Design of a Portable Control Platform for Rod-Driven Continuum Parallel Robots

Josué Licona Mármol

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Supervisor
Jonathan Camargo Leyva, M.Sc.

Department of Mechanical Engineering
Universidad de los Andes
Bogotá D.C., Colombia
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To my mother, Gildes Ester.

Success is the sum of small efforts, repeated day in, and day out.

— Robert Collier

Abstract

This project focuses on designing and implementing a portable, modular, and scalable platform alongside a control system tailored for rod-driven continuum parallel robots. The main goal was to develop a versatile mounting solution facilitating efficient robot movement across diverse applications. The project involved the design and construction of the mounting platform, as well as the development of the control interface. A rod-driven continuum parallel robot was designed and implemented, with a focus on miniaturization and optimization of the structure. Additionally, the project aimed to implement a customized language specification for programming the linear actuators, enabling tailored control and operational flexibility. Furthermore, an application was developed to interface with the control system, utilizing the created protocol to ensure seamless communication and precise control.

Acknowledgements

I want to thanks to God...

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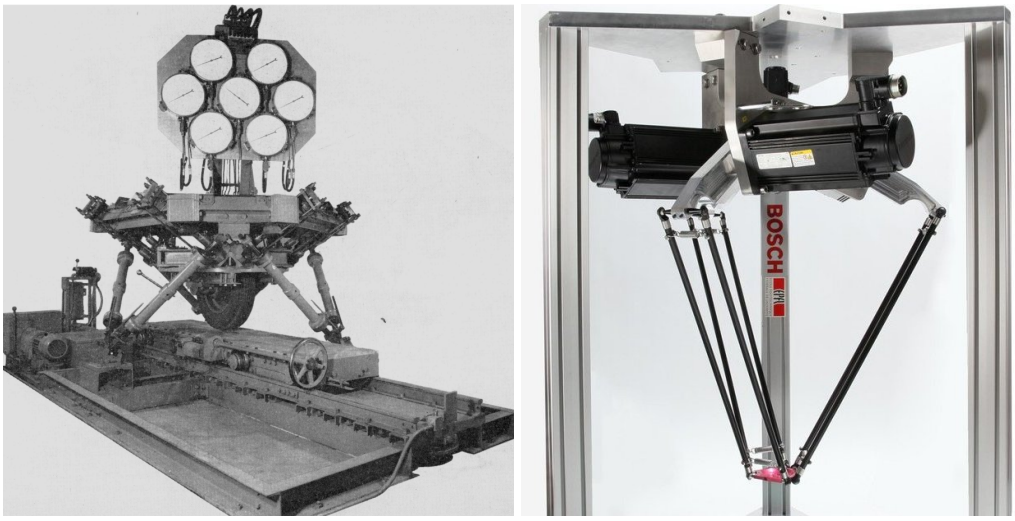
Chapter 1

Introduction

Robots in general can be categorized into serial and parallel types. Serial robots are characterized by a series of linked joints while parallel robots have multiple axes that move in parallel, usually working together to support a single platform.

Parallel robots represent a significant branch in the field of robotics due to their precision and versatility in various applications such as pick-and-place manipulation, simulators, manufacturing, and tooling, among others. As described in [1], these applications span both industry and medicine, leveraging the high rigidity, precision, and speed of these robots to compensate for the performance limitations of serial robots.

The origin of parallel robots dates back to the 1960s with the development of the Gough-Stewart [2] parallel mechanism (Figure 1.1a), which has become one of the most iconic in the field of parallel robotics. Later, in the 1980s, Reymond Clavel designed a robust parallel structure with three translational degrees of freedom and one rotational degree of freedom, as illustrated in Figure 1.1b. This robot, known as the Delta Robot, has become one of the most significant examples in the field of parallel robotics.



(a). Gough-Stewart Platform
Source: Adapted from [2]

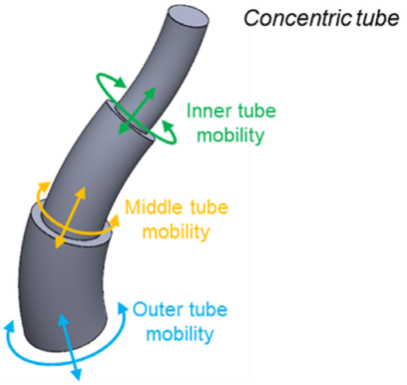
(b). Clavel's Delta Robot
Source: Adapted from [3]

Figure 1.1: Traditional parallel robots

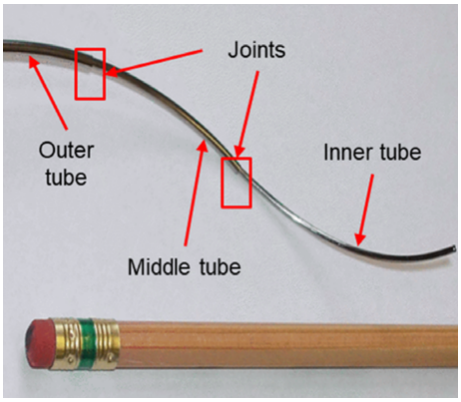
Another distinguishing feature of these robots is the presence of multiple closed kinematic chains that connect and move the mobile platforms, in contrast to serial robots, which operate with an open kinematic chain and move in a linear sequence. However, according to Briot and Kahrs [4] the fundamental questions about this class of robots have been addressed. As a result, in recent years, interest in parallel robots has shifted towards exploring new alternatives.

Current research in robotics transcends conventional definitions, pushing the boundaries of this field and fostering new possibilities and innovations. Briot and Kahrs [4] illustrate how parallel manipulators have been integrated into various novel robot types, such as continuum robots, flying robots, cable-driven robots, underactuated robots, multi-fingered hands, and microscale parallel robots. However, this emerging class of robots presents significant scientific challenges in design, modeling, and control. Among these categories, aerial robots, parallel robots, and continuum or soft robots are particularly noteworthy for their ability to venture into new areas due to their lightness and flexibility.

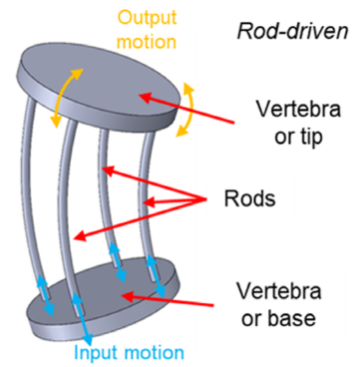
Expanding on these insights, Russo et al. [5] offer a comprehensive review



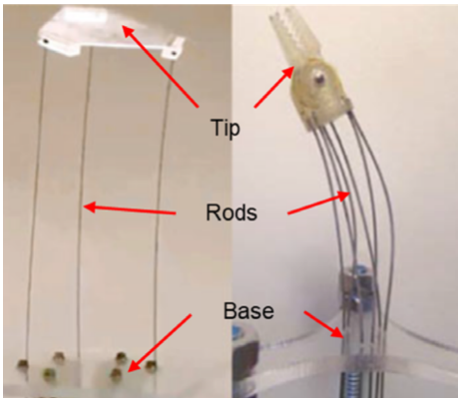
(a). Concentric tube robot mobility



(b). Concentric tube prototype



(c). Rod-driven continuum robot conceptual scheme



(d). Parallel continuum rod-driven robot prototype

Figure 1.2: Continuum robots with extrinsic actuation

Source: Adapted from [5]

focusing on recent advancements, current limitations, and ongoing challenges in the design, modeling, and control of continuum robots. They classify continuum robots based on their design, distinguishing them by their extrinsic or intrinsic actuation methods. Extrinsic actuation (Figure 1.2) involves transmitting motion from the robot's base along its structure, categorized into three main families depending on the transmission elements used: tendon-driven, concentric tube (Figures 1.2a, 1.2b), and rod-driven robots (Figures 1.2c, 1.2d). Furthermore, robots with intrinsic actuation employ actuators integrated into their structure to generate movement, meaning the actuation occurs within the robot's body.

Current challenges in designing and modeling parallel continuum robots in-

clude improving performance through miniaturization of actuators, integrating with rigid robots, exploring smart materials, precise environmental modeling, and implementing proprioception with new sensors [5]. Modeling efforts also focus on representing interaction environments and improving real-time implementations, alongside standardizing simulation environments. Control challenges involve ensuring precise manipulation and adapting to dynamic environments using advanced sensor technology and adaptive strategies

This project aims to address the efficiency challenges of continuum robots through the miniaturization of their parallel linear actuators. Specifically, it focuses on implementing adaptive control strategies for diverse applications using an extrinsic actuation platform for rod-driven continuum robots. This research endeavors to enhance affordability and user-friendliness, aiming to broaden adoption and usability in practical contexts.

1.1 Objectives

1.1.1 General Objective

Design and develop a portable, modular, and scalable platform with a control system for the actuation of rod-driven continuum parallel robots.

1.1.2 Specific Objectives

- Adapt an existing design of a rod-driven continuum parallel robot, optimizing it for reduced size while maintaining functionality and performance.
- Design linear actuators that provide precise control and enable dexterous movements, ensuring high accuracy and reliability.
- Fabricate all necessary components and assemble a fully functional physical

prototype of the platform, adhering to the design specifications.

- Implement a customized language specification for programming the linear actuators, allowing for tailored control and flexibility in operations.

- Develop an application to interface with the control system, utilizing the created protocol to facilitate seamless communication and control.

- Conduct comprehensive experimental testing and validation of the system, ensuring it meets all performance criteria and operational standards.

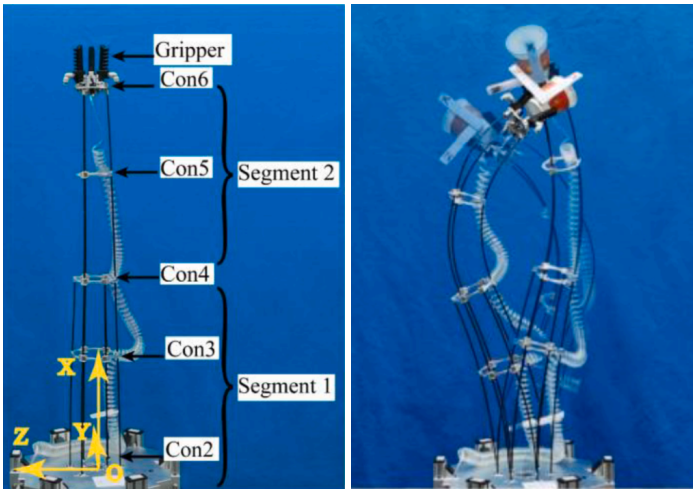
Chapter 2

Target Robot Structure

Rod-driven Continuum Parallel Robots (RDCPR) represent a relatively new class of robots characterized by their unique rod-driven actuation mechanism. Limiting and defining the dimensions and structure of these robots is crucial for the development of the platform, which aims to facilitate their movement and operation in various applications. In the following sections, a detailed exploration will be conducted on the configuration and essential components that define the structure and operational capabilities of the RDCPR.

2.1 Reference Model

The reference model, depicted in Figure 2.1, was developed by Wu and Shi [6]. It was chosen due to its representation as one of the most comprehensive RDCPR designs, showcasing versatility and a wide range of motion. With 5 DoFs, it features two independently manipulable segments, making it extensible.

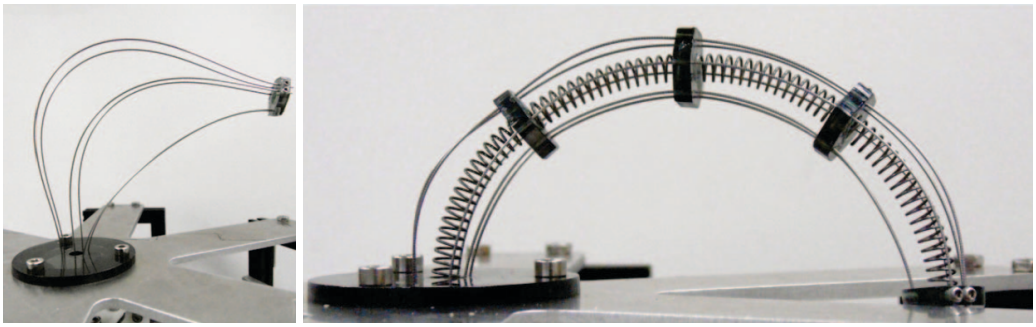


(a). Sections and structure **(b).** Some end poses

Figure 2.1: Reference robot structure

Source: Adapted from [6]

The inclusion of intermediate constraints, as illustrated in Figure 2.2, enhances the robot's operational range.



(a). No constraints **(b).** Extended range with intermediate constraints

Figure 2.2: Constraints and range of motion

Source: Adapted from [7]

2.2 Rod Material

A rod, denoted as r, is defined with the inequality $L \gg r$, where L represents its length and r its radius. In the reference model, rods are constructed from fiberglass, while in Figure 2.2, they are made from steel. These materials are commonly

used due to their high stiffness and ability to withstand significant bending without plastic deformation or fracture. Steel alloys like AISI 302, commonly used in springs, exemplify these properties well. Table 2.1 details the material properties of AISI 302 steel and fiberglass.

Table 2.1: Fiberglass and AISI 302 steel properties

Symbol	Property	Fiberglass	AISI 302
ρ	Density $[g/cm^3]$	2.6	8.0
E	Young's Modulus [GPa]	85	187.5
G	Shearing Modulus [GPa]	36	70.3

While the Cosserat rod model [5] is commonly used for analyzing these robots, understanding the maximum deflection that a rod can withstand involves applying the Euler-Bernoulli beam equation 2.1, where I is given by equation 2.2. For practical purposes, a configuration of AISI 302 steel rods was chosen due to its commercial availability, with dimensions specified in Table 2.2.

$$\delta_{max} = \frac{PL^3}{3EI} \tag{2.1}$$

$$I = \frac{\pi D^4}{64} \tag{2.2}$$

Table 2.2: Comparison between Wu & Shi (2022) model and custom test model

Parameter	Wu & Shi model [6]	Custom test model
Maximum length	~ 860 mm	~ 450 mm
Minimum length	~ 400 mm	~ 250 mm
Diameters of constraints	[90, 80, 70, 60] mm	[55, 50, 45] mm
Base constraint diameter	100 mm	70 mm
Number of sections	2	2
Number of rods	6	6
Rod cross-section diameter	3 mm	0.8 mm
Rod material	Fiberglass	AISI 302

Despite steel's higher Young's modulus and the necessity for shorter rods with significantly smaller radii, we achieved greater deflections under the same load

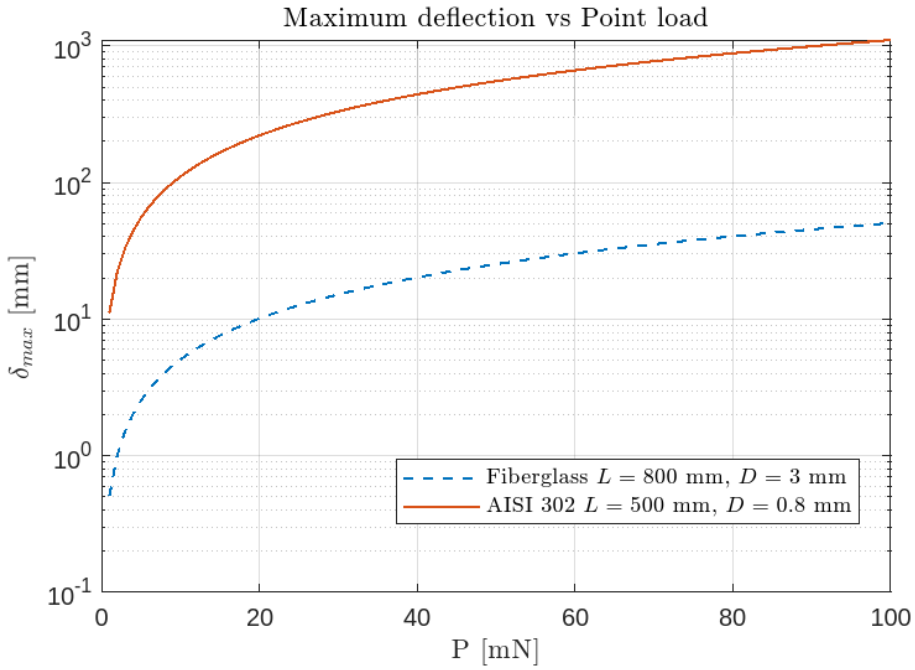


Figure 2.3: Maximum deflection and point load

compared to the reference model. This implies achieving equivalent deflection with less force, which is advantageous for actuators with limited force capabilities, as shown in Figure 2.3.

2.3 Design and Dimensions

To discuss the design and dimensions of the robot, the parts of the robot are depicted in Figure 2.4. These include rods for the first and second segments, constraints, and joints between constraints and rods, which can be either closed-form or cylindrical-form pairs designed to restrict movement. Each intermediate segment is required to have at least one closed-form pair joint with a rod for structural stability, while the remaining joints should be cylindrical to facilitate bending of the arm. At the end of each segment, all joints within the constraints must be closed-form to prevent disassembly of the segment. A minimum of three rods per segment is necessary to maintain structural integrity.

In Figure 2.5, the height of each segment and their respective constraints are il-

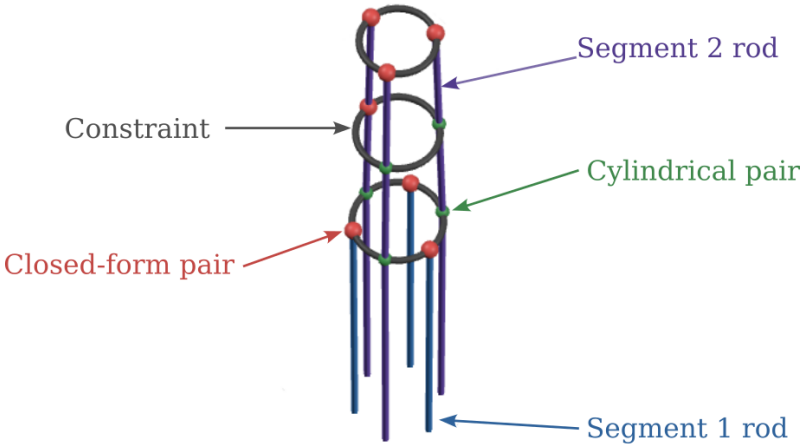
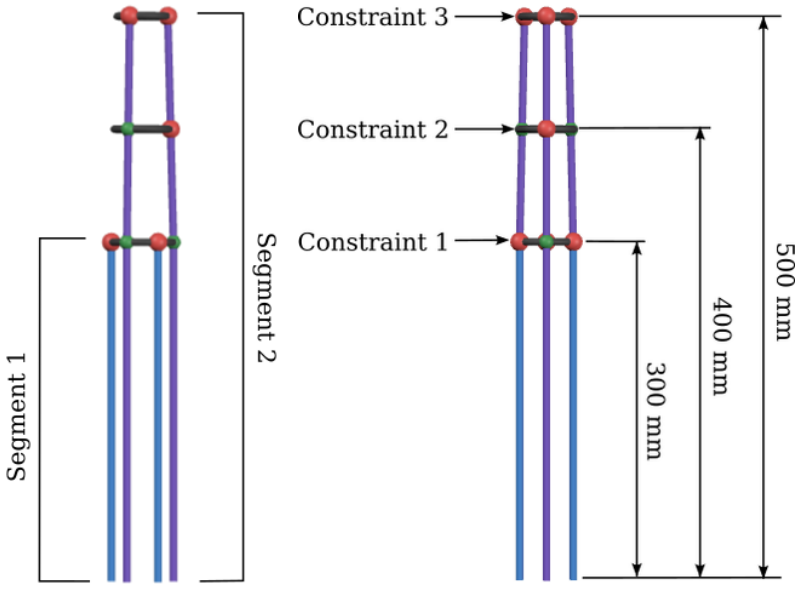


Figure 2.4: Robot body constraints and parts

lustrated. Additionally, the arm, similar to the reference model, exhibits a tapered envelope. This design choice, influenced by Wu and Shi [6], enhances structural stiffness. The tapered shape, resembling a truncated cone, is achieved by gradually reducing the cross-sectional area along the length of the arm, contributing to improved rigidity.

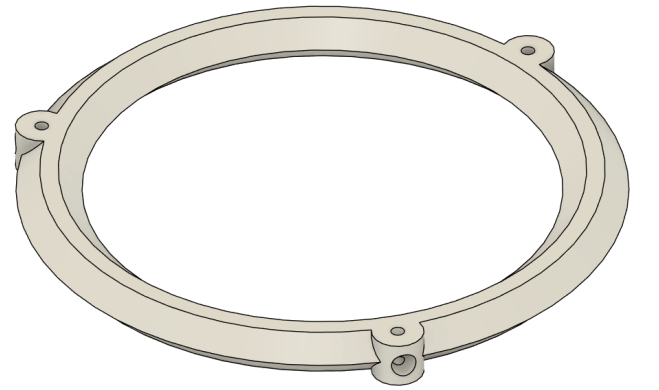


(a). Left view, and robot body segments **(b).** Frontal view, and constraints heights

Figure 2.5: Robot body lateral views

2.4 Ring Constraints

The proposed constraint design, depicted in Figure 2.6, takes the form of a ring or hoop and is specifically tailored for additive manufacturing. Its cross-sectional shape is crucial in enhancing lateral load-bearing capabilities by mitigating deformation under load. Unlike traditional circular profiles that can easily deform into ellipses, the chosen rhomboidal cross-section provides structural stability. This geometric configuration, resembling a hollowed-out egg-shaped cylinder in its cross-section, offers improved resistance to lateral forces, ensuring robust performance in rod-driven continuous parallel robots.



(a). General view

(b). Lateral view

Figure 2.6: Ring constraint

The sizes of the constraints used in the rod-driven continuous parallel robots vary, as illustrated in Figure 2.7, corresponding to the dimensions specified in Table 2.2. Each constraint size is tailored to accommodate specific rod diameters, as indicated by the rod passing through each hole in the constraint. The type of connection with the constraint, whether closed-form or cylindrical, is also noted in the image.

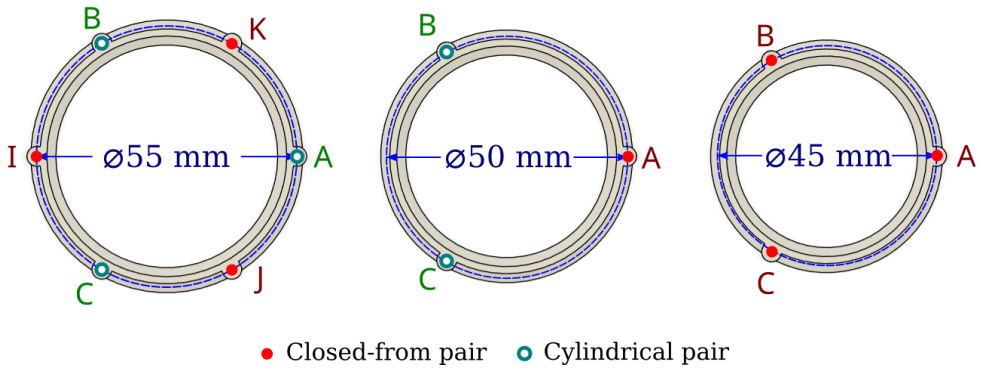
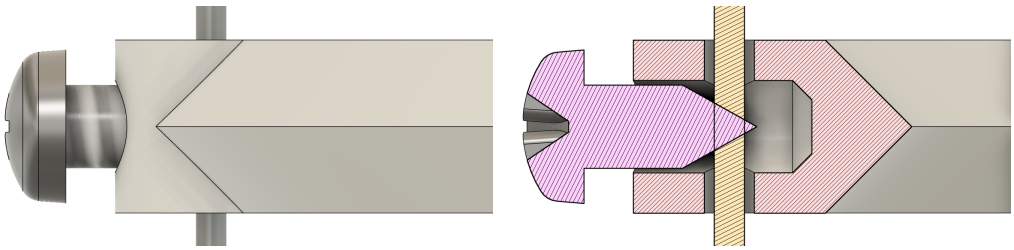


Figure 2.7: Ring constraint sizes

In *blue*, the diameters of the circumferences enclosing the rods are shown. The rods are labeled *A*, *B*, *C*, *I*, *J*, *K*. The *green* open circle indicates a cylindrical pair constraint between the ring and the rod, while the *red* indicates a closed-form pair constraint involving both.

Physically, a closed-form pair joint is created using a set screw that secures the rod in place, as illustrated in Figure 2.8. This type of joint provides a firm grip on the rod, preventing any movement. In contrast, a cylindrical-form pair joint is similar in construction but omits the set screw, allowing for both translational and rotational movement along the axis of the hole.



(a). Physical closed-form pair constraint **(b).** Section view of closed-form pair constraint

Figure 2.8: Closed-form pair constraint

Chapter 3

Linear Actuator

Actuators play a crucial role in the operation of robots by converting the rotational movement of a motor into linear motion, enabling the robot to perform various tasks. In the context of parallel robots, linear actuators are particularly important because they are responsible for the movements needed to control the robot's motion.

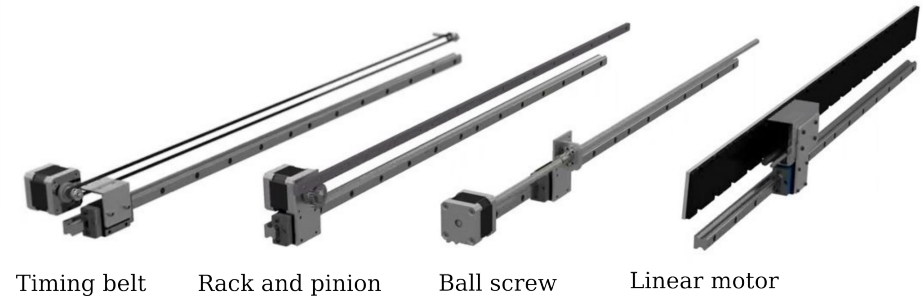
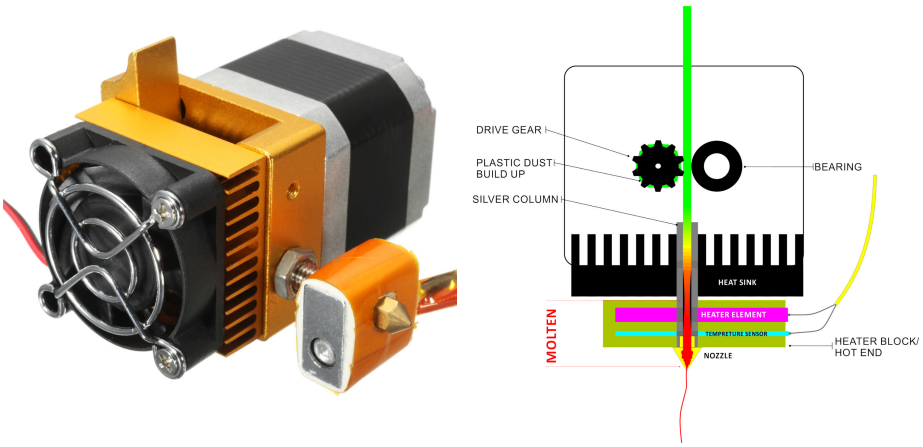


Figure 3.1: Linear motion systems

In parallel robots, linear actuators are used to manipulate the position and orientation of the end-effector. Traditional linear actuators include timing belts, rack and pinion systems, ball screws, and linear motors, as shown in Figure 3.1. However, these actuators often present challenges such as high cost, large size, and fixed or non-modifiable maximum stroke lengths.

The fixed or non-modifiable travel distance of conventional linear actuators is a major limitation, especially when the goal is to create a flexible platform capable of accommodating a wide range of rod-driven robot configurations. Flexibility is key to our platform, as it must adapt to various setups without requiring significant modifications.

Fortunately, parallel continuum robots open up a broader range of possibilities. Unlike traditional robots that move rigid elements, continuum robots use flexible elements like rods, which can be shortened or extended to achieve the desired motion. This concept is similar to the operation of 3D printer extruders (refer to Figure 3.2).



(a). 3D printer extruder **(b).** Functionality of extruder

Figure 3.2: 3D printer extruder

3D printer extruders work by using a drive gear and a bearing to push and pull the filament towards the heater. For our application, we are not interested in the heating aspect but rather the mechanism that drives the filament. This mechanism can be adapted to move rods in our robot, as shown in Figure 3.3.

Figure 3.3: Extruder without heater

A custom design is necessary for several reasons. The filaments used in standard extruders are thicker than the rods suitable for our robots (> 1.75 mm), as empirical experience suggests that rods thinner than 1.5 mm are ideal. Thicker rods require more force to bend, which these actuators are not designed to handle, making this thickness a practical upper limit for our application. Additionally, the width of the actuators must be considered, along with their weight and speed. Energy consumption is also a critical factor that must be taken into account.

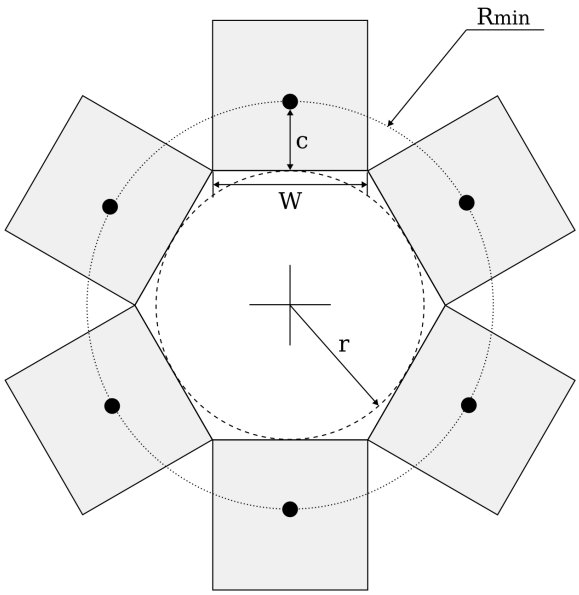


Figure 3.4: Actuators arrange

Each rod requires its own actuator. Therefore, the actuators must fit within the stipulated diameter for the base of the arm. The top view of an actuator arrangement is shown in Figure 3.4. For an arrangement of six actuators with width W and distance to the center c, the relationship with the minimum base radius R_{min} is shown in equations 3.2 and 3.1. An original extruder has a width of $W = 5.2$ cm with $c = 0.7$ cm, which requires a minimum radius of $R_{min} = 5.2$ cm according to equation 3.4. This is larger than the model presented by [6], and our aim is to design a smaller one. Therefore, we establish a minimum diameter of $R_{min} = 3.5$ cm with a maximum $c = 0.5$ cm, resulting in a maximum width of $W \approx 3.5$ cm, according to equation 3.3.

$$r = R_{min} - c \tag{3.1}$$

$$W = \frac{2}{\sqrt{3}} r \tag{3.2}$$

$$W = \frac{2}{\sqrt{3}} (R_{min} - c) \tag{3.3}$$

$$R_{min} = \frac{\sqrt{3}}{2} W + c \tag{3.4}$$

3.1 Motor

The motor is the central component in actuators, and in extruders, stepper motors are commonly used. However, stepper motors were discarded for our application due to their size and speed limitations. Instead, we selected DC N20 geared motors, which are small and fast enough to meet our requirements. To control the number of revolutions accurately, a motor with an encoder is necessary (see Figure 3.5). The dimensions of the selected motor with encoder are specified in Figure 3.6, and the specifications for the chosen variant are detailed in Table 3.1.

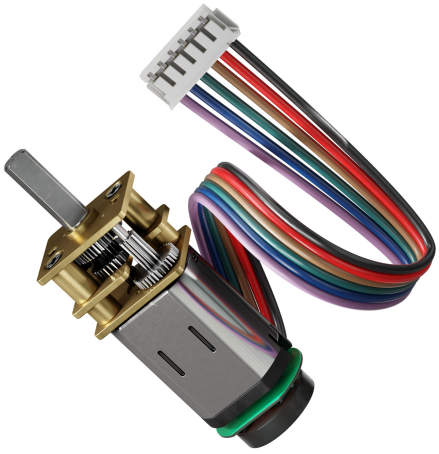


Figure 3.5: Gear motor N20 with encoder

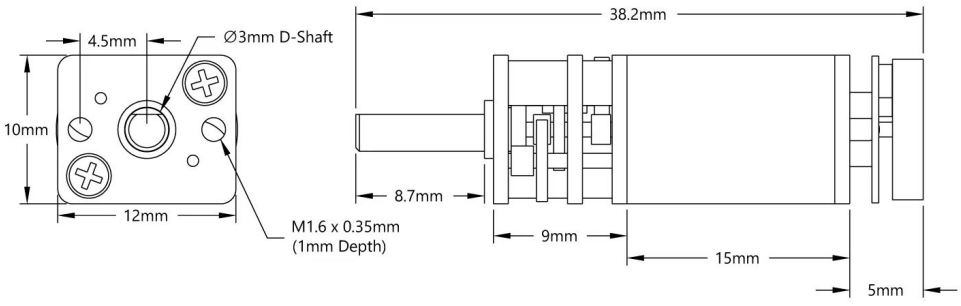


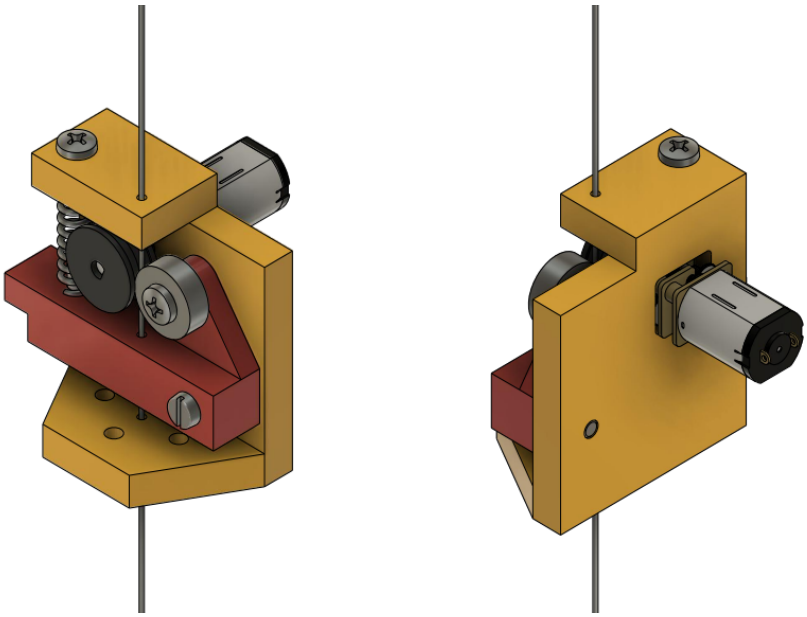
Figure 3.6: Dimensions of gear motor N20 with encoder

Table 3.1: Gear motor specifications

Property	Value
Output shaft style	D-Shaft
Voltage range	6 – 12V
Speed (no load @ 6VDC)	70 rpm
Rated torque	0.65 kg·cm
Stall torque	4 kg·cm
Gear ratio	210:1
Weight	15g
Encoder: cycles per revolution (motor shaft)	3
Encoder sensor type	Magnetic (Hall Effect)
Hall response frequency	100 kHz

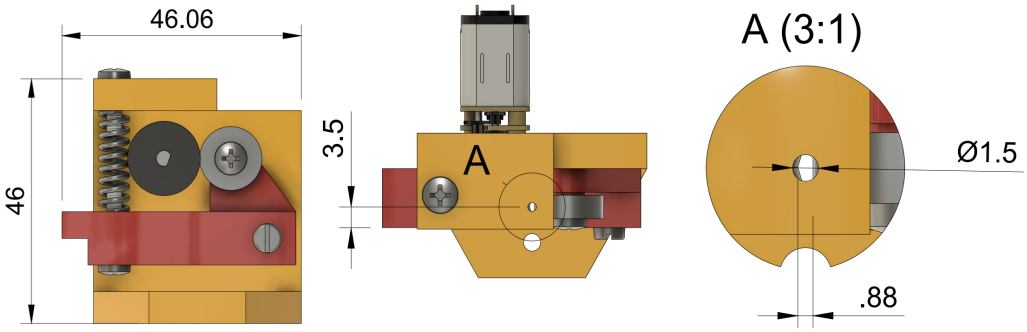
3.2 First model

A first concept of the linear actuator is shown in Figure 3.7. This simple and straightforward model was designed to understand the basic concept of a linear actuator. The idea was to make it easy to manufacture using FDM (fused deposition modeling), specifically 3D printing. The width of this model is 46.06 mm (as shown in Figure 3.8), which exceeds the previously stipulated 35 mm. We found limitations when trying to reduce the actuator's width due to the diameters of the pulley, bearing, spring, and the length of the arm. Additionally, the bearing did not provide sufficient friction, necessitating improvements in this area. Enhancements were also needed for the motor grip and support to ensure ease of printing and overall functionality.



(a). Front isometric view **(b).** Back isometric view

Figure 3.7: First model isometric view

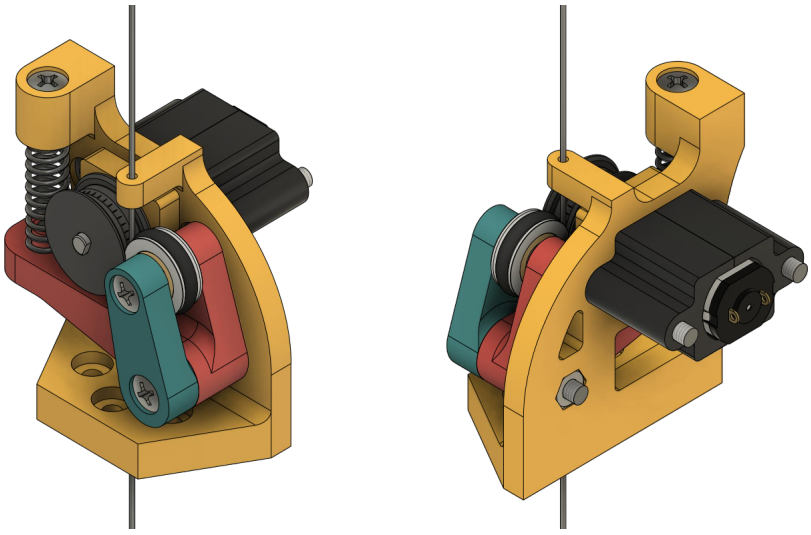


(a). Front view **(b).** Top view

Figure 3.8: First model dimensions

3.3 Final model

After some iterations, the final model was developed, as shown in Figure 3.9. The final design is more rounded to eliminate potential stress concentrators, and it is also more streamlined and material-efficient, incorporating holes in non-critical areas to reduce weight.

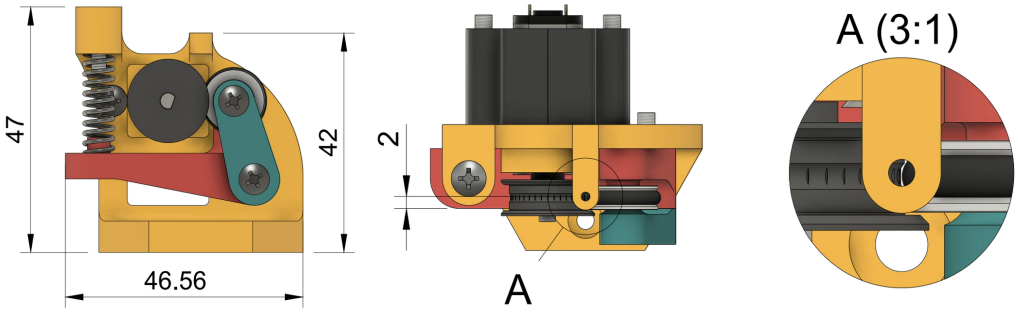


(a). Front isometric view **(b).** Back isometric view

Figure 3.9: Final model isometric view

Although the width remains the same, the arm, which previously collided with other actuators in an array, has been repositioned. It is now slightly shorter

and rounded, as shown in Figure 3.10, allowing the arm to intrude into the space of another actuator without making contact at any point. This design maintains an array of 6 actuators within the established circle diameter of 7 cm.



(a). Front view **(b).** Top view

Figure 3.10: Final model dimensions

The issue of friction was also addressed by adding an O-ring seal in a V-shaped bearing and creating a grooved pattern on the motor pulley. The space between the pulley was made narrower to enhance grip. Additionally, a pair of new components were designed to secure the motor, and an additional support was included over the arm and bearing for increased rigidity and safety. Critical parts such as the spring holder were reinforced, making them thicker to improve durability and performance.

Figure 3.11 presents an exploded view of the final actuator, detailing each component with arrows and item numbers in balloons. The corresponding part names for the assembly are listed in Table 3.2, which also indicates the quantity and source of each part. The sources are categorized as 3D printed, commercial, or manufactured. Notably, the only "manufactured" part is the spring, which was custom-made.

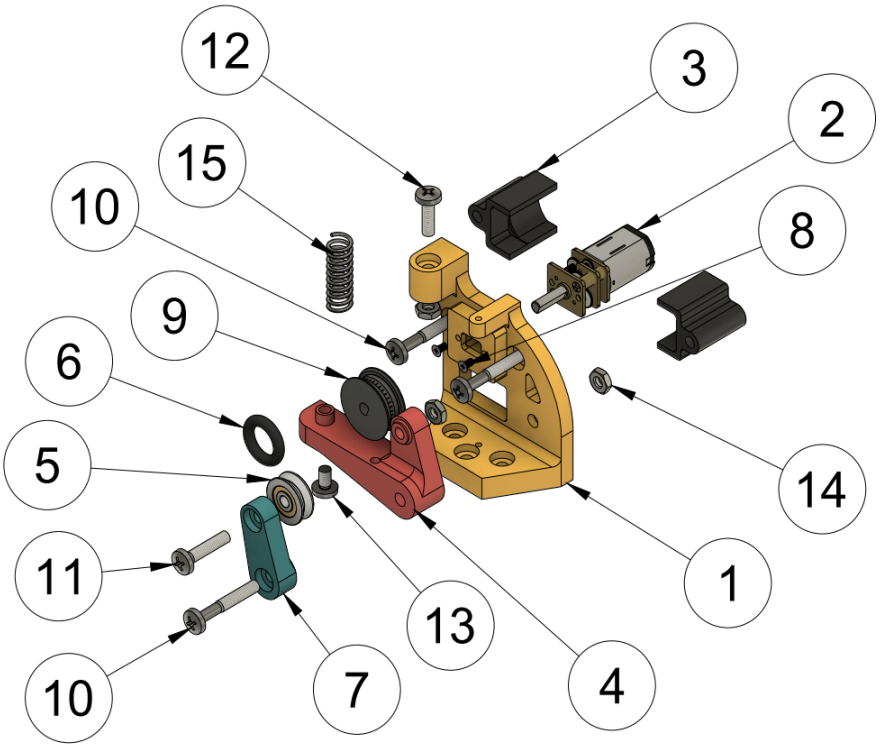


Figure 3.11: Actuator assembly exploded-view

Table 3.2: Actuator assembly parts list

Item	Qty	Part Name / Description	Source
1	1	Base	3D Printed
2	1	Motor GA12 N20 (must be with encoder)	Commercial
3	2	Motor Support	3D Printed
4	1	Arm	3D printed
5	1	V623ZZ Groove Pulley	Commercial
6	1	O-Ring - W2.62 x DI7.59 x DE2.83	Commercial
7	1	Arm Support	3D Printed
8	2	Phillips Countersunk Screw - DIN 965H M1.6x3	Commercial
9	1	Pulley	3D Printed
10	3	Binding Head Screw JIS B 1111 - M3x20	Commercial
11	1	Binding Head Screw JIS B 1111 - M3x14	Commercial
12	1	Binding Head Screw JIS B 1111 - M3x10	Commercial
13	1	Binding Head Screw JIS B 1111 - M3x5	Commercial
14	3	Hexagon Thin Nut DIN 439-2 - M3x0.5	Commercial
15	1	Spring - D5.5x20mm	Manufactured

3.4 Specifications

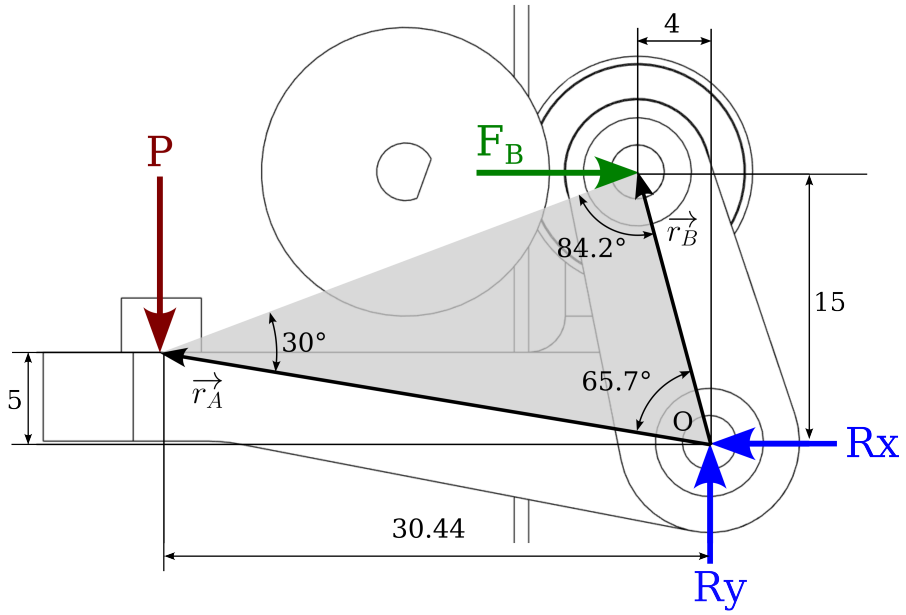


Figure 3.12: Forces in actuator arm

The pressure or grip on the rod by the actuator is provided by the bearing and the actuator arm, whose static model is shown in Figure 3.12. The sum of forces is found in Equation 3.5, and the sum of moments at point O is given in Equation 3.6. The force P is exerted by the spring, as described by Equation 3.7, where k is the spring constant and Δy is the compression. At the pin O, the components of the reaction force, R_x and R_y, are present. From Equation 3.6, we can determine the reaction force F_B at the bearing, as shown in Equation 3.8.

$$\sum \overrightarrow{F} = 0 \quad \therefore \quad \overrightarrow{P} + \overrightarrow{R_y} + \overrightarrow{F_B} + \overrightarrow{R_x} = 0 \tag{3.5}$$

$$\sum \overrightarrow{M_O} = 0 \quad \therefore \quad \overrightarrow{r_A} \times \overrightarrow{P} + \overrightarrow{r_B} \times \overrightarrow{F_B} = 0 \tag{3.6}$$

$$P = -k\Delta y \tag{3.7}$$

$$F_B = \frac{r_{A,x}}{r_{B,y}} P = \frac{30.44}{15} P = -2.0293 k \Delta y \tag{3.8}$$

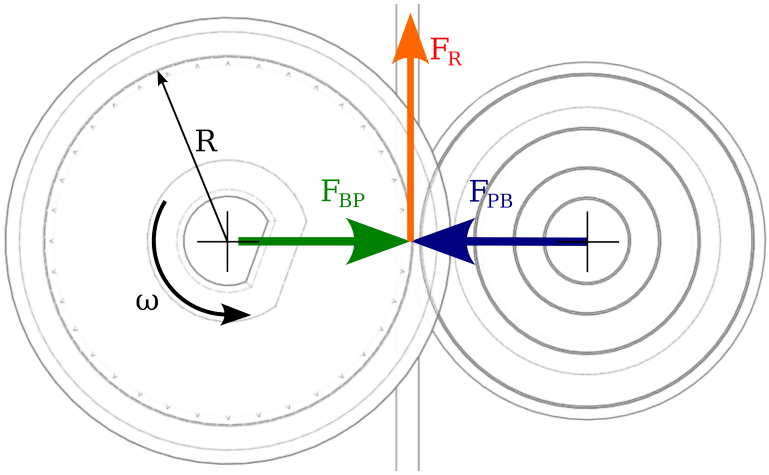


Figure 3.13: Friction force in rod

From the force F_B, the friction force on the rod can be calculated, as shown in Figure 3.13, using Equation 3.10. However, these formulas were not applied in depth because static friction factors of the robot μ_s were measured instead. Geometric constraints were of greater importance. Therefore, the spring was selected by empirically testing those with the appropriate stiffness. The drive pulley, with radius R, rotates at speed ω. Considering the motor's RPM, the actuator's speed specifications are provided in Table 3.3.

$$F_{BP} = F_B \tag{3.9}$$

$$F_R = \mu_s F_{BP} = -2.0293 \mu_s k \Delta y \tag{3.10}$$

Table 3.3: Actuator specification

Property	Value
Pulley ratio (R)	5.3 mm
Maximum angular velocity (ω_{max})	7.3304 rad/s
Maximum linear velocity (v_{max})	38.85 mm/s

Chapter 4

Platform Assembly

The assembly of the structure involves the integration of the array of all actuators, the platform on which they are mounted, and the electronics responsible for controlling the linear actuators. The components of the platform are shown in Figure 4.1, and the corresponding parts list is detailed in Table 4.1. The structure features a hexagonal shape but includes only three lateral structural supports, made of acrylic, as well as the upper and lower bases, which are also made of acrylic. These components are connected using 3D-printed L-shaped joints. There is a hollow space beneath the actuators to provide clearance for the rods, approximately 25 centimeters in length.

4.1 Electronics Case

The electronics case houses all the electronic components necessary to control the motors. It is an independent module from the platform structure, making it easy to remove and replace, and it is positioned beside the platform for easy access. The case contains the MCU (Microcontroller Unit), the breadboard on which the motor drivers and various connections are made, as well as the input and out-

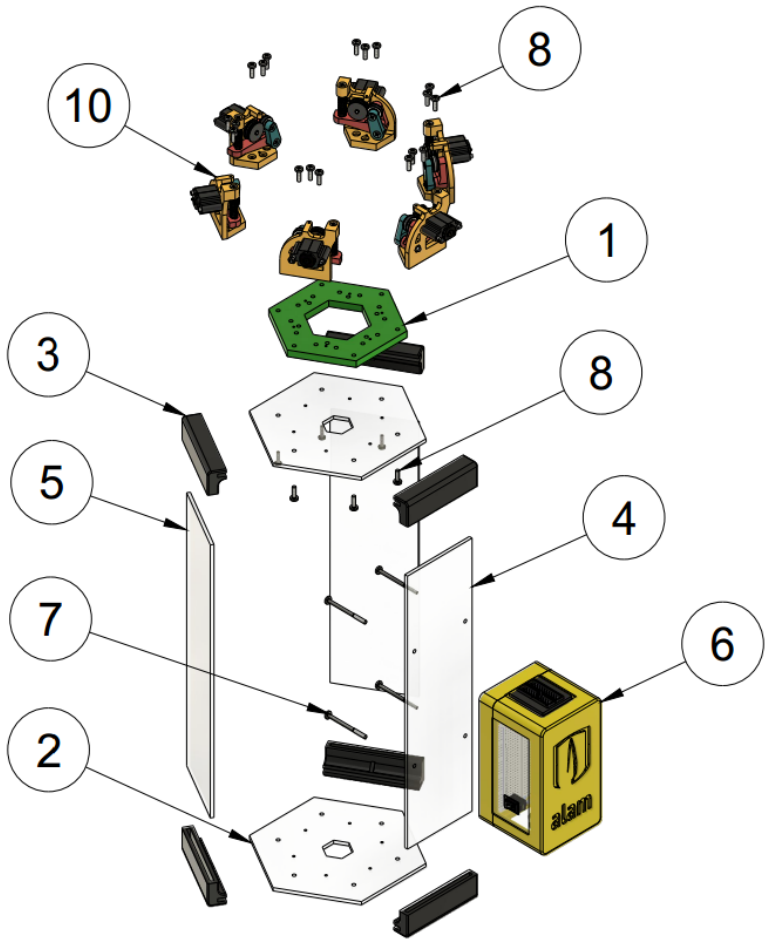


Figure 4.1: Platform assembly exploded-view

Table 4.1: Platform assembly parts list

Item	Qty	Part Name / Description	Source
1	1	Actuators Base	3D Printed
2	2	Support Base	Acrylic Laser Cut
3	6	Support Union	Acrylic Laser Cut
4	1	Support Front	Acrylic Laser Cut
5	2	Support Lateral	Acrylic Laser Cut
6	1	Electronics Assembly	
7	4	Binding Head Screw JIS B 1111 - M3x40	Commercial
8	24	Binding Head Screw JIS B 1111 - M3x10	Commercial
9	6	Actuator Assembly	

put peripherals of the module, which can be seen in Figure 4.2 and are listed in Table 4.2. The case consists of two main parts, one containing the MCU and the other housing the breadboard, both of which are 3D-printed. The peripherals are mounted on the walls, which are made of laser-cut acrylic sheets.

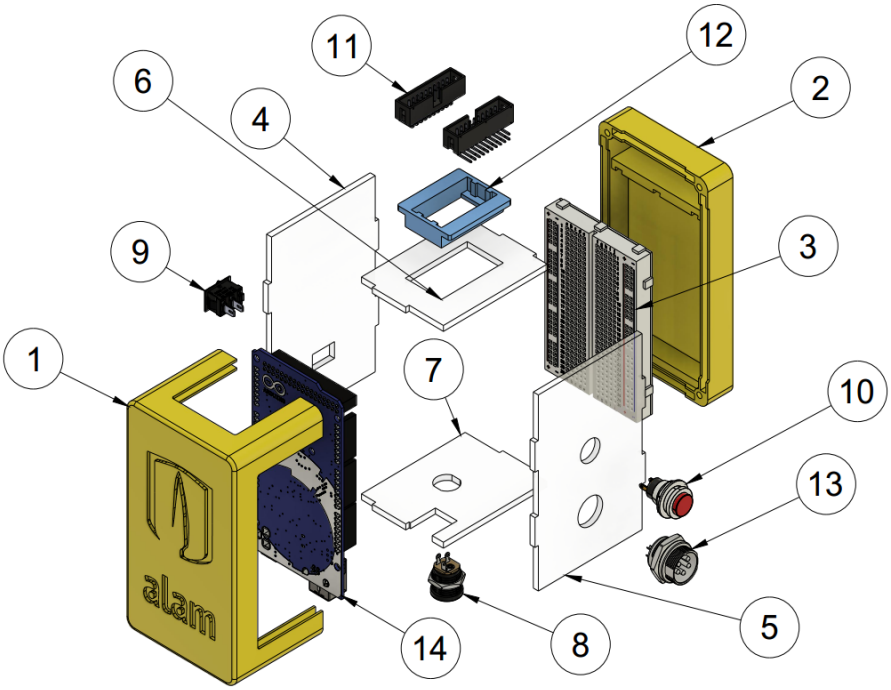


Figure 4.2: Electronics assembly exploded-view

Table 4.2: Electronics assembly parts list

Item	Qty	Part Name / Description	Source
1	1	Arduino Case	3D Printed
2	1	Breadboard Base	3D Printed
3	1	Half-Size Breadboard	Commercial
4	1	Left Wall	Acrylic Laser Cut
5	1	Right Wall	Acrylic Laser Cut
6	1	Top Wall	Acrylic Laser Cut
7	1	Bottom Wall	Acrylic Laser Cut
8	1	DC Power Input Jack - DS-223B	Commercial
9	1	Power Switch - KCD1-11-2P	Commercial
10	1	Red Push Button - DS 212	Commercial
11	2	IDC 3020-20-0200-00 - 20P 2.54MM	Commercial
12	1	IDC Support	3D Printed
13	1	MX M12 5-Pin Male MIC Connector Plug	Commercial
14	1	Arduino MEGA 2650	Commercial

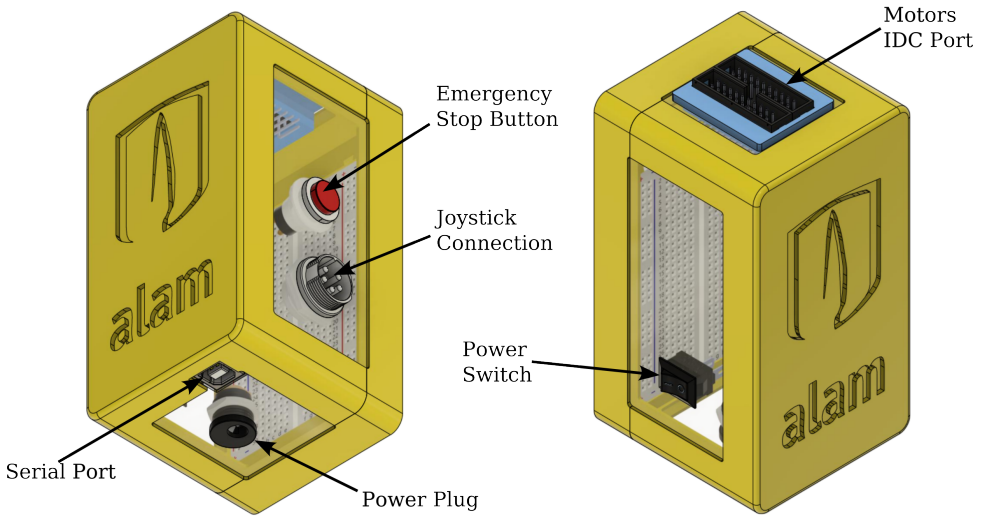


Figure 4.3: Ports and connections

Figure 4.3 shows the ports and connections of the case: on the bottom, there is the serial port input for programming the MCU and sending commands, and the power plug; on the right side, there is an emergency button to stop the robot, and a 5-pin connector input for connecting a joystick; on the left side, there is the power button; and on the top, there are a pair of 20-pin IDC inputs for connecting the unit to the motors.

4.1.1 Circuit Schematic

The schematic of the circuit connections is illustrated in Figure 4.4. As shown in Figure 4.5, each actuator motor requires six connections. The pins `M1` and `M2` supply power to the motors, while `VCC` and `GND` provide power to the magnetic encoder. The pins `A` and `B` are used for quadrature output. To accurately count the encoder pulses in both directions, one pin must be connected to an interrupt pin and the other to a digital pin. Motor polarity and speed are managed using a `DRV8833` motor driver, which requires two `PWM` connections per motor. Given the need for a cost-effective MCU with sufficient pins to connect six motors, the `Arduino MEGA 2650` was selected for this project.

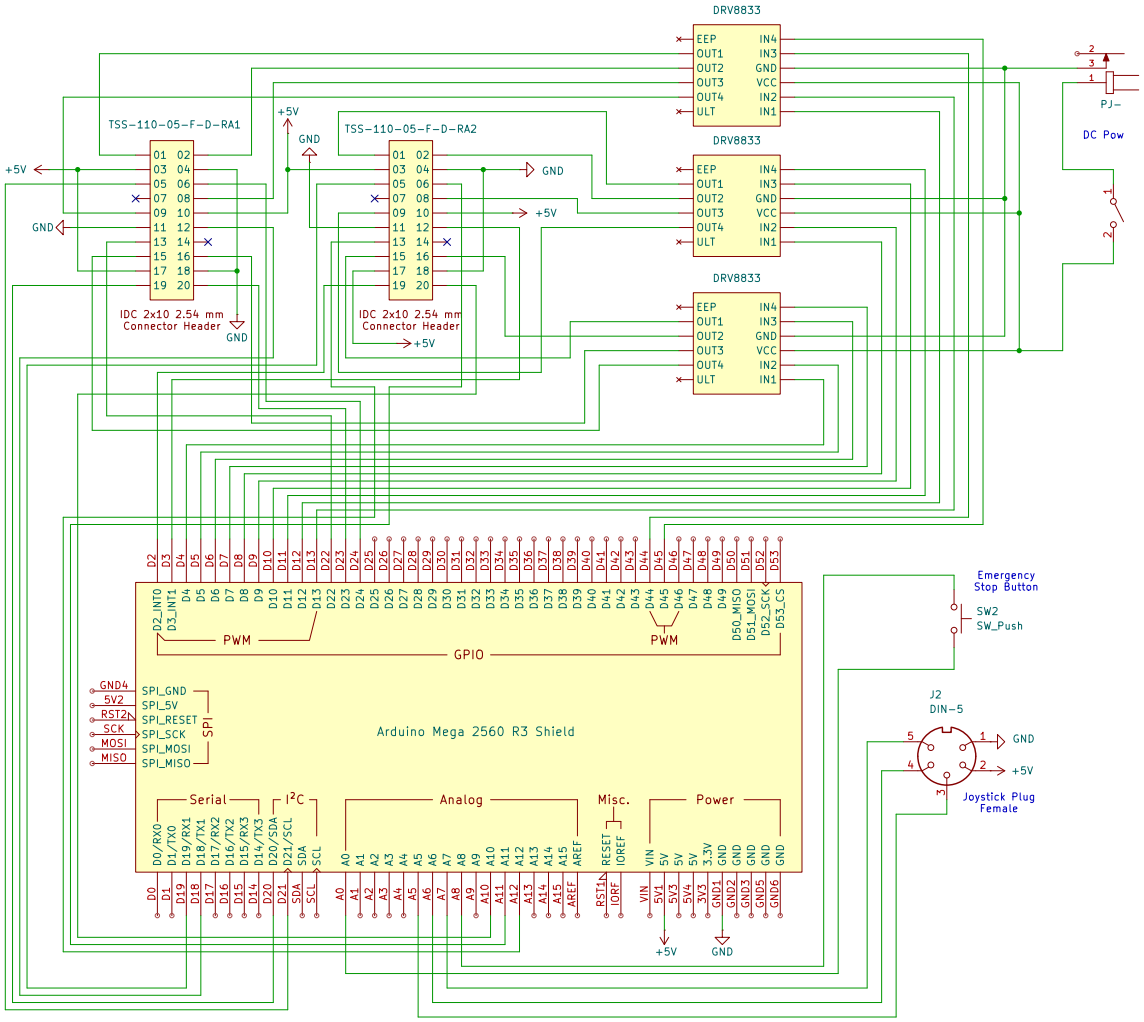


Figure 4.4: Main circuit schematic

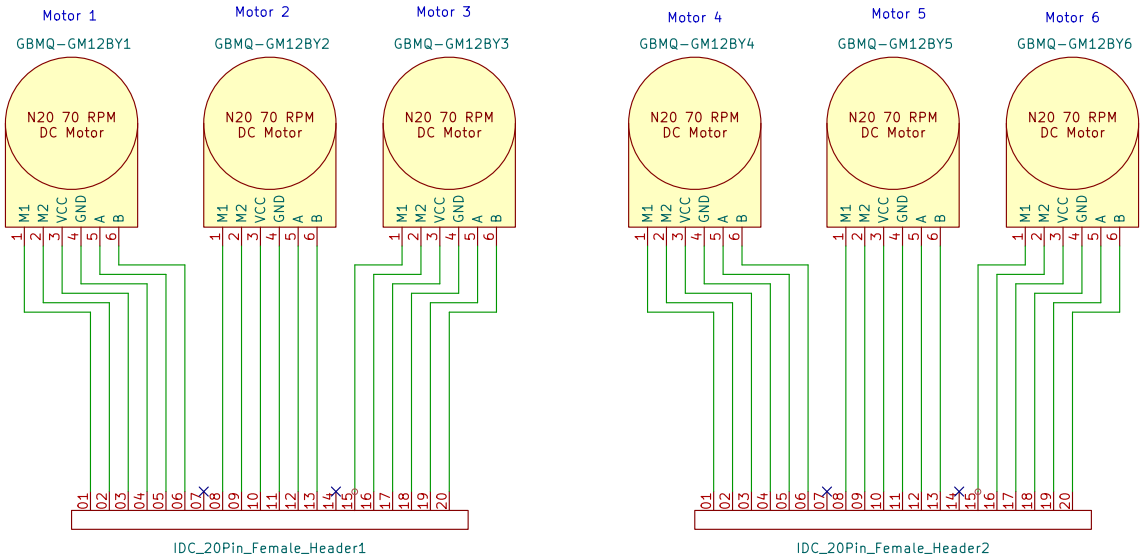


Figure 4.5: Motor circuit schematic

Chapter 5

Control System Interface

One of the project objectives was to establish a protocol for controlling the robot. Although the robot has an input for a joystick, this is insufficient for controlling the robot in a three-dimensional space. Additionally, the platform is designed to adapt to any user need, making the creation of a protocol or language for programming the robot essential. This protocol will be integrated into the controller firmware. The commands will be sent in real-time by a device, currently a computer, which serves as the interface for receiving user inputs. For this reason, a command-line application has also been developed to send commands via the established port. The source code for this project, Alam[1], can be found on GitHub[2].

The development of the robot's kinematic model was beyond the scope of this project due to the added complexity. This remains an area for future exploration. Consequently, the control system is direct, specifying the distance or position of each actuator individually and manually. However, the intention is for this protocol to be compatible with such a model in the future.

[1] This is the name of the project. It is derived from the Spanish word *"alambre"*, which translates to rod or wire.

[2] `https://www.github.com/liconaj/GraduationProject-Alam`

5.1 Protocol Specifications

The G-Code is a standard language widely used in manufacturing and CNC machining to control machine tools such as mills and lathes. It consists of alphanumeric commands specifying coordinates, speeds, and machine functions. These commands enable precise control and automation in manufacturing processes. Alongside G-Code, M-Code commands control additional machine functions like tool changes and device operations. Adopting G-Code as the foundation for our robot control protocol offers efficiency and clarity, ideal for rapid command transmission to microcontrollers like Arduino. Its hierarchical structure and diverse commands provide the flexibility needed for precise motion control and complex operations, aligning well with our platform's adaptability goals. Detailed definitions of proposed G-Code and M-Code commands are listed in Tables 5.1 and 5.2, respectively, offering a clear reference for implementation and usage.

Table 5.1: G-Code definitions

G-Code	Definition
`G1`	Move one or more actuators to specified positions at a given optional speed.
`G4`	Pause or dwell. Halts the machine for the specified duration.
`G28`	Move actuators to origin position.
`G28.1`	Move actuators to target position.
`G90`	Set absolute positioning mode. All subsequent movements are interpreted as absolute positions. This is the default mode.
`G91`	Set relative positioning mode. All subsequent movements are interpreted as displacements from the current position.
`G92`	Set origin position.
`G92.1`	Set target position. This may be a position of interest.

The application of these commands and their respective parameters is detailed in Tables 5.3 and 5.4. Each table includes practical examples demonstrating how

these commands are implemented. Additionally, Table 5.5 provides a comprehensive explanation of the parameters associated with each command.

Table 5.2: M-Code definitions

M-Code	Definition
M00	Stop program
M85	Maximum command wait time.
M114	Report current position of the actuators.
M301	Set PID parameters.
M303	Initiate autotuning process for the PID parameters.
M355	Report current status of robot parameters.
M500	Save parameters to EEPROM.
M501	Load parameters from EEPROM.
M502	Reset parameters saved in EEPROM to defaults.
M503	Display the saved configuration in EEPROM.

Table 5.3: G-Codes usage

Code	Usage	Example
G1	G1 <id><pos> [F<speed,255>]	> G1 A100.0
G4	G4 P<millis>|S<secs>	> G4 P3000
G20	G20	> G20
G21	G21	> G21
G28	G28 [<id,A B C I J K>]	> G28 A B C
G28	G28.1 [<id,A B C I J K>]	> G28.1 J K
G90	G90	> G90
G91	G91	> G91
G92	G92 [<id,A B C I J K><pos,0>]	> G92 A-100.0 I5.0
G92.1	G92.1 [<id, A B C I J K><pos,0>]	> G92.1 B250.0

Table 5.4: M-Codes usage

Note that only commands with parameters are explained. All others can be used by simply entering the code.

Code	Usage	Example
M85	M85 P<millis,5000>|S<secs,5>	> M85 S3
M301	M301 [P<kp,0>] [I<ki,0>] [D<kd,0>]	> M301 P1000 I0.5
M500	M500 <optn>	> M500 T P
M502	M502 <optn>	> M502 I J K

Table 5.5: Code parameters

Parameter	Meaning
<id>	Actuator identification letter: A, B, C, I, J or K.
<pos>	Position number.
<kp>	Proportional constant.
<ki>	Integral constant.
<kd>	Derivative constant.
<speed>	Maximum speed of actuator as integer number from 50 to 255.
<millis>	Milliseconds as integer number.
<secs>	Seconds as integer number.
<optn>	Parameter of the robot. T for PID tuning constants; A, B, C, I, J or K for position of given actuator; P for **all** actuator positions
<...,VALUE>	Default value.
[...]	Optional parameter. If omitted, default value will be used.

5.2 Command Line Application

The robot's firmware was developed in Arduino C++ using the Arduino library and the *SerialCommands* library [3] for command definitions. Communication occurs via a serial data bus, as suggested by its name. The command-line application, written in Python, utilizes the *pyserial* library [4] to establish a connection with the Arduino.

5.2.1 Architecture

Figure 5.1 depicts the dependency relationships between the firmware source components and the packages used. Additionally, a flowchart diagram illustrating the interaction between the command-line application and the robot is included in Figure 5.2.

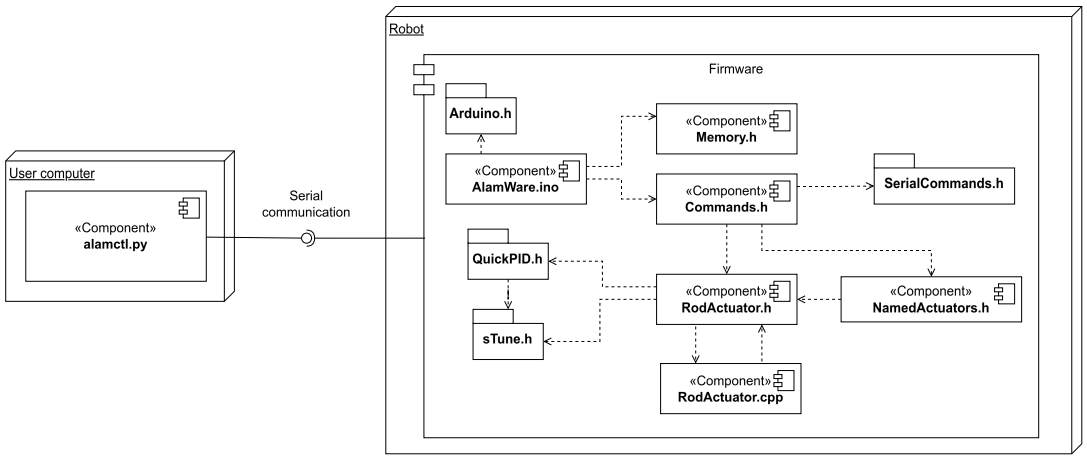


Figure 5.1: Relationships of control system components

The serial port data buffer is 128 bytes, meaning each command can have a maximum of 128 characters. Only one command can be sent at a time, separated by a newline. After executing a command, the robot sends a message indicating completion. The robot has a configurable maximum timeout to handle commands

[3] `https://github.com/ppedro74/Arduino-SerialCommands`
[4] `https://pypi.org/project/pyserial/`

that take too long; it will not interrupt or modify its current task until a new instruction is received. The robot's firmware does not support comments, so these are removed by the application's parser to send only essential instructions to the robot.

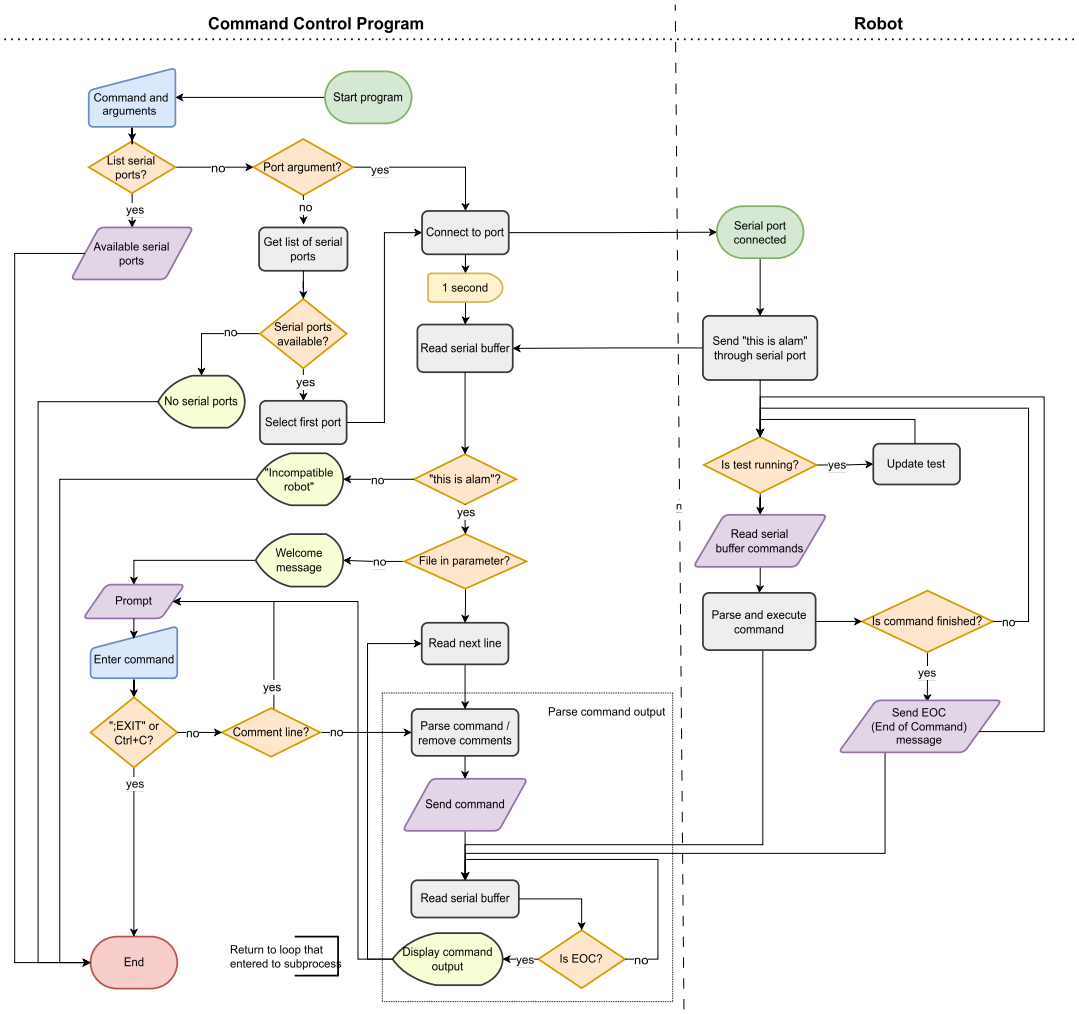


Figure 5.2: System flowchart

5.2.2 Usage

To control the robot, the `alamctl.py` script must be used. The code for this script can be found in Appendix D. Figure 5.3 shows how to use the application via the help parameter output.

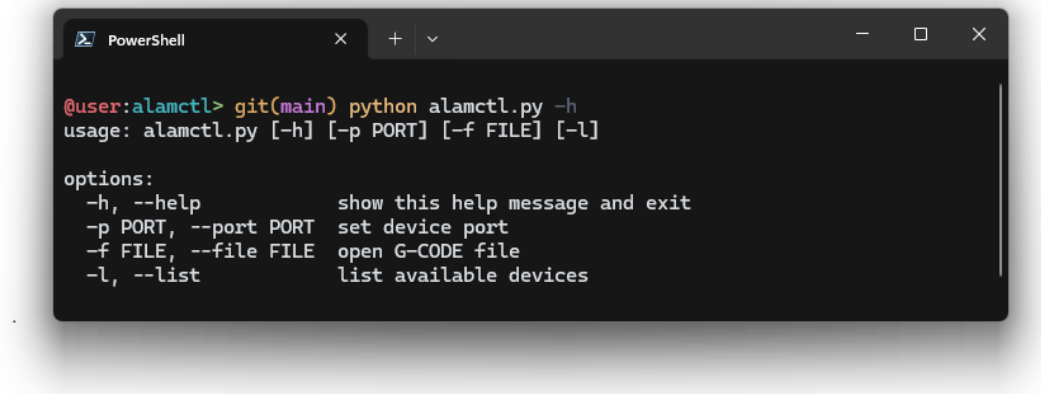


Figure 5.3: Command line usage

Note that all parameters are optional. If no parameters are passed, as explained in the flowchart in Figure 5.2, the application will attempt to connect to one of the available ports. However, the recommended method is to search for available ports and then try to connect to the one whose description matches that of the controller, as shown in Figure 5.4.

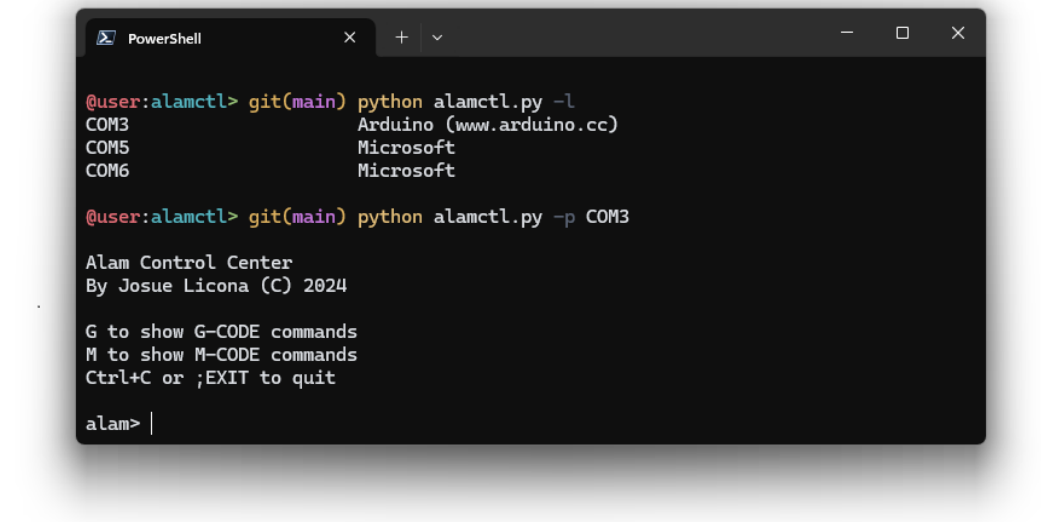


Figure 5.4: Command line connection

When a successful connection with the robot is established, the application displays a welcome message and a short help guide to start using the robot interactively (see Figure 5.5). However, it is also possible to pass a G-Code script as a

parameter for the program to send commands automatically (Figure 5.6). This is the most efficient and powerful way to use the platform to control a robot.

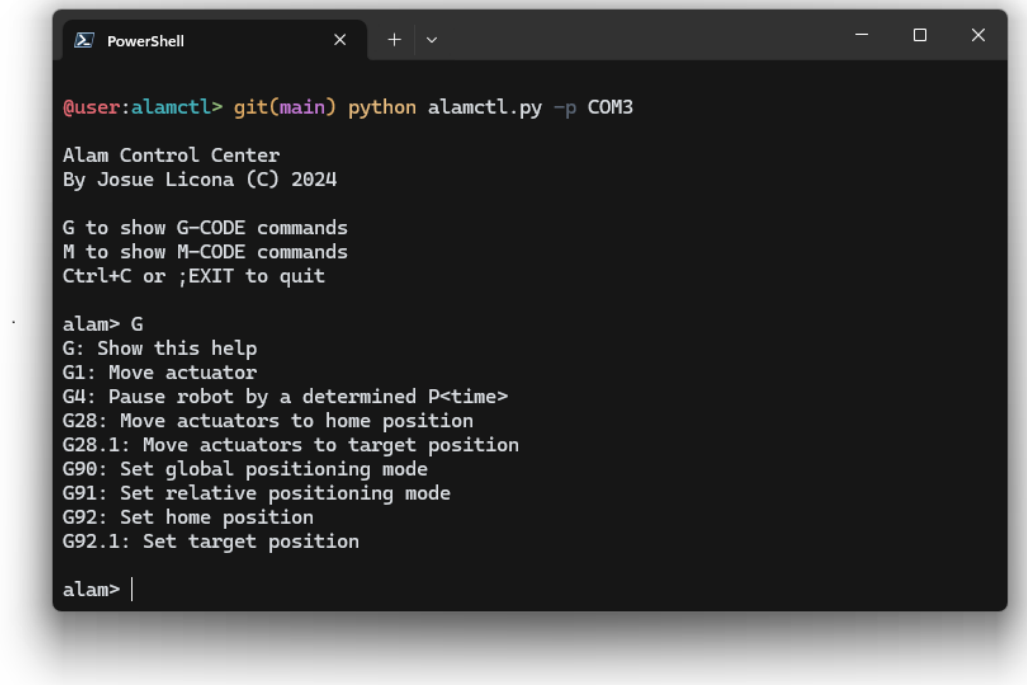


Figure 5.5: Command line manual input

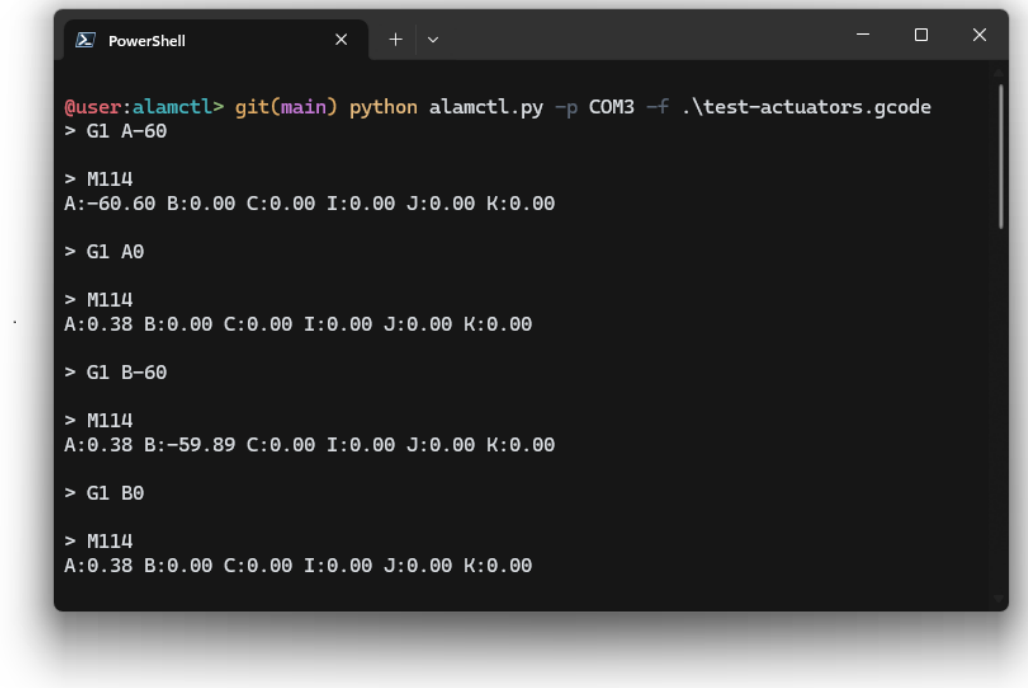


Figure 5.6: Command line file parsing

5.3 PID Control and Tuning

Given that the actuators are equipped with DC motors, the controllable variable is the speed, but the position can be determined thanks to the magnetic encoder, which counts the number of motor revolutions. Based on this, a PID control is implemented to use the position as the input variable, allowing the controller to manipulate the speed to reach the desired position. To implement this control, the *QuickPID*[5] library was used, which can be integrated with the *sTune* library to determine the actuator tunings automatically. An attempt was made to use this latter library to find the tunings; however, its methods are designed for systems with an S-shaped response to a constant input, which does not apply to our system. Therefore, the results from this library were often unsatisfactory. For this reason, a more powerful tool, such as MATLAB and Simulink, was used to find the tunings.

5.3.1 Test Data

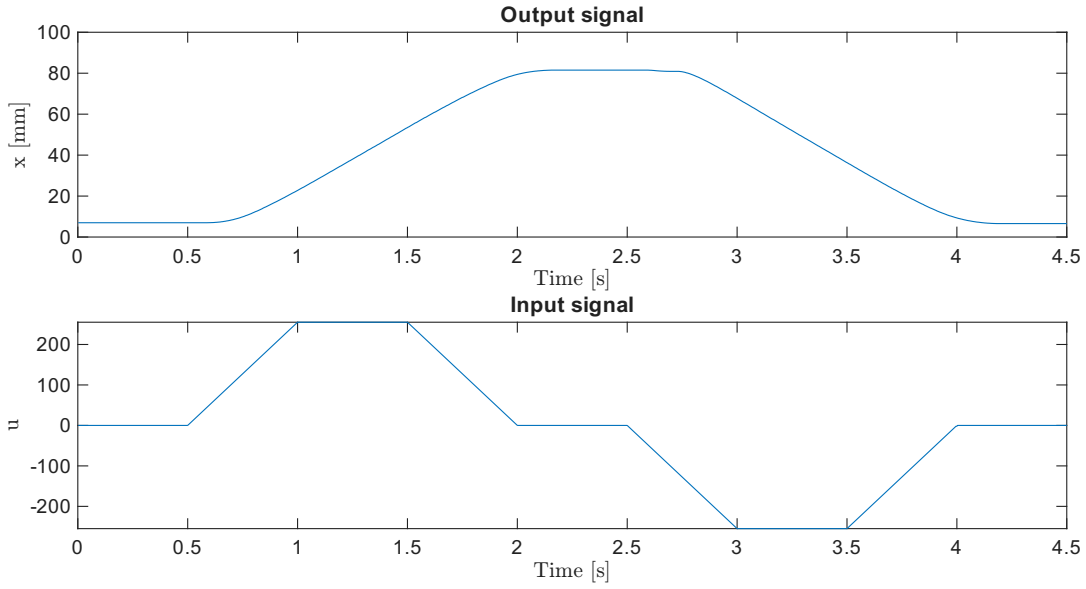


Figure 5.7: Input and output signals

First, a test to obtain data from the actuators was conducted to understand the

[5] https://github.com/Dlloydev/QuickPID

system. This test lasts 4.5 seconds and can be executed with the command `M300`. It sends a PWM signal to the actuators that varies over time, showing the linear position of the actuator at each time instant, as seen in Figure 5.7.

5.3.2 System Identification

Based on the obtained data, the system's transfer function is identified using MATLAB's *System Identification Toolbox*. The process carried out is shown in Figure 5.8. The model fit to the real data is depicted in Figure 5.9. The MATLAB code used is provided in Appendix B.

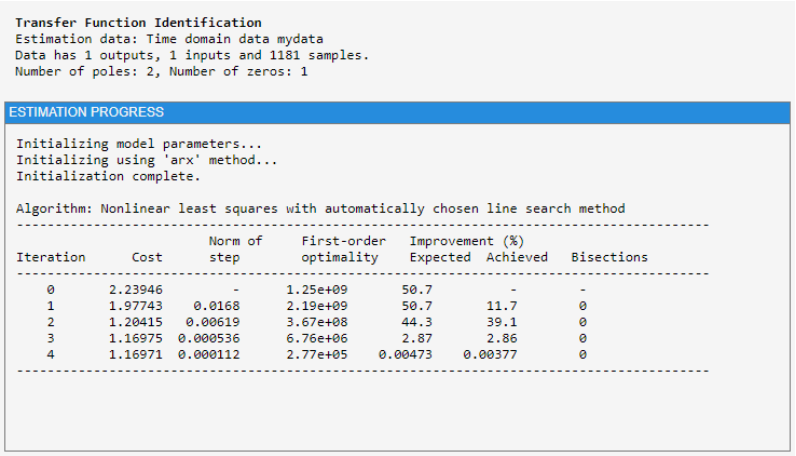


Figure 5.8: Transfer function identification in MATLAB

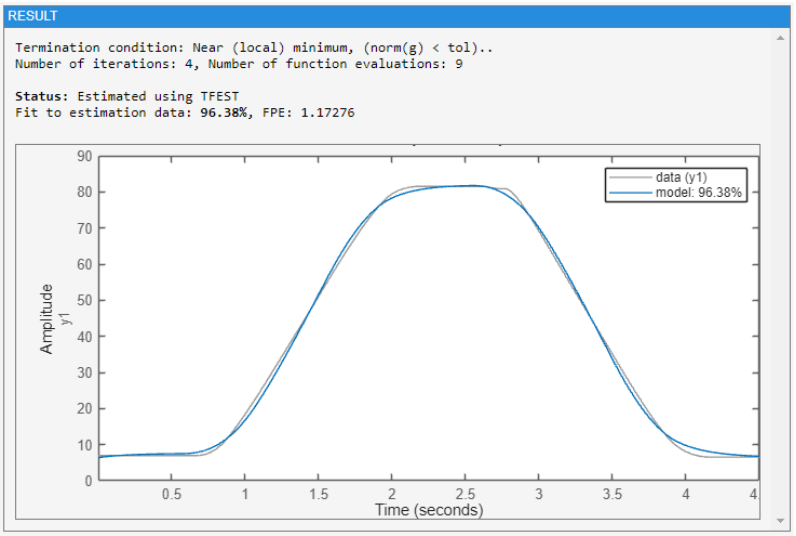


Figure 5.9: Transfer function model in MATLAB

The transfer equation of the linear actuator that was identified is shown in Equation 5.1, where the variable of the function is z^{-1}.

$$tf = \frac{(4.808 - 4.596z^{-1}) \times 10^{-4}}{1 - 1.982z^{-1} + 0.9824z^{-2}} \tag{5.1}$$

5.3.3 PID Tuning

The tunings of the PID controller were determined using the *pidTuner* utility from MATLAB. The type of controller that provided the best response was the PI controller, which is a PID controller with $K_d = 0$. In our case, this control is discrete, and the resulting constants are shown in Table 5.6. These variables are specified in the controller of the *QuickPID* library in Arduino.

$$C = Kp + Ki * \frac{Ts}{z - 1} \tag{5.2}$$

Table 5.6: PID tunings

Property	Value
Proportional constant, Kp	21.4
Integrative constant, Ki	1.97
Sample time, Ts	0.00381s

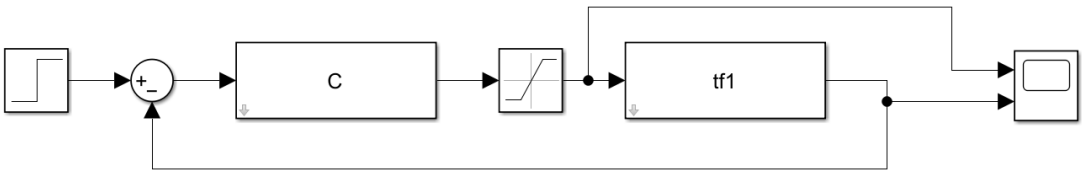


Figure 5.10: Blocks diagram of control system

A general block diagram of the control system is shown in Figure 5.10, where `C` represents the transfer function of the PID controller (equation 5.2) and `tf1` rep-

resents the transfer function of the actuator. The system's response to a 100 mm input is shown in Figure 5.11. The blue curve indicates that the system responds quickly, taking just under two seconds theoretically to reach the desired value; however, it exhibits overshoot and takes nearly four seconds to settle into a steady state. Often, when the robot is in motion, it is unnecessary to wait for it to reach exact intermediate positions. Therefore, the firmware was programmed to allow new commands to be entered once the desired position is passed, sacrificing accuracy for speed.

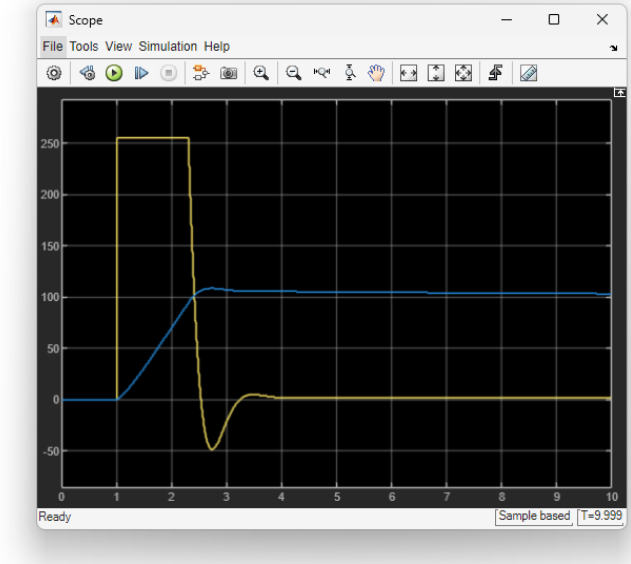


Figure 5.11: System response of simulation in Simulink

Additionally, the control signal, shown in yellow, experiences saturation, highlighting the need to implement an anti-windup control. Fortunately, the *QuickPID* library offers a function for this, making implementation straightforward.

Chapter 6

Performance and Results

The Alam robot platform was successfully constructed using steel rod segments, as depicted in Figure 6.1. The constraints securely fasten to the rods, ensuring stability and structural integrity.

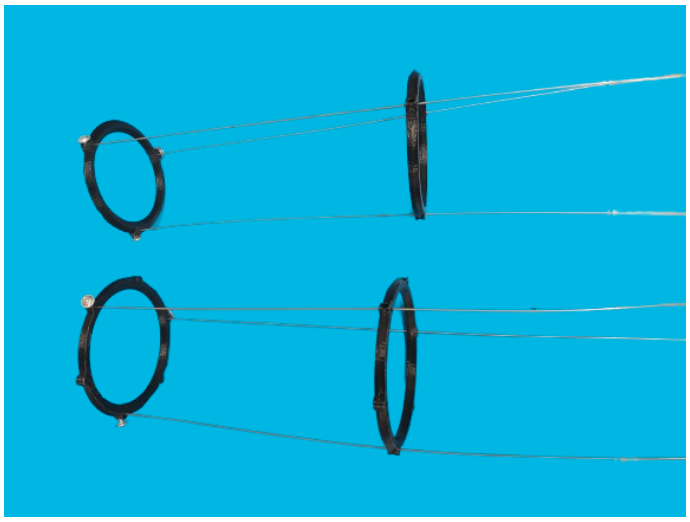
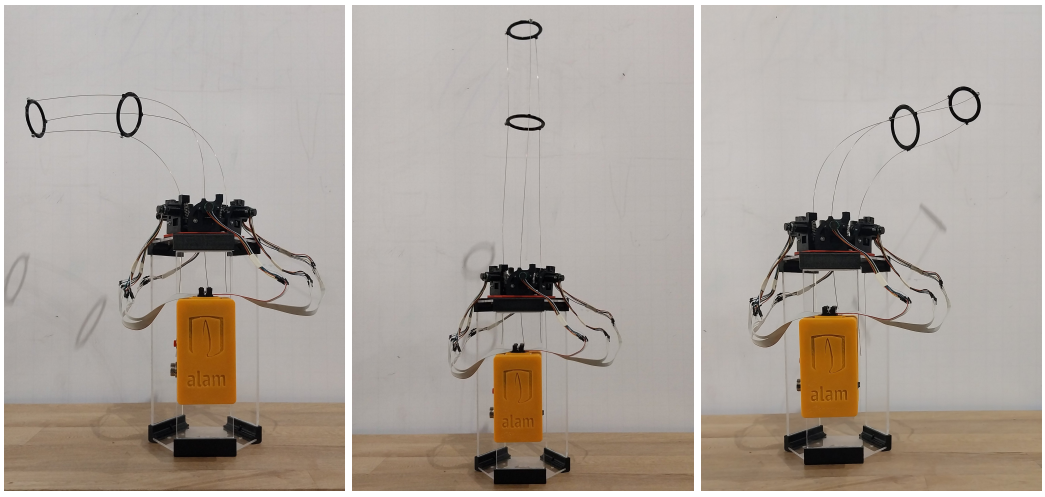


Figure 6.1: Arm segments

Figure 6.2 illustrates the robot in three different poses using a single segment: one with the arm to the left, another in a straight configuration, and the third with the arm to the right. The actuators demonstrated sufficient friction and force to

maintain each position effectively.



(a). Arm to the left **(b).** Straight arm **(c).** Arm to the right

Figure 6.2: One segment arm positions

The firmware and control application functioned well during testing; however, the firmware remains incomplete, particularly in handling commands with erroneous parameters. Most code functionalities were tested, but aspects related to EEPROM memory and robot status display were not fully implemented. Additionally, joystick control remains unimplemented.

Figure 6.3: Electronics case and connections

The electronics case, shown in Figure 6.3, was initially prototypical, utilizing

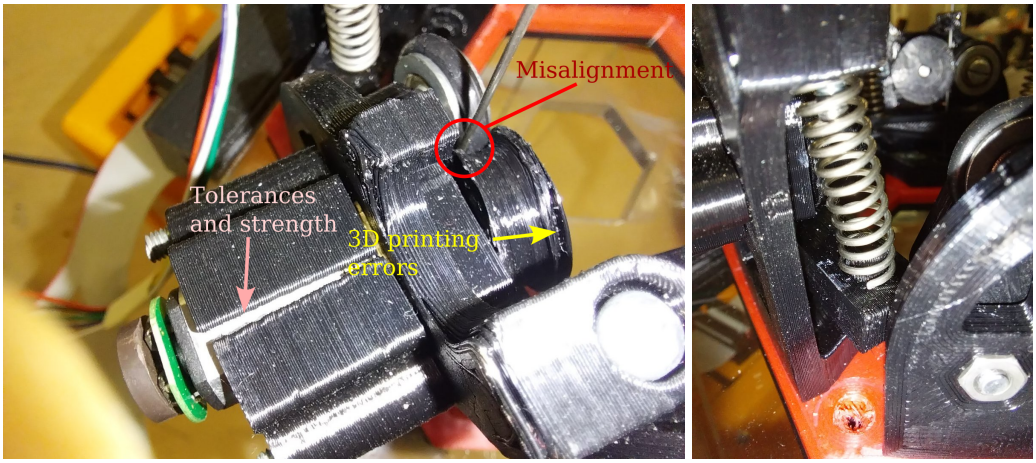
a breadboard and jumper wires for connections. This setup proved cumbersome and prone to disconnection, complicating assembly and debugging processes.

Figure 6.4 compares the prototype with two segments against the initial design. The prototype closely resembles the design, demonstrating successful realization of the intended structure.

(a). Real prototype **(b).** Designed prototype

Figure 6.4: Complete prototype

Issues encountered with the linear actuators are depicted in Figure 6.5, including tolerance discrepancies, alignment challenges between rod and bearing, printing errors, and base deformation due to spring force, which occasionally caused detachment of the arm from its support.



(a). Fabrication and alignment **(b).** Spring and arm

Figure 6.5: Linear actuator issues

Finally, Table 6.1 presents general specifications of the platform, including height, maximum arm reach, body dimensions, and actuator tolerances.

Table 6.1: Platform specifications

Property	Value
Height	30 cm
Maximum height (with arm)	70 cm
Weight	1 kg
Linear actuators tolerance	±1 mm

Conclusions

Throughout this project, the development of the Alam robot platform has showcased the successful integration of mechanical design, control theory, and software development. The platform, constructed from steel rod segments and 3D-printed components, offers a robust framework for robotic experimentation and control. Despite challenges in firmware completion and electronic assembly, the platform achieved its primary goal of providing a flexible and programmable robotic system.

Testing and experimentation highlighted both achievements and areas for improvement in the Alam platform. The implementation of PID control algorithms demonstrated effective position control, though issues with overshoot and controller saturation necessitated further refinement. Challenges with linear actuators underscored the importance of precision manufacturing and iterative design enhancements. These insights inform future iterations aimed at optimizing performance and reliability.

In summary, the Alam robot platform serves as a foundational tool for exploring advanced robotics concepts and applications. By addressing challenges in mechanical design, control algorithms, and software integration, this project sets a precedent for future developments.

Future Work and Recommendations

- Develop a PCB for the electronics to mitigate potential issues and eliminate current problems. Currently, connecting IDC 2 with the power off causes the motor drivers to draw power from the Arduino, posing a risk of MCU and computer damage. The root cause of this issue remains elusive.

- When establishing serial communication with Arduino, the LED linked to pin `D13` blinks twice, necessitating the power of the motors to be off or another PWM pin to be utilized when connecting the module.

- Implement joystick functionality for direct control. This feature was intended to facilitate simultaneous adjustment of all actuators, aiding in rod insertion and removal.

- Complete the implementation of missing command functionalities in the control language.

- Enhance the design of actuators to streamline assembly. The current placement of screws securing actuators to the base is inaccessible and cumbersome.

- Address challenges with spring installation and adjustability. Utilize mathematical models or adopt extruder-like systems to regulate spring tension effectively.

- Refine model tolerances to improve alignment of the rod with bearings and drive pulleys. Explore alternative materials or manufacturing methods to rectify identified defects in the actuator design for 3D printing.

- Enhance portability by transitioning the system from mains power to battery operation.

- Develop a static or kinetic model of the robot using analytical methods or machine learning algorithms, leveraging the platform and robot for practical applications.

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Appendices

A Forces in Actuator Arm

```
syms Fb P rAx rAy rBx rBy

vecFb = [Fb 0 0];
vecP = [0 P 0];
rA = [rAx rAy 0];
rB = [rBx rBy 0];

eq = cross(rA, vecP) + cross(rB, vecFb);
solve(eq, Fb)
```

B PID Tuning Code

```
% Get data
dataTable = readtable("datos.csv");
t = dataTable.t/1000;  %convert time from milliseconds to seconds
PWM = dataTable.PWM;
A = dataTable.A;
startTime = t(1);
sampleTime = mean(diff(t));
mydata = iddata(A,PWM,sampleTime,"Tstart", startTime);

% Find transfer function of system
npoles = 2; nzeros = 1;
Options = tfestOptions;
Options.Display = 'on';
Options.EnforceStability = true;
tf1 = tfest(mydata, npoles, nzeros, Options, 'Ts', sampleTime, ...
    'Feedthrough', true);

% PID Tune
opts = pidtuneOptions("PhaseMargin", 90);
[C, info] = pidtune(tf1, 'PI', 5, opts);
```

C Test Code

```
;ALAM ROBOT TEST
;BY LICONAJ (c) 2024

G4 P5000  ; WAIT 3 SECONDS
;MOVE ACTUATOR A
G1 A-60
G4 P500
G1 A0
G4 P500
;MOVE ACTUATOR B
G1 B-60
G1 P500
G1 B0
G4 P500
;MOVE ACTUATOR C
G1 C-60
G1 C0
;MOVE ACTUATORS A AND B
G4 P1000
G1 A-60 B-60
G4 P500
G1 A0 B0
;MOVE ACTUATORS B AND C
G4 P1000
G1 B-60 C-60
G4 P500
G1 B0 C0
;MOVE ACTUATORS C AND A
G4 P1000
G1 C-60 A-60
G4 P500
G1 C0 A0
;MOVE ALL ACTUATORS
G4 P1000
G1 A-60 B-60 C-60
G4 P1000
;MOVE ACTUATORS A B C TO HOME
G28 A B C
```

D Command Line Interface Source Code

```
#!/usr/bin/python3
#alamctl.py

import serial
import sys
import argparse
import time
import serial.tools.list_ports

EOC = "!EOC"
EOL = "\r\n"

def get_ports():
    ports = []
    patterns = ["COM", "ttyACM", "ttyUSB"]
```

```
    for pattern in patterns:
        ports += serial.tools.list_ports.grep(pattern)
    return ports

def list_ports():
    ports = get_ports()
    for port in ports:
        print("{0:<20} \t {1:<30}".format(port.device, port.manufacturer))

parser = argparse.ArgumentParser()
parser.add_argument("-p", "--port", help="set device port")
parser.add_argument("-f", "--file", help="open G-CODE file")
parser.add_argument("-l", "--list", help="list available devices", action="store_true")
args = parser.parse_args()

if args.list:
    list_ports()
    sys.exit()

if args.port:
    port = args.port
else:
    ports = get_ports()
    print(f"{len(ports)} device(s) found")
    if not ports:
        print("No serial ports available")
        sys.exit()
    else:
        port = ports[0].device
    print(f"Connecting to {port}...")

try:
    mcu = serial.Serial(port=port, baudrate=250000, timeout=.1)
    time.sleep(1)
    reponse = mcu.readline().decode()
    if not reponse.startswith("this is alam"):
        print("Incompatible robot")
        sys.exit()
except serial.SerialException:
    print("Serial port unavailable")
    sys.exit()

def send_command(value: str):
    mcu.write(bytes(value, "utf-8"))

def parse_command(cmd: str) -> str:
    cmd = cmd.strip().split(";")[0]
    cmd += EOL
    # print(f"Parsing command {repr(cmd)}")
    send_command(cmd)
    output = ""
    value = ""
    while not EOC in value:
        value = mcu.readline().decode()
        if not EOC in value:
            output += value
    return output

if __name__ == "__main__":
    if args.file is None:
        print("\nAlam Control Center")
        print("By Josue Licona (C) 2024\n")

        print("G to show G-CODE commands")
        print("M to show M-CODE commands")
        print("Ctrl+C or ;EXIT to quit\n")

        try:
            while True:
```

```
                cmd = input("alam> ").upper()
                if ";EXIT" in cmd:
                    break
                elif not cmd or cmd.startswith(";"):
                    continue
                print(parse_command(cmd))
            except KeyboardInterrupt:
                print("\n\nPROGRAM ENDED BY USER\n")

        else:
            time.sleep(1)
            try:
                with open(args.file, "r", encoding="utf-8") as fh:
                    lines = fh.readlines()
                    fh.close()
            except FileNotFoundError:
                print(f"File `{args.file}` not found")
                sys.exit()

            for cmd in lines:
                cmd = cmd.strip().upper()
                if not cmd or cmd.startswith(";"):
                    continue
                print(f"> {cmd.strip()}")
                print(parse_command(cmd))
```

E Firmware Source Code

E.1 Arduino Main Entry Point

```
// AlamWare.ino

#include "Memory.h"
#include "Commands.h"

// SerialCommands Setup
char serialCommandBuffer[128];
SerialCommands serialCommands(&Serial, serialCommandBuffer, sizeof(serialCommandBuffer));

void addSerialCommands() {
    serialCommands.SetDefaultHandler(cmdUnrecognized);

    serialCommands.AddCommand(&GHelp);
    serialCommands.AddCommand(&G1);
    serialCommands.AddCommand(&G4);
    serialCommands.AddCommand(&G92);
    serialCommands.AddCommand(&G92_1);
    serialCommands.AddCommand(&G28);
    serialCommands.AddCommand(&G28_1);
    serialCommands.AddCommand(&G90);
    serialCommands.AddCommand(&G91);

    serialCommands.AddCommand(&MHelp);
    serialCommands.AddCommand(&M00);
    serialCommands.AddCommand(&M85);
    serialCommands.AddCommand(&M114);
    serialCommands.AddCommand(&M303);
    serialCommands.AddCommand(&M301);
    serialCommands.AddCommand(&M300);
}

void setup() {
```

```
    Serial.begin(250000);
    Serial.print("this is alam");
    addSerialCommands();
}

void loop() {
    if (testing) {
    updateTest();
    } else {
    serialCommands.ReadSerial();

    updateNamedActuators();
    nextCommand();
    }
}
```

E.2 Persistence Memory Management Class Header

```
// Memory.h

#ifndef MEMORY_H
#define MEMORY_H

#include <EEPROM.h>

class Memory {
 private:
  float kp;
  float kd;
  float ki;

  uint8_t kpAddress = 10;
  uint8_t kiAddress = 12;
  uint8_t kdAddress = 14;

  int lastPositions[6];
  uint8_t pAddresses[6];

 public:
  Memory();
  ~Memory();

  int GetLastPosition(uint8_t actuatorId);
  void SavePosition(uint8_t actuatorId, int position);
  void GetTunings(float* kp, float* ki, float* kd);
  void SaveTunings(float kp, float ki, float kd);
};

#endif
```

E.3 Persistence Memory Management Class

```
// Memory.cpp
#include "Memory.h"

Memory::Memory() {
  for (int i = 0; i < 6; i++) {
    pAddresses[i] = 20 + sizeof(float) * i;
  }
}
```

```
Memory::~Memory() {
}

void Memory::SavePosition(uint8_t actuatorId, int position) {
  EEPROM.put(pAddresses[actuatorId], position);
}

int Memory::GetLastPosition(uint8_t actuatorId) {
  return lastPositions[actuatorId];
}

void Memory::SaveTunings(float kp, float ki, float kd) {
  EEPROM.put(kpAddress, kp);
  EEPROM.put(kiAddress, ki);
  EEPROM.put(kdAddress, kd);
}

void Memory::GetTunings(float* kp, float* ki, float* kd) {
  EEPROM.get(kpAddress, kp);
  EEPROM.get(kiAddress, ki);
  EEPROM.get(kdAddress, kd);
}
```

E.4 Commands Definitions

```
// Commands.h

#ifndef COMMANDS_H
#define COMMANDS_H

#include "SerialCommands.h"

#include "NamedActuators.h"
#include "RodActuator.h"

bool sendingCommand = false;
bool testing = false;
unsigned long startTimeTest;

void updateTest();
void nextCommand();

// G-Code Definitions

void cmdUnrecognized(SerialCommands *, const char *);
void cmdGetGCodes(SerialCommands *);
void cmdDelay(SerialCommands *);
void cmdMoveActuator(SerialCommands *);
void cmdSetGlobalMode(SerialCommands *);
void cmdSetRelativeMode(SerialCommands *);
void cmdSetHome(SerialCommands *);
void cmdSetTarget(SerialCommands *);
void cmdMoveToHome(SerialCommands *);
void cmdMoveToTarget(SerialCommands *);

// M-Code Definitions

void cmdGetMCodes(SerialCommands *);
void cmdStop(SerialCommands *);
void cmdSetTimeout(SerialCommands *);
void cmdGetActuatorPositions(SerialCommands *);
void cmdTestActuators(SerialCommands *);
void cmdStartAutoTuning(SerialCommands *);
void cmdSetPIDConstants(SerialCommands *);

SerialCommand GHelp("G", &cmdGetGCodes);
SerialCommand G4("G4", &cmdDelay);
SerialCommand G1("G1", &cmdMoveActuator);
SerialCommand G28("G28", &cmdMoveToHome);
SerialCommand G28_1("G28.1", &cmdMoveToTarget);
SerialCommand G90("G90", &cmdSetGlobalMode);
SerialCommand G91("G91", &cmdSetRelativeMode);
SerialCommand G92("G92", &cmdSetHome);
SerialCommand G92_1("G92.1", &cmdSetTarget);

SerialCommand MHelp("M", &cmdGetMCodes);
SerialCommand M00("M00", &cmdStop);
SerialCommand M85("M85", &cmdSetTimeout);
```

```
SerialCommand M114("M114", &cmdGetActuatorPositions);
SerialCommand M300("M300", &cmdTestActuators);
SerialCommand M303("M303", &cmdStartAutoTuning);
SerialCommand M301("M301", &cmdSetPIDConstants);

void endCmd(SerialCommands *sender) {
  sender->GetSerial()->println("!EOC");
}

void nextCommand() {
  if (!sendingCommand)
    return;
  for (NamedActuator actuator : namedActuators) {
    if (!actuator.object->Next()) {
      return;
    }
  }
  Serial.println("!EOC");
  sendingCommand = false;
}

float getvel(int t) {
  float v;
  float m = 255.0 / 500.0;
  if (t < 500 || t > 4000) {
    v = 0;
  } else if (t < 1000) {  // entre 500 y 1000 ms rampa
    v = m * (t - 500);
  } else if (t < 1500) {  // mantener velocidad máxima por 500 ms
    v = 255;
  } else if (t < 2000) {  // disminuir velocidad
    v = -m * (t - 1500) + 255;
  } else if (t < 2500) {  // mantener velocidad máxima en reversa por 500 ms
    v = 0;
  } else if (t < 3000) {
    v = -m * (t - 2500);
  } else if (t < 3500) {
    v = -255;
  } else if (t < 4000) {
    v = m * (t - 3500) - 255;
  }
  return v;
}

void updateTest() {
  unsigned long t = millis() - startTimeTest;
  Serial.print(t);
  float v = getvel(t);
  Serial.print(";");
  Serial.print(v);
  for (NamedActuator actuator : namedActuators) {
    Serial.print(";");
    actuator.object->TestVelocity(v);
    actuator.object->Update();
    Serial.print(actuator.object->GetPosition());
  }
  Serial.println("");
  if (t >= 4500) {
    testing = false;
    for (NamedActuator actuator : namedActuators) {
      actuator.object->Stop();
    }
    Serial.println("!EOC");
  }
}

void cmdUnrecognized(SerialCommands *sender, const char *cmd) {
  sendingCommand = true;

  sender->GetSerial()->print("Unrecognized command [");
  sender->GetSerial()->print(cmd);
  sender->GetSerial()->println("]");
}

void cmdGetGCodes(SerialCommands *sender) {
  sendingCommand = true;

  sender->GetSerial()->println("G: Show this help");
  sender->GetSerial()->println("G1: Move actuator");
  sender->GetSerial()->println("G4: Pause robot by a determined P<time>");
  sender->GetSerial()->println("G28: Move actuators to home position");
  sender->GetSerial()->println("G28.1: Move actuators to target position");
  sender->GetSerial()->println("G90: Set global positioning mode");
  sender->GetSerial()->println("G91: Set relative positioning mode");
  sender->GetSerial()->println("G92: Set home position");
  sender->GetSerial()->println("G92.1: Set target position");
}

void cmdGetMCodes(SerialCommands *sender) {
```

```
  sendingCommand = true;

  sender->GetSerial()->println("M: Show this help");
  sender->GetSerial()->println("M00: Stop actuators");
  sender->GetSerial()->println("M85: Set command timeout with P<milliseconds> or S<seconds>");
  sender->GetSerial()->println("M114: Report actual position of actuators");
  sender->GetSerial()->println("M300: Test actuators");
  sender->GetSerial()->println("M301: Set PID constants with P<value> I<value> D<value>");
  sender->GetSerial()->println("M303: Starts autotuning");
}

void cmdDelay(SerialCommands *sender) {
  sendingCommand = true;

  // sender->GetSerial()->println("Starting delay");
  char *arg = sender->Next();
  if (arg != NULL) {
    char parameter = arg[0];
    float value = atof(arg + 1);
    if (parameter == 'P') {
      delay(value);
    }
  }
}

void cmdMoveActuator(SerialCommands *sender) {
  sendingCommand = true;
  uint8_t speed = 255;
  char *arg;
  while ((arg = sender->Next()) != NULL) {
    char id = arg[0];
    float value = atof(arg + 1);
    if (id == 'F') {
      speed = value;
      continue;
    }
    RodActuator *actuator = getActuatorByName(id);
    actuator->Move(value);
    actuator->SetMaxSpeed(speed);
  }
}

void cmdStop(SerialCommands *sender) {
  sendingCommand = true;
  for (NamedActuator actuator : namedActuators) {
    actuator.object->Stop();
  }
}

void cmdSetTimeout(SerialCommands *sender) {
  sendingCommand = true;
  float maximumTimeout = 60e3;
  float timeout = 5000;
  char *arg = sender->Next();
  if (arg != NULL) {
    char parameter = arg[0];
    float value = atof(arg + 1);
    if (parameter == 'P') {
      timeout = value;
    } else if (parameter == 'S') {
      timeout = value * 1000;
    }
    if (timeout > maximumTimeout)
      timeout = maximumTimeout;
    for (NamedActuator actuator : namedActuators) {
      actuator.object->SetTimeout(timeout);
    }
  } else {
    timeout = namedActuators[0].object->GetTimeout();
  }
  sender->GetSerial()->print("Timeout:");
  sender->GetSerial()->println(timeout);
}

void cmdGetActuatorPositions(SerialCommands *sender) {
  sendingCommand = true;

  int decimalPlaces = 5;

  String positions = "";
  for (int i = 0; i < N_ACTUATORS; ++i) {
    String name = (String)namedActuators[i].name;
    float position = namedActuators[i].object->GetPosition();
    positions += name + ":" + String(position);
    if (i < N_ACTUATORS - 1) {
      {
        positions += " ";
      }
    }
```

```
  }
  sender->GetSerial()->println(positions);
}

void cmdStartAutoTuning(SerialCommands *sender) {
  sendingCommand = true;

  char *arg;
  while ((arg = sender->Next()) != NULL) {
    char id = arg[0];
    Serial.print("Starting auto tuning in actuator ");
    Serial.println(id);
    RodActuator *actuator = getActuatorByName(id);
    actuator->AutoTune();
  }
}

void cmdTestActuators(SerialCommands *sender) {
  testing = true;
  startTimeTest = millis();
  sender->GetSerial()->print("t");
  sender->GetSerial()->print(";PWM");
  for (NamedActuator actuator : namedActuators) {
    sender->GetSerial()->print(";");
    sender->GetSerial()->print(actuator.name);
  }
  sender->GetSerial()->println("");
}

void cmdSetPIDConstants(SerialCommands *sender) {
  sendingCommand = true;

  float kp = 0;
  float ki = 0;
  float kd = 0;

  char *arg;
  while ((arg = sender->Next()) != NULL) {
    char id = arg[0];
    float value = atof(arg + 1);
    if (id == 'P')
      kp = value;
    else if (id == 'I')
      ki = value;
    else if (id == 'D')
      kd = value;
  }

  for (NamedActuator actuator : namedActuators) {
    actuator.object->SetPIDConstants(kp, ki, kd);
  }

  sender->GetSerial()->print("Kp:");
  sender->GetSerial()->print(kp);
  sender->GetSerial()->print(" Kd:");
  sender->GetSerial()->print(kd);
  sender->GetSerial()->print(" Ki:");
  sender->GetSerial()->println(ki);
}

void cmdSetGlobalMode(SerialCommands *sender) {
  for (NamedActuator actuator : namedActuators) {
    actuator.object->SetMoveMode(actuator.object->Global);
  }
}

void cmdSetRelativeMode(SerialCommands *sender) {
  for (NamedActuator actuator : namedActuators) {
    actuator.object->SetMoveMode(actuator.object->Relative);
  }
}

void cmdSetHome(SerialCommands *sender) {
  sendingCommand = true;
  char *arg;
  while ((arg = sender->Next()) != NULL) {
    char id = arg[0];
    float value = atof(arg + 1);
    RodActuator *actuator = getActuatorByName(id);
    actuator->SetHomePosition(value);
  }
}

void cmdSetTarget(SerialCommands *sender) {
  sendingCommand = true;
  char *arg;
  while ((arg = sender->Next()) != NULL) {
    char id = arg[0];
    float value = atof(arg + 1);
```

```
    RodActuator *actuator = getActuatorByName(id);
    actuator->SetTargetPosition(value);
  }
}

void cmdMoveToHome(SerialCommands *sender) {
  sendingCommand = true;
  char *arg;
  arg = sender->Next();
  if (arg == NULL) {
    for (NamedActuator actuator : namedActuators) {
      actuator.object->MoveToHome();
    }
  } else {
    char id = arg[0];
    float value = atof(arg + 1);
    RodActuator *actuator = getActuatorByName(id);
    actuator->MoveToHome();

    while ((arg = sender->Next()) != NULL) {
      id = arg[0];
      float value = atof(arg + 1);
      actuator = getActuatorByName(id);
      actuator->MoveToHome();
    }
  }
}

void cmdMoveToTarget(SerialCommands *sender) {
  sendingCommand = true;
  char *arg;
  arg = sender->Next();
  if (arg == NULL) {
    for (NamedActuator actuator : namedActuators) {
      actuator.object->MoveToTarget();
    }
  } else {
    char id = arg[0];
    float value = atof(arg + 1);
    RodActuator *actuator = getActuatorByName(id);
    actuator->MoveToTarget();

    while ((arg = sender->Next()) != NULL) {
      id = arg[0];
      float value = atof(arg + 1);
      actuator = getActuatorByName(id);
      actuator->MoveToTarget();
    }
  }
}

#endif
```

E.5 Actuators Instances

```
// NamedActuators.h
#ifndef NAMEDACTUATORS_H
#define NAMEDACTUATORS_H

#include "RodActuator.h"

// 1.1
#define A_ENA 21
#define A_ENB 24
#define A_IN1 13
#define A_IN2 12
// 1.3
#define B_ENA 20
#define B_ENB 23
#define B_IN1 6
#define B_IN2 7
// 2.2
#define C_ENA 3
#define C_ENB 66
#define C_IN1 10
#define C_IN2 11
// 2.1
#define I_ENA 19
#define I_ENB 65
#define I_IN1 9
#define I_IN2 8
// 2.3
#define J_ENA 2
#define J_ENB 64
#define J_IN1 5
#define J_IN2 4
```

```
// 1.2
#define K_ENA 18
#define K_ENB 22
#define K_IN1 44
#define K_IN2 45

enum Actuators {
  A, B, C, I, J, K,
  N_ACTUATORS
};

struct NamedActuator {
  char name;
  RodActuator *object;
};

// Posiciones
volatile long angPosition[N_ACTUATORS] = {0, 0, 0, 0, 0, 0};

//
// Interrupt Handlers
//
static void A_interruptHandler() {
  if (digitalRead(A_ENA) != digitalRead(A_ENB))
    angPosition[A]++;
  else
    angPosition[A]--;
}
static void B_interruptHandler() {
  if (digitalRead(B_ENA) != digitalRead(B_ENB))
    angPosition[B]++;
  else
    angPosition[B]--;
}

static void C_interruptHandler() {
  if (digitalRead(C_ENA) != digitalRead(C_ENB))
    angPosition[C]++;
  else
    angPosition[C]--;
}

static void I_interruptHandler() {
  if (digitalRead(I_ENA) != digitalRead(I_ENB))
    angPosition[I]++;
  else
    angPosition[I]--;
}

static void J_interruptHandler() {
  if (digitalRead(J_ENA) != digitalRead(J_ENB))
    angPosition[J]++;
  else
    angPosition[J]--;
}

static void K_interruptHandler() {
  if (digitalRead(K_ENA) != digitalRead(K_ENB))
    angPosition[K]++;
  else
    angPosition[K]--;
}

NamedActuator namedActuators[N_ACTUATORS] = {
    {'A', new RodActuator(A_ENA, A_ENB, A_IN1, A_IN2, angPosition[A], A_interruptHandler)},
    {'B', new RodActuator(B_ENA, B_ENB, B_IN1, B_IN2, angPosition[B], B_interruptHandler)},
    {'C', new RodActuator(C_ENA, C_ENB, C_IN1, C_IN2, angPosition[C], C_interruptHandler)},
    {'I', new RodActuator(I_ENA, I_ENB, I_IN1, I_IN2, angPosition[I], I_interruptHandler)},
    {'J', new RodActuator(J_ENA, J_ENB, J_IN1, J_IN2, angPosition[J], J_interruptHandler)},
    {'K', new RodActuator(K_ENA, K_ENB, K_IN1, K_IN2, angPosition[K], K_interruptHandler)},
};

RodActuator *getActuatorByName(char name) {
  for (int i = 0; i < N_ACTUATORS; ++i) {
    if (namedActuators[i].name == name) {
      return namedActuators[i].object;
    }
  }
  return nullptr;
}

void updateNamedActuators() {
  for (NamedActuator actuator : namedActuators) {
    actuator.object->Update();
  }
}

#endif
```

E.6 Actuator Class Header

```
//RodActuator.h
#ifndef RODACTUATOR_H
#define RODACTUATOR_H

#include <Arduino.h>
#include <QuickPID.h>
#include <sTune.h>

class RodActuator {
 public:
  RodActuator(uint8_t ENA, uint8_t ENB, uint8_t IN1, uint8_t IN2,
    volatile long &angPosition, void (*interruptHandler)());

  enum MoveMode {
    Global,
    Relative
  };

  void Stop();
  void Update();
  void SetPIDConstants(float Kp, float Ki, float Kd);
  void Move(float desiredPosition);
  float GetPosition();
  int GetTimeout();
  void TestVelocity(float velocity);
  void SetLeftLimit(float leftLimit);
  void SetRightLimit(float rightLimit);
  void SetMaxSpeed(uint8_t maxSpeed);
  void SetMoveMode(MoveMode);
  void SetTimeout(float timeout);
  void MoveToHome();
  void MoveToTarget();
  void SetHomePosition(float newHomePosition);
  void SetTargetPosition(float newSecondHomePosition);
  float GetHomePosition();
  float GetTargetPosition();
  void AutoTune();
  bool Next();

 private:
  float homePosition = 0;
  float targetPosition = 0;

  bool isStable(float threshold);
  volatile long &angPosition;
  uint8_t IN1;  // Pin forward velocity
  uint8_t IN2;  // Pin backwards velocity
  uint8_t ENA;  // Pin encoder A
  uint8_t ENB;  // Pin encoder B

  float ticksRev = 7.0;     // ticks in angPosition that makes a rev
  float gearRatio = 210.0;  // reducion gear of gearRatio:1
  float R = 5.3;
  float positionFactor;

  uint8_t speed = 255;
  unsigned long timeout = 5000;
  unsigned long timer = millis();
  float position = 0;
  float lastPosition = 0;
  float desiredPosition = 0;
  float lastAngvelocity = 0;
  float angVelocity = 0;  // motor angular position

  MoveMode moveMode = Global;

  bool next = true;
  bool move = false;
  float Kp, Kd, Ki;
  float outputMin = -255;
  float outputMax = 255;
  float outputSpan;
  bool startup = false;
  QuickPID PID;  // Controlador PID

  bool test = false;
  bool tune = false;
  sTune tuner = sTune(&position, &angVelocity, tuner.NoOvershoot_PI, tuner.directIP, tuner.printALL);

  float _leftLimit = -2000;
  float _rightLimit = 2000;

  void updateVelocity();
  void updatePosition();
};

#endif
```

E.7 Actuator Class

```
//RodActuator.cpp

#include "RodActuator.h"

#include <Arduino.h>

#define DEBUG false

RodActuator::RodActuator(uint8_t ENA, uint8_t ENB, uint8_t IN1, uint8_t IN2,
    volatile long &angPosition, void (*interruptHandler)()) :
    ENA(ENA), ENB(ENB), IN1(IN1), IN2(IN2), angPosition(angPosition) {
  pinMode(ENA, INPUT);
  pinMode(ENB, INPUT);
  pinMode(IN1, OUTPUT);
  pinMode(IN2, OUTPUT);

  attachInterrupt(digitalPinToInterrupt(ENA), interruptHandler, CHANGE);

  // Calculate position factor
  // 1 Revolución en el encoder son 7 cambios
  // La relación de engranages de 235:1
  // El valor de _position está en revoluciones
  // 1/(7*235) = 6.0790273556231e-4
  positionFactor = 2.0 * R * PI / (ticksRev * gearRatio);

  // Inicializar control PID
  PID = QuickPID(&position, &angVelocity, &desiredPosition);
  PID.SetOutputLimits(outputMin, outputMax);
  PID.SetSampleTimeUs(2030);
  PID.SetDerivativeMode(QuickPID::dMode::dOnError);
  PID.SetProportionalMode(QuickPID::pMode::pOnError);
  PID.SetAntiWindupMode(QuickPID::iAwMode::iAwCondition);
  PID.SetMode(QuickPID::Control::automatic);
  PID.SetTunings(22.1, 67, 3.8632);
}

void RodActuator::Update() {
  updatePosition();

  if (tune) {
    switch (tuner.Run()) {
      case tuner.sample:
        updateVelocity();
        break;

      case tuner.tunings:
        angVelocity = 0;
        updateVelocity();
        tuner.GetAutoTunings(&Kp, &Ki, &Kd);
        SetPIDConstants(Kp, Ki, Kd);
        tune = false;
        next = true;
        break;

      default:
        break;
    }
  }

  else if (move) {
    if (startup && position > desiredPosition - 10) {
      startup = false;
      angVelocity = 0.01 * angVelocity;
      updateVelocity();
      PID.SetMode(QuickPID::Control::manual);
      PID.SetMode(QuickPID::Control::automatic);
    }
    PID.Compute();
    updateVelocity();
  }

  else if (test) {
    updateVelocity();
  }

  lastPosition = position;
  lastAngvelocity = angVelocity;

  if (isStable(1.5)) {
    next = true;
  }

  if (!next && move) {
    unsigned long currentTime = millis();
    if (currentTime - timer > timeout) {
      next = true;
    }
  }
```

```
}

void RodActuator::Stop() {
  angVelocity = 0;
  next = true;
  move = false;
  test = false;
  updateVelocity();
  updatePosition();
}

void RodActuator::Move(float desiredPosition) {
  next = false;
  timer = millis();
  move = true;
  startup = true;
  if (moveMode == MoveMode::Global) {
    RodActuator::desiredPosition = desiredPosition;
  } else if (moveMode == MoveMode::Relative) {
    RodActuator::desiredPosition += desiredPosition;
  }
}

float RodActuator::GetHomePosition() {
  return homePosition;
}

float RodActuator::GetTargetPosition() {
  return targetPosition;
}

void RodActuator::SetHomePosition(float newHome) {
  RodActuator::homePosition = newHome;
}

void RodActuator::SetTargetPosition(float newSecondHome) {
  RodActuator::targetPosition = newSecondHome;
}

void RodActuator::MoveToHome() {
  float desiredPosition = homePosition;
  if (moveMode == MoveMode::Relative) {
    desiredPosition = homePosition - desiredPosition;
  }
  Move(desiredPosition);
}

void RodActuator::MoveToTarget() {
  float desiredPosition = targetPosition;
  if (moveMode == MoveMode::Relative) {
    desiredPosition = targetPosition - desiredPosition;
  }
  Move(desiredPosition);
}

float RodActuator::GetPosition() {
  return position;
}

void RodActuator::SetPIDConstants(float Kp, float Ki, float Kd) {
  Kp = Kp;
  Ki = Ki;
  Kd = Kd;
  PID.SetTunings(Kp, Ki, Kd);
}

bool RodActuator::Next() {
  return next;
}

void RodActuator::SetMaxSpeed(uint8_t maxSpeed) {
  if (maxSpeed < 50) {
    maxSpeed = 50;
  }
  RodActuator::speed = maxSpeed;
}

void RodActuator::TestVelocity(float velocity) {
  RodActuator::angVelocity = velocity;
  test = true;
}

void RodActuator::SetTimeout(float timeout) {
  RodActuator::timeout = timeout;
}

int RodActuator::GetTimeout() {
  return timeout;
}

void RodActuator::AutoTune() {
  tune = true;
  next = false;
```

```
  tuner.Configure(1000, 200, 100, 0, 3, 1, 500);
  tuner.SetEmergencyStop(1000);
}

void RodActuator::SetMoveMode(MoveMode moveMode) {
  RodActuator::moveMode = moveMode;
}

// ========================================
// Private methods
// ========================================
bool RodActuator::isStable(float threshold = 1) {
  return abs(position - desiredPosition) <= threshold;
}

void RodActuator::updateVelocity() {
  uint8_t vel1 = 0;
  uint8_t vel2 = 0;
  float minInput = 0;
  uint8_t minPWM = 0;
  if (angVelocity > minInput) {
    // vel1 = abs((float)_angVelocity / (float)_outputMax) * (float)_speed;
    vel1 = map(abs(angVelocity), minInput, outputMax, minPWM, RodActuator::speed);
    if (vel1 < 40)
      vel1 = 0;
  } else if (angVelocity < -minInput) {
    // vel2 = abs((float)_angVelocity / (float)_outputMax) * (float)_speed;
    vel2 = map(abs(angVelocity), minInput, outputMax, minPWM, RodActuator::speed);
    if (vel2 < 40)
      vel2 = 0;
  }
  // Serial.println(vel1);
  if (DEBUG && (move && !next)) {
    Serial.print("Velocity: ");
    Serial.print(angVelocity);
    Serial.print(" ");
    Serial.print(vel1);
    Serial.print(" ");
    Serial.print(vel2);
    Serial.print("  Position: ");
    Serial.print(position);
    Serial.println();
  }
  analogWrite(IN1, vel1);
  analogWrite(IN2, vel2);
}

void RodActuator::updatePosition() {
  position = angPosition * positionFactor;
}
```