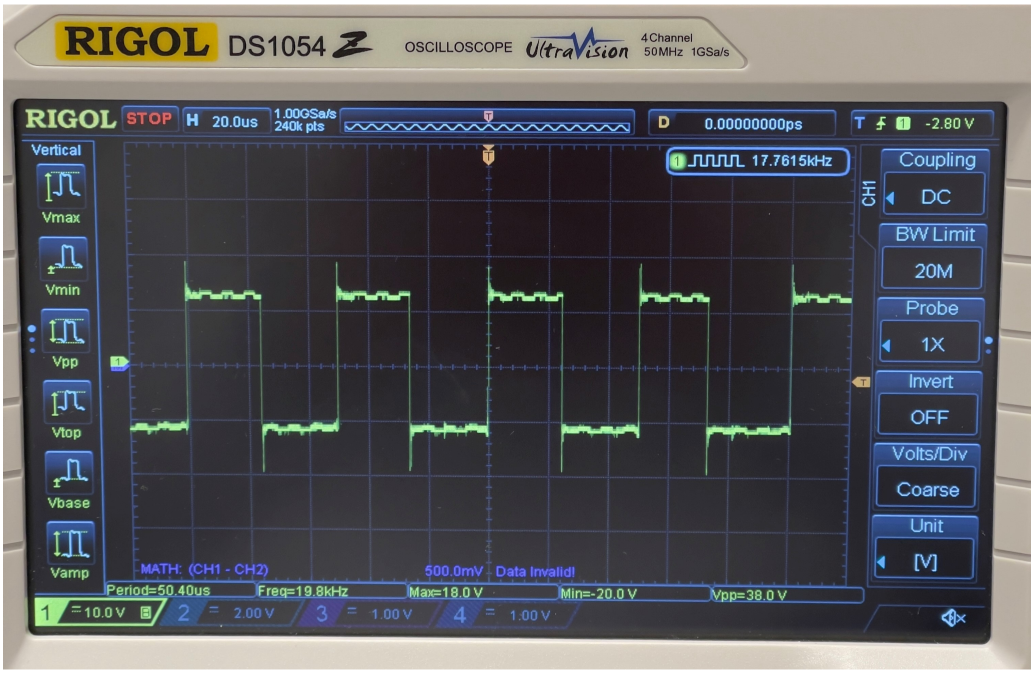


Figure 6.1: Oscilloscope picture of stepper running with 50us period

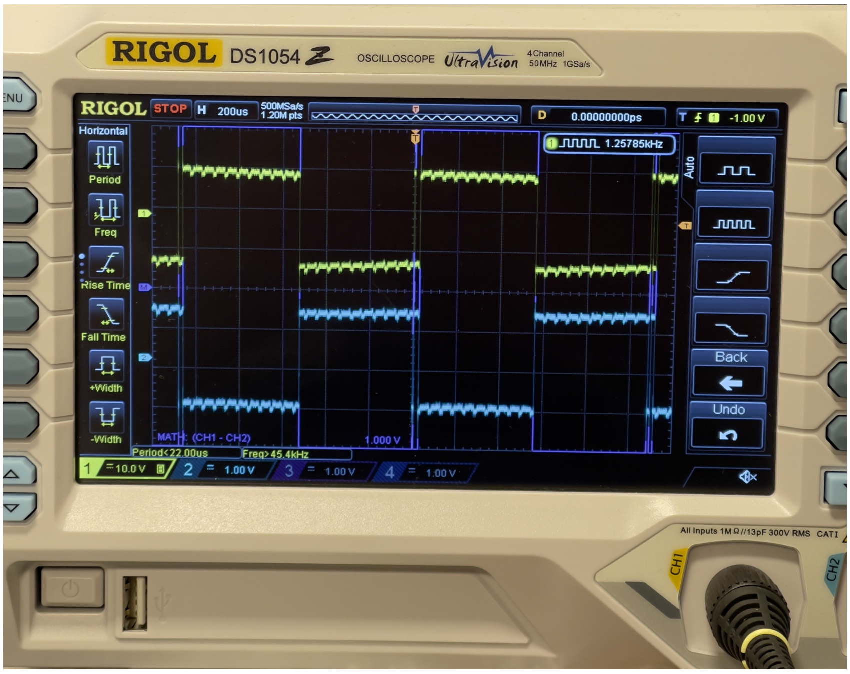


Figure 6.2: Oscilloscope picture of winding with 10us

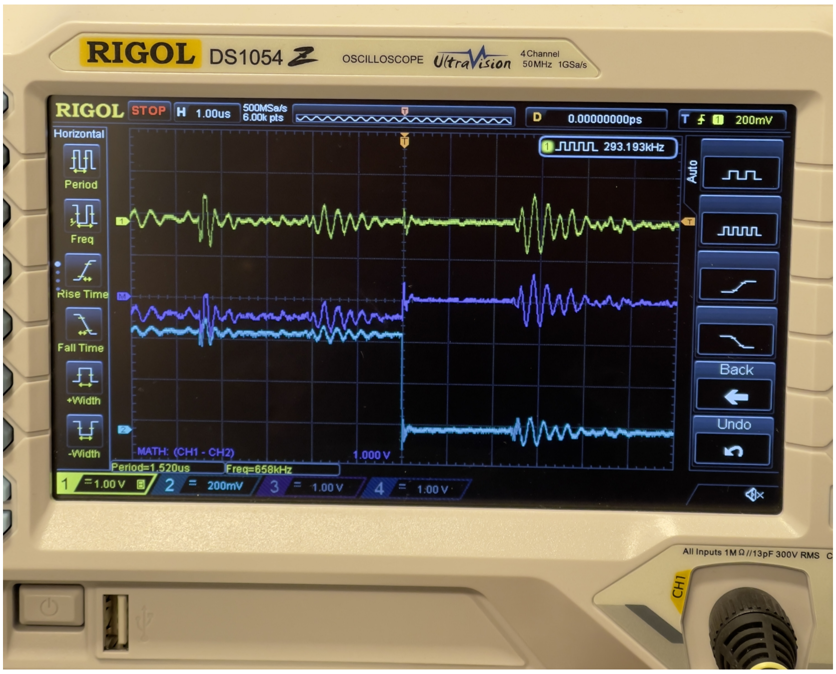


Figure 6.3: Oscilloscope picture of Stepper and direction

6.3 System testing

System testing is a phase of software testing where the entire system is tested as a whole. It is conducted to evaluate if the system meets the specified requirements and that it functions correctly.

The software system of the Stewart platform has been tested in different ways to evaluate each step of the process.

Firstly, one stepper motor was tested with Arduino code. This code provided information regarding the precise length of the distance covered by the stepper cylinder. After verifying that the Arduino code worked as expected, the communication method I2C was tested with the Arduino code. The Raspberry Pi code with I2C succeeded to control the stepper cylinder and provided information as desired.

In the next phase, the code was optimized to enable simultaneous operation of three stepper cylinders by utilizing I2C communication. This test was done with a different code that did not give out the length of the stepper cylinder movements. The primary objective of this test was to ensure the proper functioning of the I2C connection for multiple cylinders.

Lastly, the code was optimized to be able to operate all the stepper cylinders simultaneously by utilizing I2C. However, an issue arose as only four out of the six cylinders were functioning. It was discovered that the two Arduinos providing a 5V power supply to the RS485 modules were unable to drive the stepper cylinder concurrently. Consequently, in order to achieve simultaneous operation of all cylinders, it was necessary to disconnect the RS485s, resulting in the loss of encoder feedback regarding the cylinder's travel distance.

6.4 Discussion

Based on the results of the tests most of the goals are accomplished.

During mechanical testing, improvements have been done to strengthen the platform and make it easier to transport. For future work changing the base plate must be done to further improve the stability of the platform.

The mechanical safety mechanisms work but they are not sufficiently robust for normal use and must therefore be strengthened.

During electrical testing, most equipment functioned as expected but there can be some challenges with the speed of the stepper motors if the stepper drivers draw 8.0A each. This could happen in a event of both winding A/B getting drawn simultaneously, and since there is two steppers per power supply the total possible amount of current could be 16.0A. The Arduino also has an unstable voltage output depending on the quality of the connections on the board, and could have been better if jump wires with cable rivets had been installed.

Testing of the software system did not give the desired results. Due to a lack of spare parts and power supplies testing of the final results has not been possible. Although the code has been made and tested for some parts of the system, it is not enough to conclude that it will work as intended. Without these results, the system can't be connected to the digital twin as originally planned.

However, the communication system works for all stepper cylinders and feedback has been established for four cylinders simultaneously.

Chapter 7

Conclusion

The results confirm that most of the goals were accomplished. The electrical components are mounted and organized in junction boxes. The mechanical structure is modified with new mounting brackets connecting the stepper cylinders to the base plate, resulting in a strengthened construction. To simplify transportation, the bottom plate has been modified to fit through doors by folding the bottom plate. I2C communication has been selected as an appropriate communication method for the system and has been implemented in the system code. The code from the PhD student has been modified and is capable of controlling all six cylinders simultaneously.

The feedback system is not yet accomplished. The code is completed but due to problems with the power supply for the RS485 and lack of spare parts (the mechanical safety mechanism), testing for all six cylinders has not been possible.

7.1 Suggestions for improvement

- Change base plate:

  The current base plate lacks sufficient strength, causing the platform to sway. To ensure the platform's stability, it is necessary to replace the base plate with a more robust alternative like Aluflex.

- Install limit switches:

  The encoders don't know where they are. In the current code, the encoders are programmed to know that if the last position is the same as the new position it is either at the top or bottom of its range. This system doesn't always work and the cylinders struggle to change direction. By installing limit switches it will be easier for the encoder to know when it reaches the bottom and prevent damage to the equipment.

- Touch Display and Xbox controller:

  A display screen compatible with Raspberry Pi has been acquired for connection to the platform. Additionally, an Xbox controller can be connected to control the platform's movements based on the commands given by the Xbox controller.

- Power supply to RS485

The Arduino doesn't manage to drive the stepper motors while supplying 5V to the RS485s. Therefore it will be necessary to power them from another power supply to be able to run the system as a whole.

Bibliography

[1] *About us*. en. Dec. 2016. URL: https://www.hvl.no/en/about/ (visited on Apr. 13, 2023).

[2] *All About Stepper Motors*. en-US. URL: https://learn.adafruit.com/all-about-stepper-motors/what-is-a-stepper-motor (visited on Apr. 13, 2023).

[3] *Arduino Uno For Beginners - Projects, Programming and Parts (Tutorial)*. URL: https://www.makerspaces.com/arduino-uno-tutorial-beginners/ (visited on Apr. 13, 2023).

[4] *Arduino Uno Rev3 SMD*. en. URL: https://store.arduino.cc/products/arduino-uno-rev3-smd (visited on Apr. 13, 2023).

[5] *Capacitive, Magnetic, and Optical Encoders – Comparing the Technologies*. en. June 2019. URL: https://www.cuidevices.com/blog/capacitive-magnetic-and-optical-encoders-comparing-the-technologies (visited on Apr. 13, 2023).

[6] Danielle Collins. *Stepper motors: Permanent magnet, variable reluctance, and hybrid*. en-US. Apr. 2018. URL: https://www.linearmotiontips.com/stepper-motors-differences-between-permanent-magnet-variable-reluctance-and-hybrid-types/ (visited on May 11, 2023).

[7] Danielle Collins. *When should you use microstepping control for stepper motors?* en-US. May 2019. URL: https://www.linearmotiontips.com/when-should-you-use-microstepping-control-for-stepper-motors/ (visited on May 11, 2023).

[8] Encoder Products Company. *Encoder: The Ultimate Guide — What is an Encoder, Uses & More — EPC*. en. URL: https://www.encoder.com/article-what-is-an-encoder (visited on Apr. 13, 2023).

[9] Bhaskar Dasgupta and T. S. Mruthyunjaya. "The Stewart platform manipulator: a review". en. In: *Mechanism and Machine Theory* 35.1 (Jan. 2000), pp. 15–40. ISSN: 0094-114X. DOI: 10.1016/S0094-114X(99)00006-3. URL: https://www.sciencedirect.com/science/article/pii/S0094114X99000063 (visited on Apr. 13, 2023).

[10] T. A. Dwarakanath, Bhaskar Dasgupta, and T. S. Mruthyunjaya. "Design and development of a Stewart platform based force–torque sensor". en. In: *Mechatronics* 11.7 (Oct. 2001), pp. 793–809. ISSN: 0957-4158. DOI: 10.1016/S0957-4158(00)00048-9. URL: https://www.sciencedirect.com/science/article/pii/S0957415800000489 (visited on Apr. 13, 2023).

[11] ed. *Raspberry Pi Arduino Serial Communication - Everything You Need To Know*. en-US. Nov. 2019. URL: https://roboticsbackend.com/raspberry-pi-arduino-serial-communication/ (visited on Apr. 13, 2023).

[12] Sondre Espeland. *Stewart_Py*. original-date: 2023-02-28T10:14:49Z. Feb. 2023. URL: https://github.com/Sondreesp/Stewart_Platform (visited on May 22, 2023).

[13] *Everything You Need to Know About Arduino Code*. Section: circuito.io blog. Aug. 2018. URL: https://www.circuito.io/blog/arduino-code/ (visited on Apr. 13, 2023).

[14] *Figure 3: Permanent magnet stepper motor [2].* en. URL: https://www.researchgate.net/figure/Permanent-magnet-stepper-motor-2_fig3_339738022 (visited on May 11, 2023).
[15] *G201X / G210X User Manual REV-6 — Geckodrive.* URL: https://www.geckodrive.com/support/g201x-g210x-rev-6 (visited on Apr. 13, 2023).
[16] K. S. Galal. *MODERN ROBOTICS MECHANICS, PLANNING, AND CONTROL Modern Robotics Mechanics, Planning, and Control c.* Jan. 2017. URL: https://www.academia.edu/39668978/MODERN_ROBOTICS_MECHANICS_PLANNING_AND_CONTROL_Modern_Robotics_Mechanics_Planning_and_Control_c (visited on May 21, 2023).
[17] *How a Stepper Motor Works - How To Mechatronics.* URL: https://howtomechatronics.com/how-it-works/electrical-engineering/stepper-motor/?utm_content=cmp-true (visited on May 11, 2023).
[18] *How Bidirectional Logic Level Converter Works? Logic Level Shifter.* URL: https://www.electronicshub.org/bidirectional-logic-level-converter/ (visited on Apr. 13, 2023).
[19] Eric Peña and Mary Grace Legaspi. *Understanding the UART.* en-US. Jan. 2021. URL: https://www.embedded.com/understanding-the-uart/ (visited on Apr. 13, 2023).
[20] Bo Long. "Three degree of freedom universal joint". en. US8333526B2. Dec. 2012. URL: https://patents.google.com/patent/US8333526B2/en (visited on Apr. 13, 2023).
[21] Raspberry Pi Ltd. *Raspberry Pi 4 Model B specifications.* en-GB. URL: https://www.raspberrypi.com/products/raspberry-pi-4-model-b/specifications/ (visited on Apr. 13, 2023).
[22] *MAX485 TTL To RS485 Converter Module.* en. URL: https://www.flyrobo.in/max485-ttl-rs485-converter-module (visited on Apr. 13, 2023).
[23] *Microstepping in Stepper Motors Tutorial — automate.org.* URL: https://www.automate.org/blogs/microstepping-tutorial-a-brief-overview (visited on May 11, 2023).
[24] *Offshore Passenger Transfer System — PALFINGER MARINE.* en. URL: https://www.palfingermarine.com/en/deck-equipment/offshore-passenger-transfer-system (visited on Apr. 20, 2023).
[25] *Operating Principles of a Microstep Stepper Motor Drive.* URL: https://www.orientalmotor.com/stepper-motors/stepper-motor-videos/stepper-motor-microstep-principles.html (visited on Apr. 27, 2023).
[26] *Optical Encoder — Types, Structure, Application, and more — MELTEC Corporation.* en-US. Mar. 2022. URL: https://etching-meltec.com/optical-encoder/ (visited on Apr. 13, 2023).
[27] *Raspberry Pi 4 Model B 8GB.* URL: https://www.amazon.com/Raspberry-Pi-4-4G-Model/dp/B081YD3VL5 (visited on Apr. 13, 2023).
[28] *RS-485 Serial Interface Explained.* en. Aug. 2020. URL: https://www.cuidevices.com/blog/rs-485-serial-interface-explained (visited on May 11, 2023).
[29] *RS485 modul.* no. URL: https://artigereliv.no/produkt/elektronikk/mikrokontrollere/sensorer-og-tilbehor/rs485-modul (visited on Apr. 13, 2023).
[30] *Sensors — Free Full-Text — A Geometric Approach for Real-Time Forward Kinematics of the General Stewart Platform.* URL: https://www.mdpi.com/1424-8220/22/13/4829 (visited on May 21, 2023).
[31] *Serial Peripheral Interface (SPI) - SparkFun Learn.* URL: https://learn.sparkfun.com/tutorials/serial-peripheral-interface-spi/programming-for-spi (visited on Apr. 13, 2023).
[32] Diego Silva, Julio Garrido, and Enrique Riveiro. "Stewart Platform Motion Control Automation with Industrial Resources to Perform Cycloidal and Oceanic Wave Trajectories".

en. In: *Machines* 10.8 (Aug. 2022). Number: 8 Publisher: Multidisciplinary Digital Publishing Institute, p. 711. ISSN: 2075-1702. DOI: 10.3390/machines10080711. URL: https://www.mdpi.com/2075-1702/10/8/711 (visited on Apr. 13, 2023).

[33] *SparkFun Logic Level Converter - Bi-Directional - BOB-12009 - SparkFun Electronics.* URL: https://www.sparkfun.com/products/12009 (visited on Apr. 13, 2023).

[34] Ravi Teja. *What are the Differences Between Raspberry Pi and Arduino?* en-US. Apr. 2021. URL: https://www.electronicshub.org/raspberry-pi-vs-arduino/ (visited on Apr. 13, 2023).

[35] *The Basics of the Stewart Platform — Acrome Robotics.* URL: https://acrome.net/post/the-basics-of-the-stewart-platform (visited on Apr. 13, 2023).

[36] The Engineering Mindset. *Hybrid Stepper Motor Basics.* Dec. 2021. URL: https://www.youtube.com/watch?v=Da63f16KKDo (visited on May 11, 2023).

[37] *The Variable Reluctance Stepper Motor - YouTube.* URL: https://www.youtube.com/watch?v=vc0ZW44fXgc (visited on May 11, 2023).

[38] *UART vs I2C vs SPI – Communication Protocols and Uses.* en-US. Sept. 2019. URL: https://www.seeedstudio.com/blog/2019/09/25/uart-vs-i2c-vs-spi-communication-protocols-and-uses/ (visited on Apr. 13, 2023).

[39] *UNO R3 — Arduino Documentation.* URL: https://docs.arduino.cc/hardware/uno-rev3 (visited on Apr. 13, 2023).

[40] *What is a Raspberry Pi?* en-GB. URL: https://www.raspberrypi.org/help/what-is-a-raspberry-pi/ (visited on Apr. 13, 2023).

[41] *What is a Raspberry Pi? — Opensource.com.* en. URL: https://opensource.com/resources/raspberry-pi (visited on Apr. 13, 2023).

[42] *What is a stepper motor? - Principles, types and crontollers.* URL: https://www.omega.co.uk/prodinfo/stepper_motors.html (visited on Apr. 13, 2023).

[43] *What is RS485 - Wiring, Communication and Difference with RS232 - Renke.* en-US. Section: Blogs. URL: https://www.renkeer.com/what-is-rs485/ (visited on Apr. 13, 2023).

[44] *What Programming Language Does Raspberry Pi Use?* URL: https://linuxhint.com/what-programming-language-raspberry-pi-use/ (visited on Apr. 13, 2023).

Appendix A

Loop figures

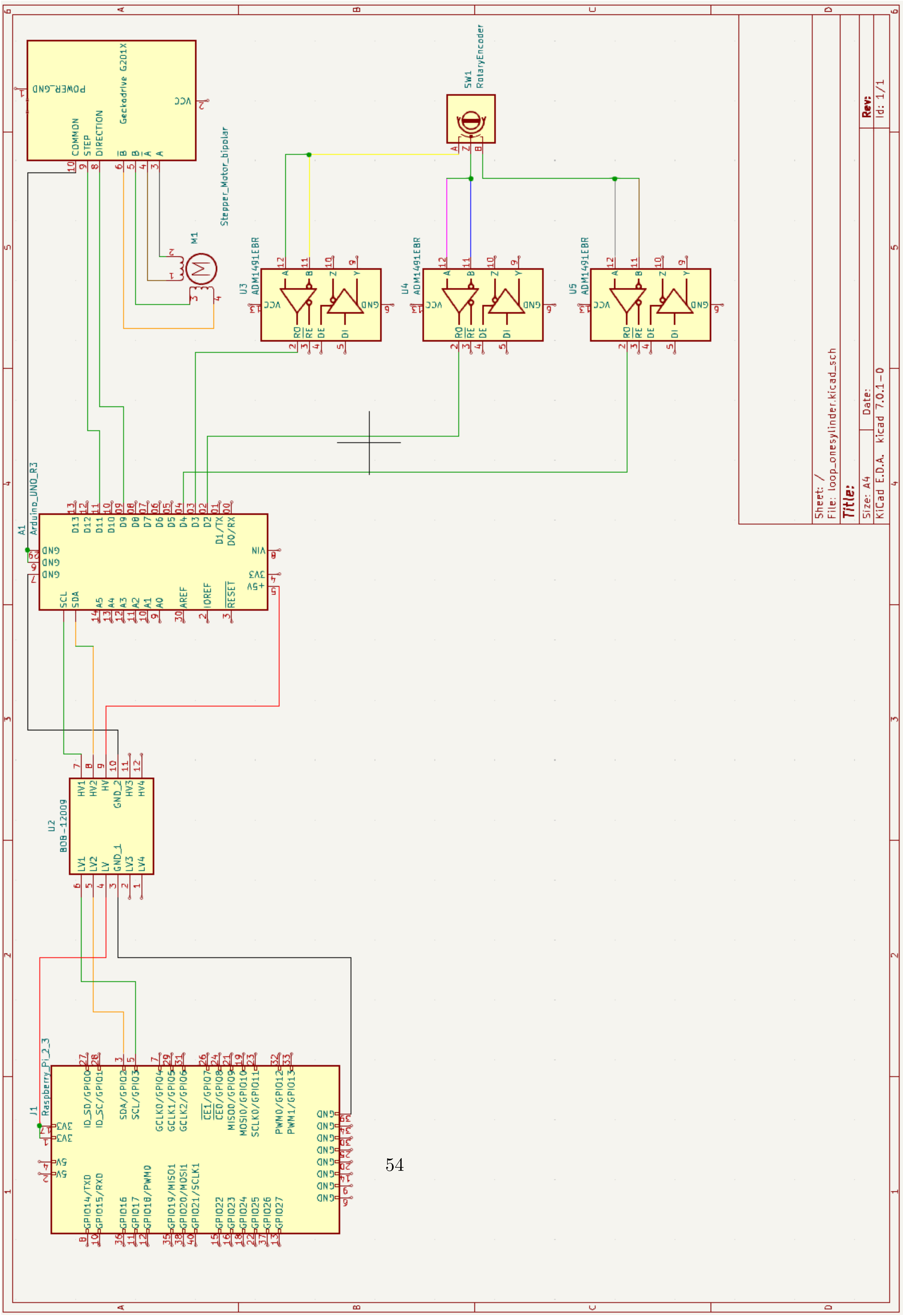


Figure A.1: Loop Cylinder

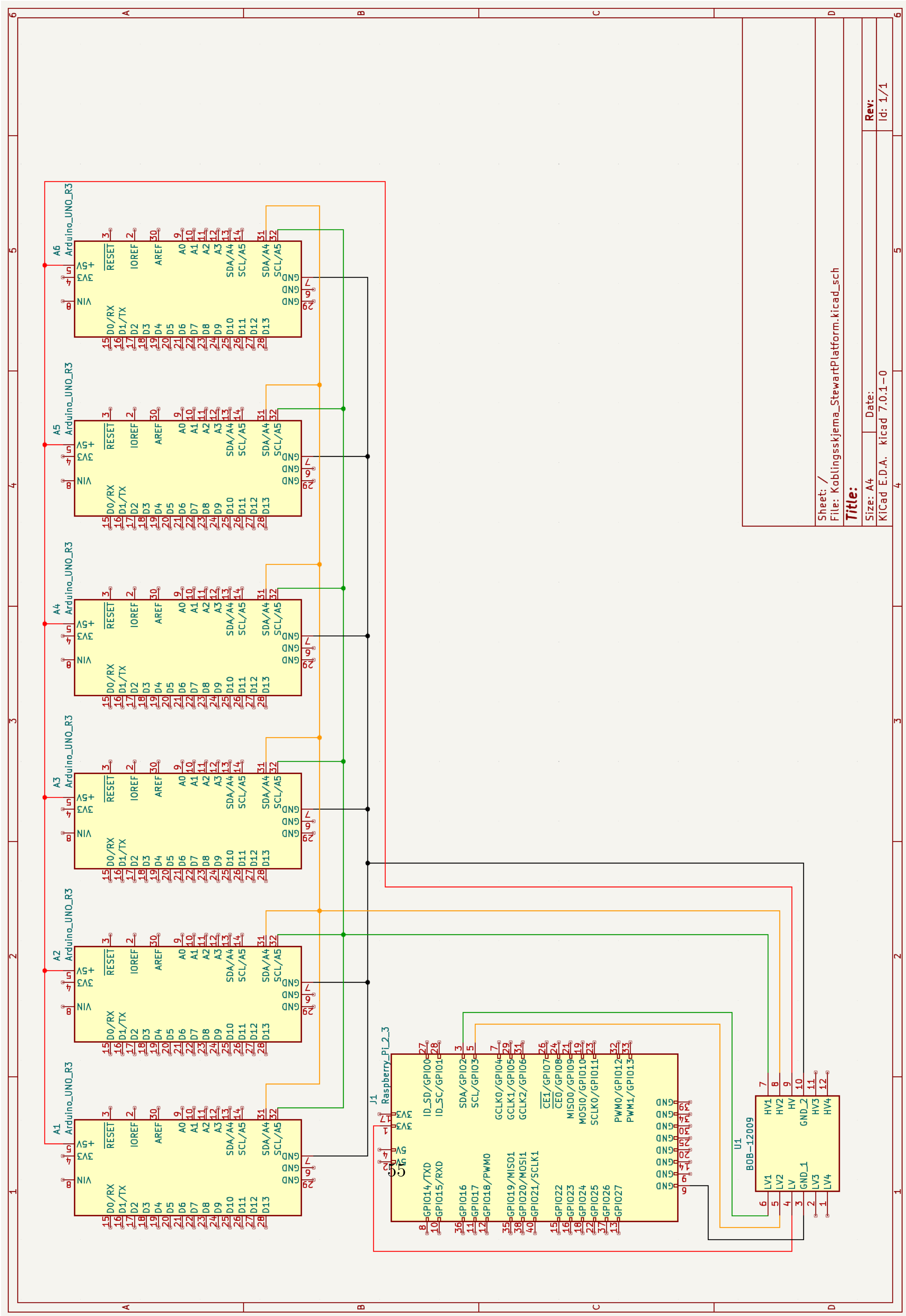


Figure A.2: Loop I2C

Appendix B

Pdf-files

https://atnel.pl/download/poradniki/rs485/AN-960.pdf

https://pdfserv.maximintegrated.com/en/an/AN723.pdf

Link to Github with all code-files:
https://github.com/Sondreesp/bachelor-stewart-platform.git

FEATURES

- Universal 85 - 264V AC Active PFC
- Slimline design: width 32mm
- Efficiency up to 93%
- DC OK function
- Operating temperature range - 40℃ to +70℃
- DC ON output status indicator LED
- Output short circuit, over-current, over-voltage protection.
- EMI performance meets. CISPR32 / EN55032 CLASS B
- Safety according to IEC/EN/UL62368/IEC/EN60079/UL 61010
- ATEX, IECEx increased safety type explosion-proof certification approved

RS PRO Embedded Switch Mode Power Supplies

RS Stock No:2205410,2205411

RS Professionally Approved Products bring to you professional quality parts across all product categories. Our product range has been tested by engineers and provides a comparable quality to the leading brands without paying a premium price.

Product Description

AC-DC DIN rail power supply suitable for a wide range of Industrial, Machinery and Instrumentation applications. cost-effective, energy efficient **explosion-proof solution** for standard DIN-rail mounting. The products offer a high level of stability and immunity to noise, compliant with international IEC62368 standards for EMC and safety specifications meet IEC/EN/UL62368, IEC/EN60079. These lightweight AC-DC converters also have an extremely compact design for space saving and are ideal for applications such as industrial control equipment, machinery, and all kinds of applications in a harsh environments. The power supply meets the 'ec' increased safety and 'nC' enclosed-break type n explosion-proof certification and is suitable for explosive environments where the equipment protection level is Gc in zone 2.

General Specifications

Model	AC-DC 120W ATEX and IECEx power supply
Mounting Type	DIN Rail mount
MTBF	MIL-HDBK-217F@25°C > 300,000 h
Applications	Industrial control systems, instrumentation and machinery equipment

RS Stock#	Input Voltage	Output Voltage	Output Current	Adj'range (V)	Wattage	Efficiency (Typ)
2205410	85 to 264V ac 120 to 370V dc	12V	10A	11.8-14V	120W	92%
2205411	85 to 264V ac 120 to 370V dc	24V	5A	23.5-28V	120W	93%

Input Specifications

Input Specification	
Voltage Range	85 to 264V ac, 120 to 370V dc
Frequency	47 to 63Hz
AC Current Rating	1.5A/115V ac, 0.75A/230V ac
Inrush Current	15A/ 115V ac, 30A / 230V ac
Leakage	<1mA
Power Factor	0.98 115Vac, 0.94 230Vac

Output Specifications

Output Specification		
MPN	2205410	2205411
Output voltage	12V	24V
Trim range	11.8-14V	23.5-28V
Rated Current	10A	5A
Ripple & Noise (max.) *	100mV	100mV
Rated Power	120W	120W
Line Regulation typ.	±0.5%	±0.5%
Load Regulation typ.	±1%	±1%
Max Capacitive load µF	80,000µF	50,000µF
Minimum Load	0%	0%

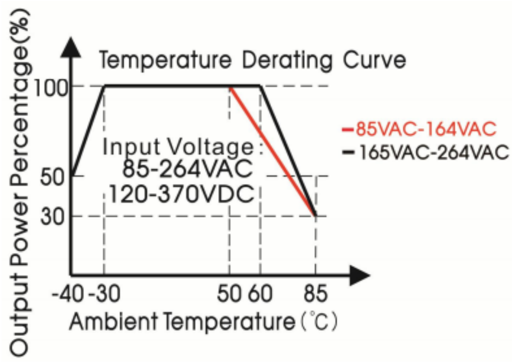
Hold Up Time (Typ)	15ms					
DC OK Signal*	30VDC/1A Max					
Over Voltage Protection	12V output ≤18V (Hiccup, self-recovery after the abnormality is removed)					
	24V output ≤35V (Hiccup, self-recovery after the abnormality is removed)					
Over-current Protection	105% - 200% Io, self-recovery					
Short Circuit Protection	Constant current hiccup mode (constant current mode works 1s and stop 10s) continuous, self-recovery.					
Over-temperature Protection	230VAC, 30% load	Over-temperature protection start	-	105	-	℃
		Over-temperature protection release	60	-	-	
Isolation	3KVAC					

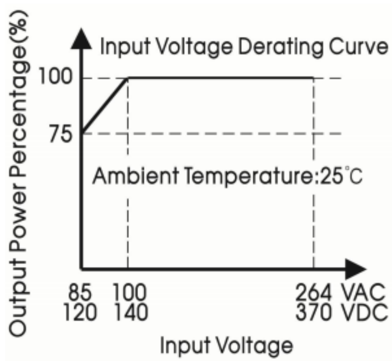
Note: *The "Tip and barrel method" is used for ripple and noise test, output parallel 47uF electrolytic capacitor and 0.1uF ceramic capacitor, please refer to Enclosed Switching Power Supply Application Notes for specific information.

General Specifications

<table>
<tr><th colspan="2">Item</th><th colspan="3">Operating Conditions</th><th>Min</th><th>Typ</th><th>Max.</th><th>Unit</th></tr>
<tr><td rowspan="3">Isolation</td><td>Input-Output</td><td colspan="3" rowspan="3">Electric strength test for 1min., leakage current <15mA</td><td>3000</td><td>-</td><td>-</td><td rowspan="3">VAC</td></tr>
<tr><td>Input-Earth</td><td>1500</td><td>-</td><td>-</td></tr>
<tr><td>Output-Earth</td><td>500</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">Insulation Resistance</td><td>Input-Earth</td><td colspan="3" rowspan="3">At 500VDC</td><td>100</td><td>-</td><td>-</td><td rowspan="3">MΩ</td></tr>
<tr><td>Input-Output</td><td>100</td><td>-</td><td>-</td></tr>
<tr><td>Output-Earth</td><td>100</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Operating Temperature</td><td colspan="3"></td><td>-40</td><td>-</td><td>+85</td><td rowspan="2">℃</td></tr>
<tr><td colspan="2">Storage Temperature</td><td colspan="3"></td><td>-40</td><td>-</td><td>+85</td></tr>
<tr><td colspan="2">Storage Humidity</td><td colspan="3" rowspan="2">Non-condensing</td><td>20</td><td>-</td><td>90</td><td rowspan="2">%RH</td></tr>
<tr><td colspan="2">Operating Humidity</td><td>-</td><td>-</td><td>95</td></tr>
<tr><td colspan="2" rowspan="4">Power Derating</td><td rowspan="3">Operating temperature derating</td><td colspan="2">-40 to -30℃</td><td>5</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="3">%/℃</td></tr>
<tr><td>+55 to +85℃</td><td>85VAC-164VAC</td><td>2.0</td></tr>
<tr><td>+60 to +70℃</td><td>165VAC-264VAC</td><td>2.8</td><td>-</td><td>-</td></tr>
<tr><td>Input voltage derating</td><td colspan="2">85VAC-100VAC</td><td>1.67</td><td>-</td><td>-</td><td>%/VAC</td></tr>
<tr><td colspan="2">Safety Standard</td><td colspan="3"></td><td colspan="4">Meet IEC/EN/UL62368/IEC/EN60079/UL61010</td></tr>
<tr><td colspan="2">Safety Certification</td><td colspan="3"></td><td colspan="4">IEC/EN60079/EN62368/UL61010 (UL61010 Pending)</td></tr>
<tr><td colspan="2">Safety Class</td><td colspan="3"></td><td colspan="4">CLASS I (PE and must be connected)</td></tr>
<tr><td colspan="2">MTBF</td><td colspan="3">MIL-HDBK-217F@25℃</td><td colspan="4">＞300,000 h</td></tr>
</table>

Derating





Note: 1. With an AC input voltage between 85 -100VAC and a DC input between 120-140VDC the output power must be derated as per the temperature derating curves.

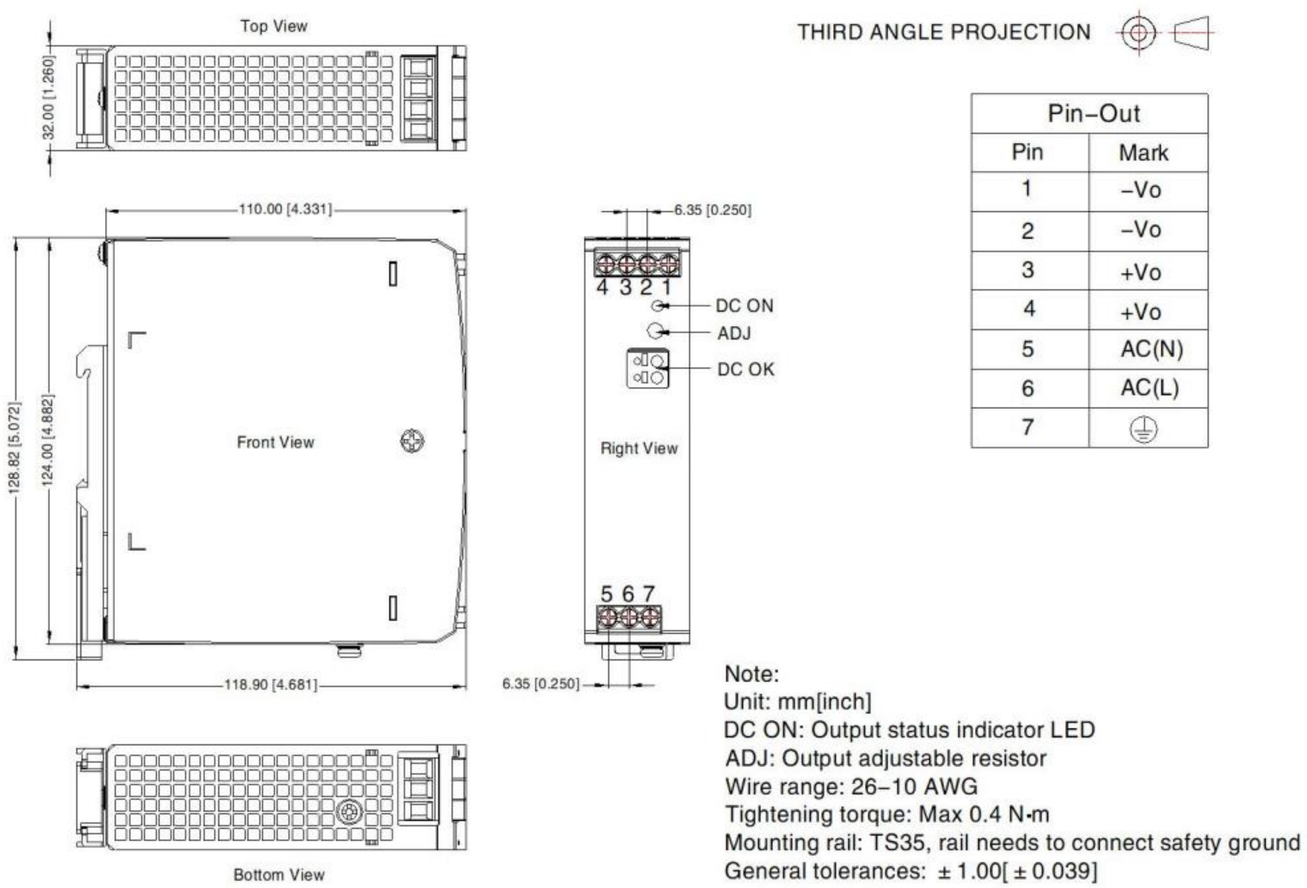
EMC Specifications

Emissions	CE	CISPR32/EN55032 CLASS B	
	RE	CISPR32/EN55032 CLASS B	
	Harmonic Current	IEC/EN61000-3-2 CLASS D	
Immunity	ESD	IEC/EN 61000-4-2 Contact ±6KV/Air ±8KV	Perf. Criteria A
	RS	IEC/EN 61000-4-3 10V/m	Perf. Criteria A
	EFT	IEC/EN 61000-4-4 ±4KV	Perf. Criteria A
	Surge	IEC/EN 61000-4-5 line to line ±2KV/line to ground ±4KV	Perf. Criteria A
	CS	IEC/EN61000-4-6 10 Vr.m.s	Perf. Criteria A
	DIP (AC input)	IEC/EN61000-4-11 0%, 70%	Perf. Criteria B

Mechanical Specifications

Case Material	Metal (AL1100, SPCC) and Plastic (PC940)
Dimensions	110.00 x 32.00 x 124mm
Weight	500g (Typ.)
Cooling Method	Free air convection

Dimensions and recommended layout



Notice: Keep the following installation clearances: 20mm on top, 20mm on the bottom, 5mm on the left and right sides are recommended when the device is loaded permanently with more than 50% of the rated power. Increase this clearance to 15mm in case the adjacent device is a heat source (e.g. another power supply).

Explosion Proof Information

The power supply is equipment intended for use in explosive atmospheres classified as Zone 2, EPL Gc.The equipment is protected by type of protection Ex 'ec' and the relay inside is protected by type of protection Ex 'nC' sealed device. It's a well performance AC-DC module with one-phase input and single output. It has functions such as output over-current protection, output over-voltage protection, output short circuit protection, over-temperature protection and so on, with well combined regulation and high efficiency. When input voltage is between 85VAC - 164VAC, and ambient temperature is between +50°C to +85°C, power derating off 2.0%/K is required; when input voltage is between 165VAC - 264VAC, and ambient temperature is between +60°C to +85°C, power derating off 2.8%/K is required.

ATEX contents

1. Satisfied standard This product complies with the EU Explosion proof certification ATEX directive 2014/34/EU.

EN IEC 60079-0:2018	Equipment - General requirements
EN IEC 60079-7:2015+A1:2018	Equipment protection by increased safety "e"
EN 60079-15:2010	Equipment protection by type of protection "n"

2. Specific conditions for safe use while the equipment services in explosive gas atmosphere: ① The equipment shall only be used in an area of pollution degree 2 or lower, as defined in EN60664-1; ② The equipment shall be installed in an enclosure that provides a minimum ingress protection of IP 54 in accordance with EN60079-0; ③ Transient protection shall be provided that is set at a level not exceeding 140% of the peak rated voltage value at the supply terminals to the equipment; ④ The equipment shall be installed according to EN60079-14; ⑤ The ambient temperature (Tamb), as specified above, has to be seen as the temperature of the surrounding atmosphere where the equipment is installed at (Operating temperature); ⑥ Minimum 5mm mounting clearances shall be remained between top, bottom, left, right and back to other device or side.

IECEx contents

1. Satisfied standard

IEC 60079-0:2017	Equipment - General requirements
IEC 60079-7:2017	Equipment protection by increased safety “e”
IEC 60079-15:2017	Equipment protection by type of protection “n”

Specific conditions of use while the equipment services in explosive gas atmosphere ：

1.The equipment shall only be used in an area of pollution degree 2 or lower, as defined in IEC60664-1.

2. The equipment shall be installed in an enclosure that provides a minimum ingress protection of IP 54 in accordance with IEC60079-0.

3.Transient protection shall be provided that is set at a level not exceeding 140% of the peak rated voltage value at the supply terminals to the equipment.

4.The equipment shall be installed according to IEC60079-14.

5.The ambient temperature (Tamb), as specified above, has to be seen as the temperature of the surrounding atmosphere where the equipment is installed at (Operating temperature).

6. Minimum 5mm mounting clearances shall be remained between top, bottom, left, right and back to other device or side.

Approvals

Safety Standards	Meet IEC/EN/UL62368/IEC/EN60079/UL61010
Safety Certification	IEC/EN60079/EN62368/UL61010 (UL61010 Pending)
Safety Class	Class I (PE and must be connected)

Note:
1. Unless otherwise specified, parameters in this datasheet were measured under the conditions of Ta=25℃, humidity.
2. The room temperature derating of 5℃/1000m is needed for operating altitude greater than 2000m.
3. All index testing methods in this datasheet are based on our company corporate standards.
4. In order to improve the efficiency at high input voltage, there will be audible noise generated, but it does not affect product performance and reliability.
5. Products are related to laws and regulations: see "Features" and "EMC".
6. The case needs to be connected to the earth of system when the terminal equipment in operating.
7. Our products shall be classified according to ISO14001 and related environmental laws and regulations, and shall be handled by qualified units

⚠ **WARNING** **Risk of electrical shock, fire, personal injury or death:**

1. Do not use the power supply without proper grounding (Protective Earth). Use the terminal on the input block for earth connection and not one of the screws on the housing.
2. Turn power off before working on the device, protect against inadvertent re-powering.
3. Make sure that the wiring is correct by following all local and national codes.
4. Do not modify or repair the unit.
5. Do not open the unit as high voltages are present inside.
6. Use caution to prevent any foreign objects from entering the housing.
7. Do not use in wet locations or in areas where moisture or condensation can be expected.
8. Do not touch during power-on, and immediately after power-off, hot surfaces may cause burns

FEATURES

- Universal 85 - 264V AC or 120-370 VDC
- 150% peak load output for 3 seconds
- Active PFC
- Slimline design: width 41mm
- Efficiency up to 94%
- DC OK function
- Operating temperature range - 40℃ to +70℃
- DC ON output status indicator LED
- Output short circuit, over-current, over-voltage protection.
- EMI performance meets. CISPR32 / EN55032 CLASS B
- Safety according to IEC/EN/UL62368, UL61010, UL508

RS PRO Embedded Switch Mode Power Supplies

- **220-5407**
- **220-5408**
- **220-5409**

RS Professionally Approved Products bring to you professional quality parts across all product categories. Our product range has been tested by engineers and provides a comparable quality to the leading brands without paying a premium price.

Product Description

AC-DC DIN rail power supply suitable for a wide range of Industrial, Machinery and Instrumentation applications. Featuring a universal AC input this cost-effective, slimline design is available in a range of standard outputs. Complying with International and European EMC and safety standards IEC/EN/UL62368, UL61010, UL508

General Specifications

Model	AC-DC 240W power supply
Mounting Type	DIN Rail mount
MTBF	MIL-HDBK-217F@25°C > 300,000 h
Applications	Industrial control systems, instrumentation and machinery equipment

RS Stock#	Input Voltage	Output Voltage	Output Current	Adj'range (V)	Wattage	Transient Output Power*3S	Efficiency (Typ)
2205407	85 to 264V ac 120 to 370V dc	12V	16A	12-14V	192W	288W	92%
2205408	85 to 264V ac 120 to 370V dc	24V	10A	24-28V	240W	360W	94%
2205409	85 to 264V ac 120 to 370V dc	48V	5A	48-53V	240W	360W	94%

Input Specifications

Input Specification	
Voltage Range	85 to 264V ac, 120 to 370V dc
Frequency	47 to 63Hz
AC Current Rating	3A/115V ac, 1.5A/230V ac
Inrush Current	15A/ 115V ac, 30A / 230V ac
Leakage	<0.5mA
Power Factor	0.98 115Vac, 0.94 230Vac
Standby power consumption	4W

Output Specifications

Output Specification			
RS Stock No	2205407	2205408	2205409
Output voltage	12V	24V	48V
Trim range	12-14V	24-28V	48-53V
Rated Current	16A	10A	5A
Ripple & Noise (max.) *	100mV	120mV	150mV
Rated Power	192W	240W	240W
Peak output power 3S	288W	360W	360W
Line Regulation typ.	±0.5%	±0.5%	±0.5%
Load Regulation typ.	±1%	±1%	±1%
Max Capacitive load µF	160,000µF	40,000µF	10,000µF
Minimum Load	0%	0%	0%

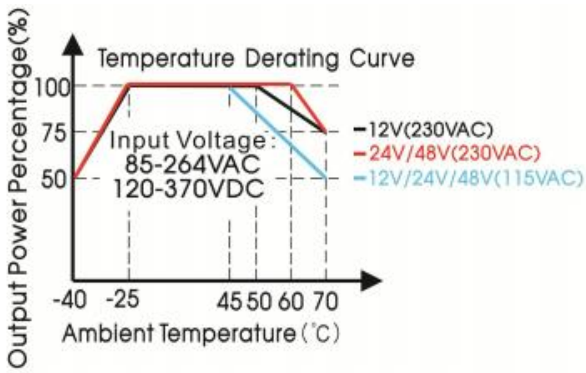
Hold Up Time (Typ)	20ms				
DC OK Signal*	30VDC/1A Max				
Over Voltage Protection	12V output ≤18V (Output voltage turn off, re-power on for recover)				
	24V output ≤35V (Output voltage turn off, re-power on for recover)				
	48V output ≤60V (Output voltage turn off, re-power on for recover)				
Over-current Protection	Normal temperature, high temperature	110% - 200% Io, self-recovery			
	Low temperature	≥105% Io, self-recovery			
Short Circuit Protection	Constant current, continuous, self-recovery				
Over-temperature Protection	230VAC, rated load	Min	Typ	Max	°C
		-	80	-	
Isolation	3KVAC				

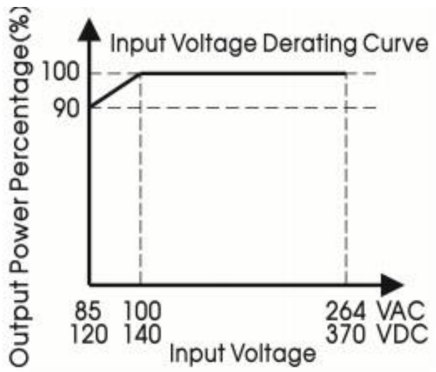
Note: 1.*The "Tip and barrel method" is used for ripple and noise test, output parallel 47uF electrolytic capacitor and 0.1uF ceramic capacitor, please refer to Enclosed Switching Power Supply Application Notes for specific information; 2.*DC OK Signal: When the output voltage is normal, the relay is connected. When the output voltage is abnormal (<90%Vo), the relay is disconnected.

General Specifications

Item		Operating Conditions				Min	Typ	Max.	Unit
Isolation	Input-Output	Electric strength test for 1min., leakage current <15mA				3000	-	-	VAC
	Input-Earth					2000	-	-	
	Output-Earth					500	-	-	
Insulation Resistance	Input-Earth	At 500VDC				50	-	-	MΩ
	Input-Output					50	-	-	
	Output-Earth					50	-	-	
Operating Temperature						-40	-	+70	℃
Storage Temperature						-40	-	+85	
Storage Humidity		Non-condensing				-	-	95	%RH
Operating Humidity						-	-	95	
Power Derating		Operating temperature derating	-40 to -25℃			3.34	-	-	%/℃
			+45 to +70℃		115VAC	2.0			
			+50 to +70℃	12V	230VAC	1.25	-	-	
			+60 to +70℃	24V	230VAC	2.5	-	-	
			+60 to +70℃	48V	230VAC	2.5			
		Input voltage derating	85VAC-100VAC			0.67	-	-	%/VAC
Safety Standard						Meet IEC/EN/UL62368/UL61010			
Safety Certification						EN62368/UL61010			
Safety Class						CLASS I (PE and must be connected)			
MTBF		MIL-HDBK-217F@25℃				＞300,000 h			

Derating





Note: 1.With an AC input voltage between 85 -100VAC and a DC input between 120-140VDC the output power must be derated as per the temperature derating curves;

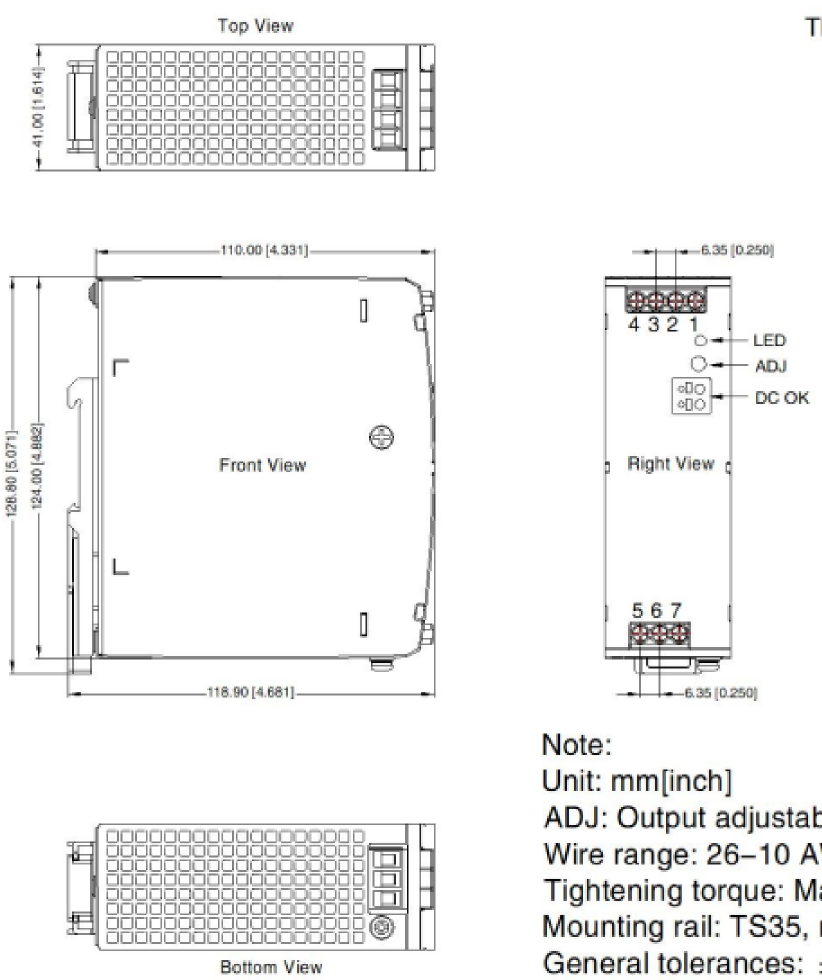
EMC Specifications

Emissions	CE	CISPR32/EN55032 CLASS B	
	RE	CISPR32/EN55032 CLASS B	
	Harmonic Current	IEC/EN61000-3-2 CLASS D	
Immunity	ESD	IEC/EN 61000-4-2 Contact ±6KV/Air ±8KV	Perf. Criteria A
	RS	IEC/EN 61000-4-3 10V/m	Perf. Criteria A
	EFT	IEC/EN 61000-4-4 ±2KV	Perf. Criteria A
	Surge	IEC/EN 61000-4-5 line to line ±2KV/line to ground ±4KV	Perf. Criteria A
	CS	IEC/EN61000-4-6 10 Vr.m.s	Perf. Criteria A
	DIP (AC input)	IEC/EN61000-4-11 0%, 70%	Perf. Criteria B

Mechanical Specifications

Case Material	Metal (AL1100, SPCC) and Plastic (PC940)
Dimensions	124.00 x 41.00 x 110.00mm
Weight	650 (Typ.)
Cooling Method	Free air convection

Dimensions and recommended layout



THIRD ANGLE PROJECTION

Pin-Out	
Pin	Mark
1	–Vo
2	–Vo
3	+Vo
4	+Vo
5	AC(N)
6	AC(L)
7	⏚

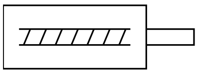
Note:
Unit: mm[inch]
ADJ: Output adjustable resistor
Wire range: 26–10 AWG
Tightening torque: Max 0.4 N·m
Mounting rail: TS35, rail needs to connect safety ground
General tolerances: ± 1.00[± 0.039]

Approvals

Safety Standards	Meet IEC/EN/UL62368/UL61010
Safety Certification	EN62368/UL61010 (Pending)
Safety Class	Class I (PE and must be connected)

Note:
1. Unless otherwise specified, parameters in this datasheet were measured under the conditions of Ta=25℃, humidity <75%RH with nominal input voltage and rated output load.
2. The room temperature derating of 5℃/1000m is needed for operating altitude greater than 2000m.
3. All index testing methods in this datasheet are based on our company corporate standards.
4. In order to improve the efficiency at high input voltage, there will be audible noise generated, but it does not affect product performance and reliability.
5. Products are related to laws and regulations: see "Features" and "EMC".
6. The out case needs to be connected to the earth of system when the terminal equipment in operating.
7. Our products shall be classified according to ISO14001 and related environmental laws and regulations and shall be handled by qualified units.

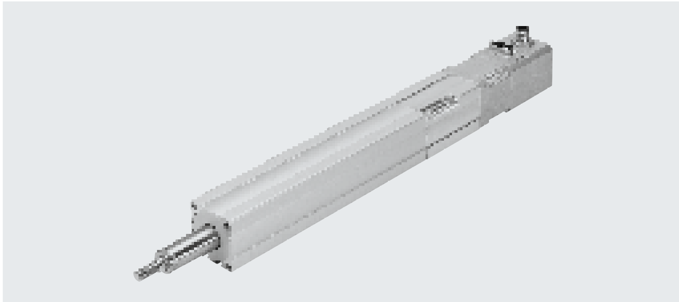
Data sheet



Size
16 ... 40

Stroke length
50 ... 400 mm

www.festo.com



General technical data				
Size		16	25	40
Design		Electric cylinder with ball screw and motor		
Piston rod thread				
Male thread		M6	M8	M10x1.25
Female thread		M4	M6	M8
Working stroke	[mm]	50 ... 200	50 ... 300	50 ... 400
Stroke reserve	[mm]	0		
Max. angle of rotation at the piston rod	[°]	≤ ±2	≤ ±1.5	≤ ±1
Impact energy in the end positions	[J]	0.1×10^{-3}	0.2×10^{-3}	0.4×10^{-3}
Position sensing		Via proximity switch		
Type of mounting		With female thread		
		With accessories		
Mounting position		Any		

Mechanical data							
Size		16		25		40	
Spindle design		3P	8P	3P	10P	5P	12.7P
Spindle pitch[1]	[mm/rev]	3	8	3	10	5	12.7
Spindle diameter	[mm]	8	8	10	10	12	12.7
Guide value for payload							
Horizontal[2]	[kg]	24	8	60	20	120	40
Vertical	[kg]	12	4	30	10	60	20
Max. feed force F_x	[N]	125	50	350	105	650	250
Max. speed	[mm/s]	125	300	150	500	180	460
Max. acceleration	[m/s^2]	10					
Reversing backlash[3]	[mm]	≤ 0.1					
Repetition accuracy	[mm]	±0.02					

1) Nominal value varies due to component tolerances
2) Note max. transverse load
3) In new condition

Data sheet

Electrical data				
Size		16	25	40
Motor				
Nominal voltage	[V DC]	24		
Nominal current	[A]	1.4	3	4.2
Holding torque	[Nm]	0.09	0.5	1.13
Brake				
Nominal voltage	[V DC]	24 ±10%		
Nominal power	[W]	8		
Holding torque	[Nm]	0.2	0.4	0.4
Mass moment of inertia	[kgmm^2]	1.8	8.2	29
Encoder				
Rotor position sensor		Incremental		
Rotor position sensor measuring principle		Optical		
Pulses/revolution	[1/rev]	500		
Interface		RS422, TTL, AB channel, zero index		
Operating voltage of encoder	[V DC]	5		

Operating and environmental conditions		
Ambient temperature[1]	[°C]	0 ... +50
Storage temperature	[°C]	–20 ... +60
Relative humidity	[%]	0 ... 85 (non-condensing)
Degree of protection to IEC 60529		IP40
Corrosion resistance CRC[2]		1
Duty cycle	[%]	100
CE marking (see declaration of conformity)		To EU EMC Directive[3]
UKCA marking (see declaration of conformity)		To UK instructions for EMC
Certification		c UL us - Recognized (OL)
		RCM compliance mark

1) Note operating range of proximity switches.
2) Corrosion resistance class CRC 1 to Festo standard FN 940070
Low corrosion stress. Dry internal application or transport and storage protection. Also applies to parts behind coverings, in the non-visible interior area, and parts which are covered in the application (e.g. drive trunnions).
3) For information about the area of use, see the EC declaration of conformity at: www.festo.com/sp ➔ Certificates.
If the devices are subject to usage restrictions in residential, commercial or light-industrial environments, further measures for the reduction of the emitted interference may be necessary.