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

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Bachelor of Science in Mechanical Engineering

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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...

Contents

List of Figures

List of Tables

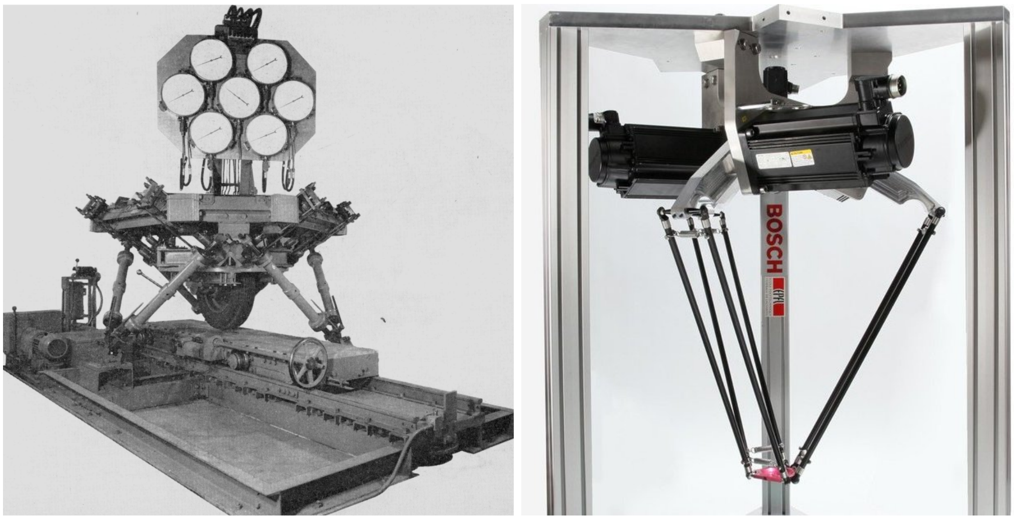
Chapter 1

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]

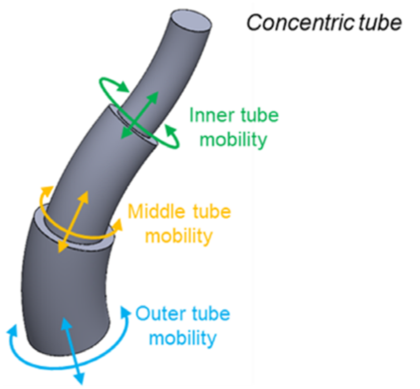
(b). Clavel's Delta Robot
Source: Adapted from [3]

Figure 1.1: Traditional parallel robots

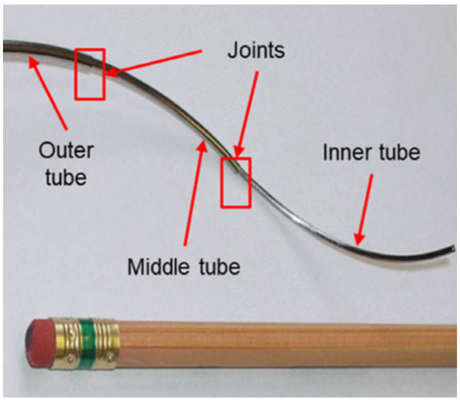
Another distinguishing feature of these robots is the presence of multiple closed kinematic chains that connect and move the mobile platforms, in contrast to serial robots, which operate with an open kinematic chain and move in a linear sequence. However, according to Briot and Kahrs [4] the fundamental 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.

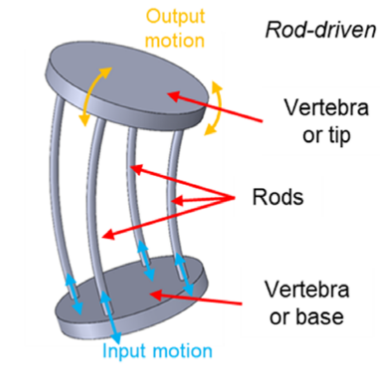
Expanding on these insights, Russo et al. [5] offer a comprehensive review



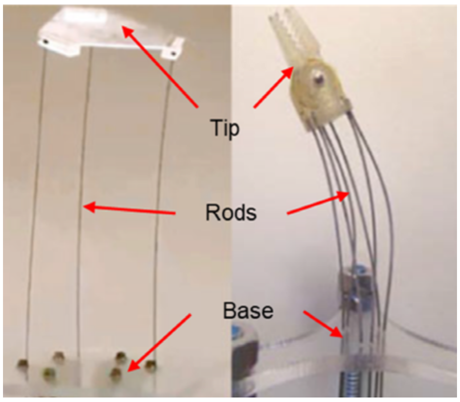
(a). Concentric tube robot mobility



(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 include 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

To 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

2.1 Reference Model

2.2 Rod Material

$L \gg r$

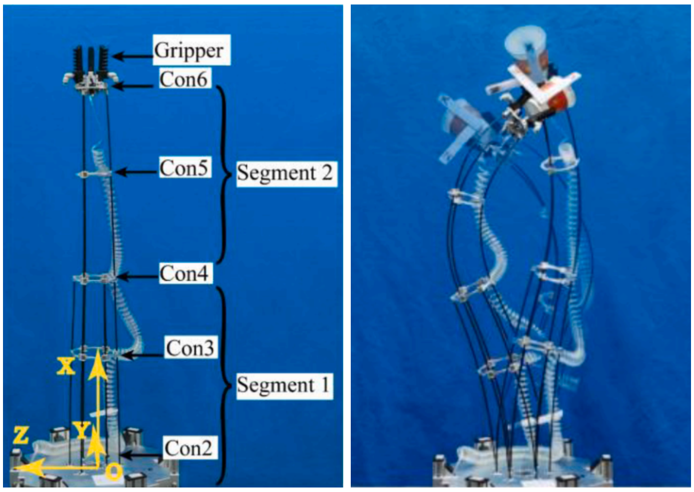
Maximum deflection Euler-Bernoulli beam

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

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

Table 2.1: Fiberglass and AISI 302 steel properties

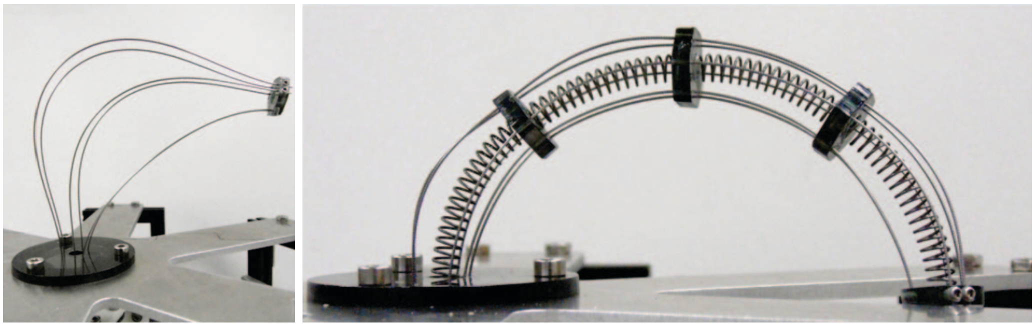
Symbol	Property	Fiberglass	AISI 302
ρ	Density $[g/cm^3]$	2.6	8.0
E	Young's Modulus [GPa]	85	187.5
G	Shearing Modulus [GPa]	36	70.3



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

Figure 2.1: Reference robot structure

Source: Adapted from [6]



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

Figure 2.2: Constraints and range of motion

Source: Adapted from [7]

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

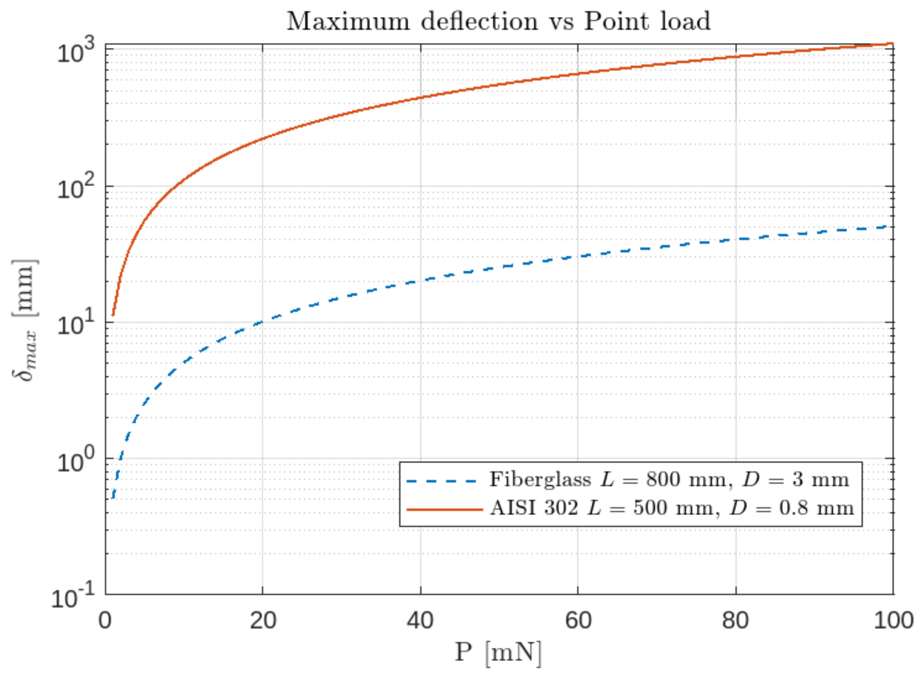


Figure 2.3: Maximum deflection and point load

2.3 Design and Dimensions

2.4 Ring Constraints

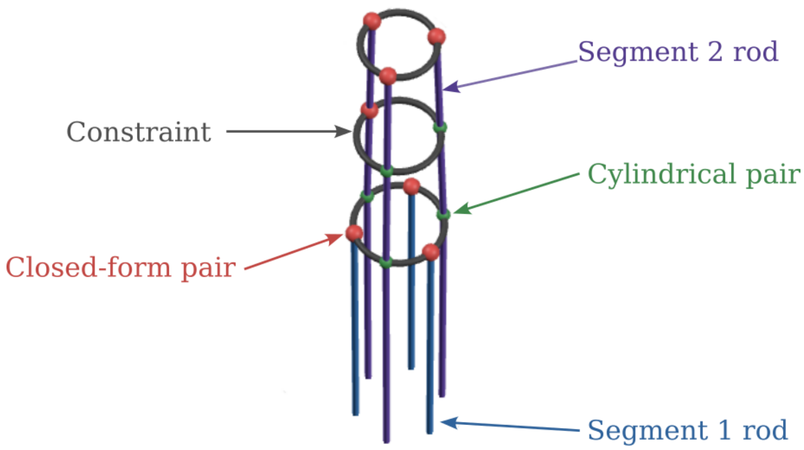
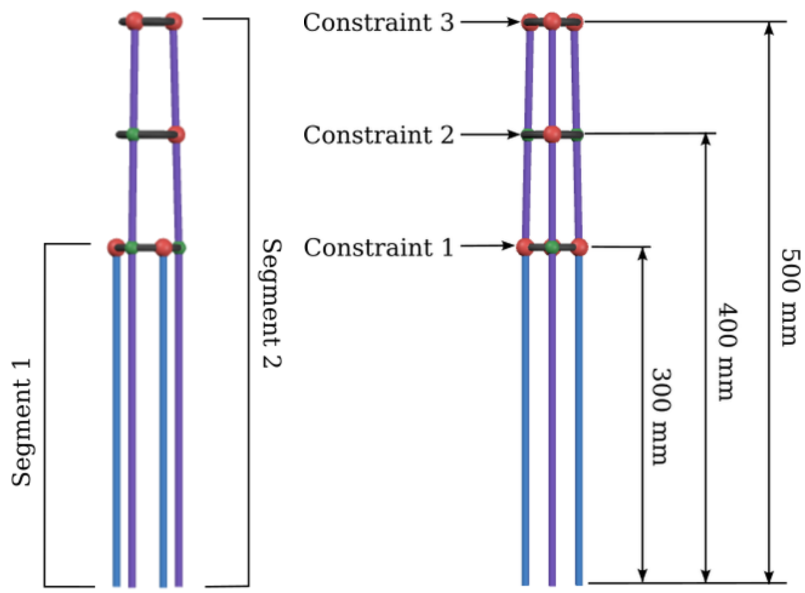
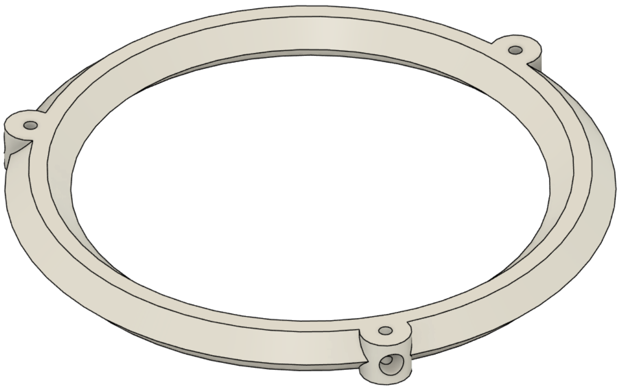


Figure 2.4: Robot body constraints and parts

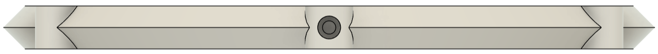


(a). Left view, and robot body segments **(b).** Frontal view, and constraints heights

Figure 2.5: Robot body lateral views



(a). General view



(b). Lateral view

Figure 2.6: Ring constraint

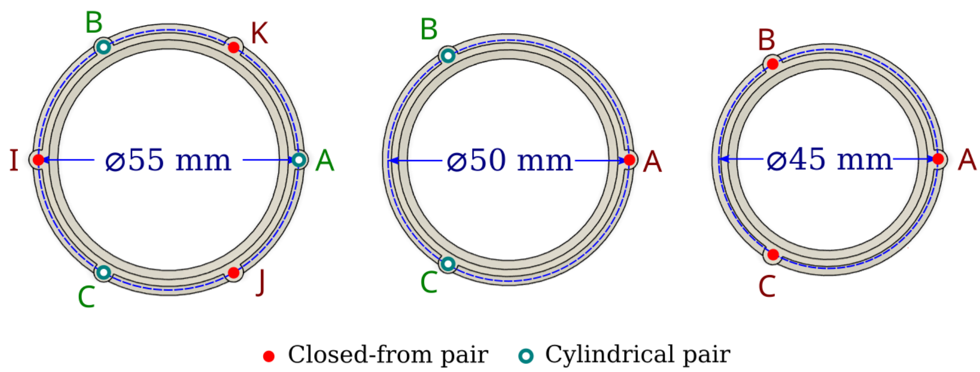
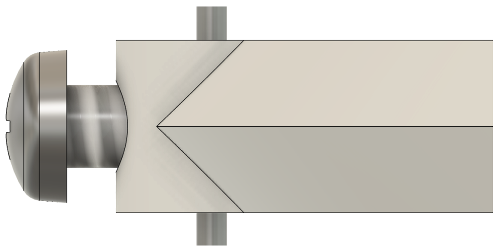
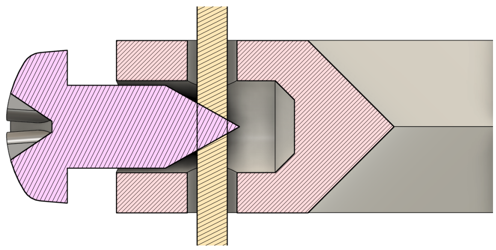


Figure 2.7: Ring constraint sizes

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.



(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

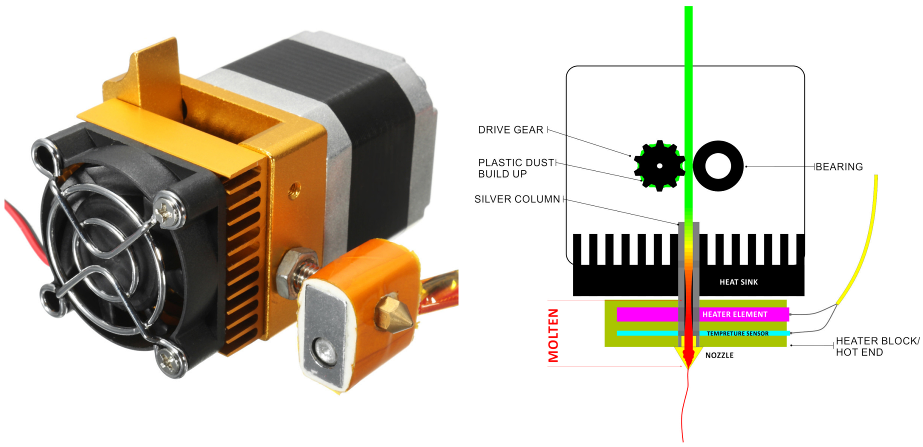
$R_{min} = 3.5$ cm, $c = 0.5$ cm, $W \approx 3.5$ cm

Original extruder $W = 5.2$ cm, $c = 0.7$ cm, $R_{min} = 5.2$ cm

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

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

Figure 3.1: Linear motion systems



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

Figure 3.2: 3D printer extruder

Figure 3.3: Extruder without heater

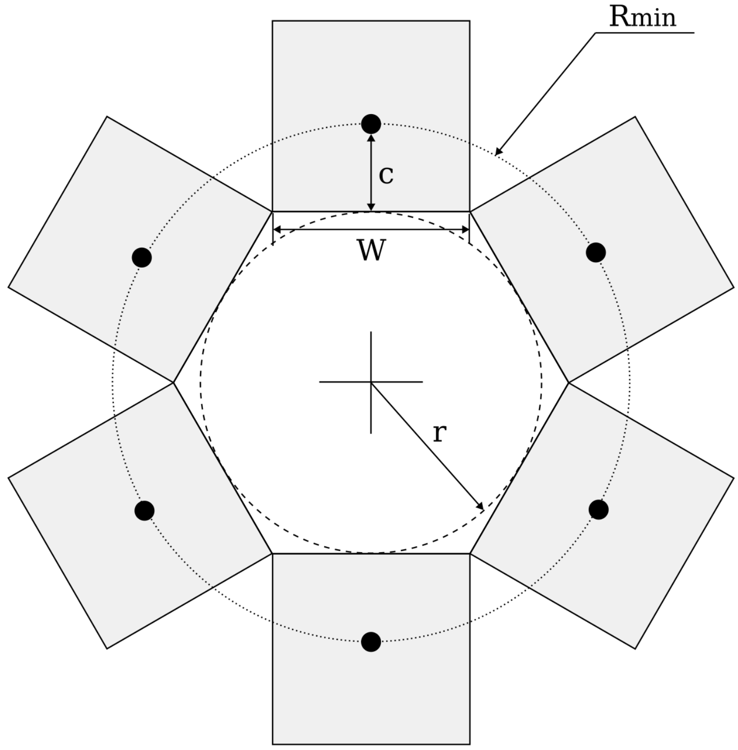


Figure 3.4: Actuators arrange

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

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

3.1 Motor

3.2 Components

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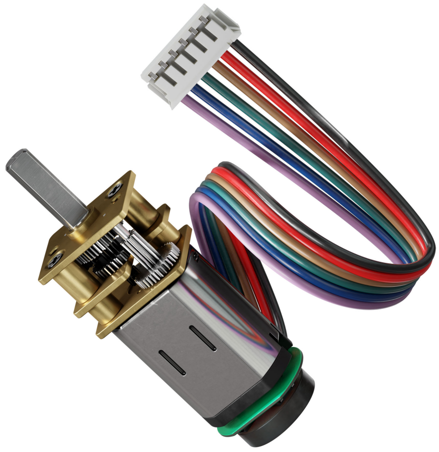

Figure 3.5: Gear motor N20 with encoder

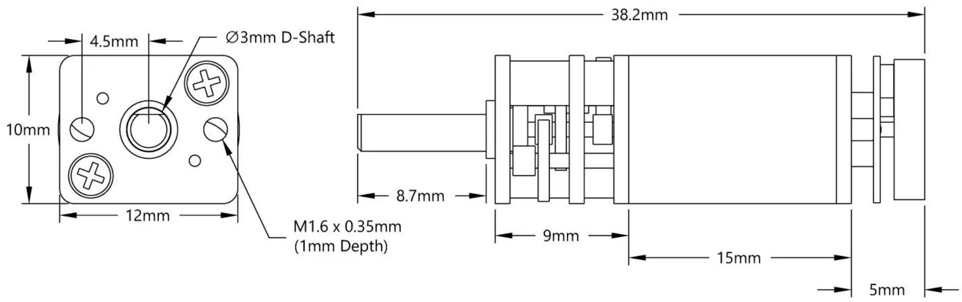

Figure 3.6: Dimensions of gear motor N20 with encoder

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

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3.3 Specifications

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Chapter 4

Platform Assembly

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4.1 Structural Supports

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4.2 Electronics Case

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4.2.1 Circuit Schematic

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4.3 General Assembly

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Chapter 5

Control System Interface

5.1 Protocol Specifications

5.2 Command Line Application

5.2.1 Architecture

5.2.2 Usage

5.3 PID Control and Tuning

5.3.1 Autotuning

5.3.2 System Identification

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.
`G20`	Set measurement units to inches for all subsequent movements.
`G21`	Set measurement units to millimeters for all subsequent movements.
`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.

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

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

Table 5.4: M-Codes usage

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

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

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.

Chapter 6

Performance and Results

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This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

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Conclusions

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Future Work and Recommendations

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Appendices