

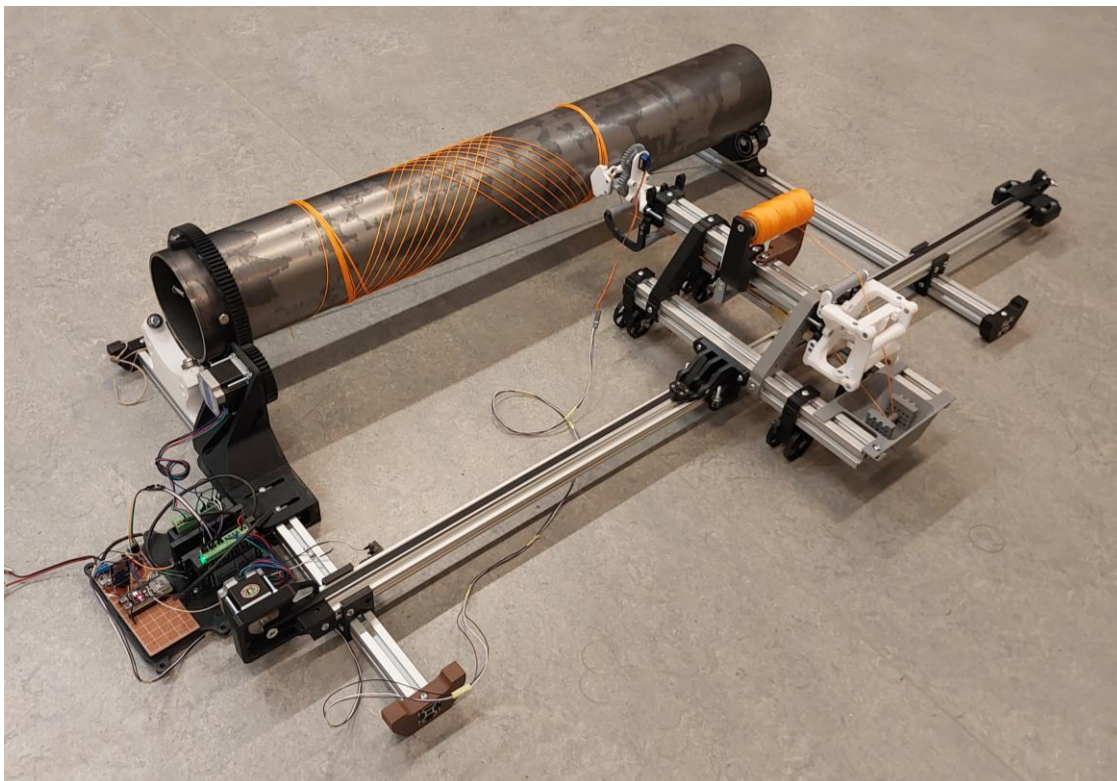
Degree Project in Technology

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# Carbon Fiber Filament Winder

A low-cost alternative to automate consistent winding of composite tubes for rocket technology applications

**FELIX EKMAN FJELKESTAM & LOKE LINDBERG NILSSON**





# **Carbon Fiber Filament Winder**

**Design and evaluation of a low-cost system for automated, consistent filament winding of composite tubes for rocket applications**

FELIX EKMAN FJELKESTAM

LOKE LINDBERG NILSSON

Degree Programme in Mechanical Engineering

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Supervisor: Andreas Cronhjort

Examiner: Daniel Frede

School of Industrial Engineering and Management

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## Abstract

Filament winding is a common manufacturing method for producing composite tubes that are used in areas such as aerospace. However, most machines are far too expensive for the scope of a smaller organization and start-ups such as the student rocketry organization ÆSIR. This thesis aims to find a functional low-cost user-friendly three-axis computer numerical control filament winder capable of consistently winding carbon fiber tubes for rocket applications.

The machine was designed to optimize for low cost by cutting down on electrical components compared to previous work in the area, as well as adding novel approaches to usability by making an IoT-based solution allowing for website control of the machine and generation of toolpath G-code through a self-written G-code generator. Much of the design process focused on ensuring the replaceability of components through the use of quick and easy-to-3D-print parts, motivated by the risk that components exposed to wet resin may experience mechanical failure and require replacement.

Experiments were run to quantify consistency at different feed-rates to find the fastest acceptable time. The results were a feed-rate of 800-1200 steps/s which equals 715.1-1072.7 mm/s giving less than 0.8 mm deviation of length between helical wind passes. Issues arose when simulating dry-winding of carbon fiber tow with string, giving insight into the importance of friction to the winding process. The results show that low-cost solutions can achieve consistent winding, but further work is required to make the result even more consistent for aerospace applications where consistency is key.

## Keywords

Filament winding, Carbon fiber, Composites manufacturing, Student rocketry, Internet of Things (IoT), Computer numerical control (CNC), Mechatronics

## Sammanfattning

Filamentlindning är en vanlig och en etablerad metod för tillverkning av kompositrör som används i många flygtekniska tillämpningar. De flesta maskinerna är dock alldeles för dyra för mindre organisationer och nystartade företag, som exempelvis studentraketorganisationen ÆSIR. Detta arbete syftar till att ta fram en funktionell, kostnadseffektiv och användarvänlig treaxlig CNC-filamentlindare som konsekvent kan linda kolfiberrör för raketillämpningar.

Maskinen designades med fokus på låg kostnad genom att skära ner på antalet elektroniska komponenter jämfört med tidigare studerade lösningar. Samtidigt gjordes användningen av maskinen enklare genom en IoT-baserad lösning som möjliggör styrning av maskinen via en webbapplikation samt generering av verktygsbanor i form av G-kod med en egenutvecklad G-kodgenerator. En stor del av konstruktionsarbetet var att säkerställa att komponenter enkelt kan bytas ut genom att designa lättutskrivna 3D-delar, eftersom delar som exponeras för ohärdat epoxiharts riskerar mekaniska fel.

Experiment genomfördes för att kvantifiera positionsnoggrannheten vid olika matningshastigheter i syfte att identifiera den högsta acceptabla hastigheten. Resultaten visar att en matningshastighet på 800-1200 steg/s, motsvarande 715,1-1072,7 mm/s, resulterar i en avvikelse på mindre än 0,8 mm i linjeavstånd mellan de spiralformade lindningspassen. Vissa problem uppstod vid torr lindning med snöre (som användes för att simulera kolfibertow), vilket belyser friktionens betydelse för processen. Sammanfattningsvis visar resultaten att kostnadseffektiva lösningar kan uppnå en likformig lindning, men ytterligare arbete krävs för att nå den precision som krävs för flygtekniska tillämpningar, där hög måttnoggrannhet är avgörande.

## Nyckelord

Filamentlindning, Kolfiber, Komposittillverkning, Studentdriven raketutveckling, Internet of Things (IoT), Datornumerisk styrning (CNC), Mekatronik

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Stockholm, June 2026

Felix Ekman Fjelkestam   Loke Lindberg Nilsson

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## List of acronyms and abbreviations

|     |                                   |
|-----|-----------------------------------|
| API | Application Programming Interface |
| CAD | Computer Aided Design             |
| CAM | Computer Aided Manufacturing      |
| CF  | Carbon Fiber                      |
| CNC | Computer Numerical Control        |
| IoT | Internet of Things                |
| KTH | KTH Royal Institute of Technology |
| PWM | Pulse-Width Modulation            |
| SPI | Serial Peripheral Interface       |

# List of Symbols Used

The following symbols will be later used within the body of the thesis.

|                       |                                                       |
|-----------------------|-------------------------------------------------------|
| $\Delta A$            | Phase shift per revolution [deg]                      |
| $\delta_u$            | Overlap per circuit [m]                               |
| $\omega$              | Angular velocity of the mandrel [rad/s]               |
| $\theta$              | Winding angle between filament and mandrel axis [deg] |
| $A_{\text{traverse}}$ | Axis rotation per traverse [deg]                      |
| $b$                   | Width of the tow [m]                                  |
| $b_{\text{eff}}$      | Effective tow width in circumferential direction [m]  |
| $C$                   | Circumference of the mandrel [m]                      |
| $e$                   | Closure residual (circumferential mismatch) [m]       |
| $L$                   | Traverse length of the mandrel [m]                    |
| $N$                   | Rounded number of circuits per pass [-]               |
| $N_{\text{ideal}}$    | Ideal number of circuits per pass [-]                 |
| $N_{\text{rev}}$      | Number of mandrel revolutions per traverse [-]        |
| $p$                   | Helical pitch [m]                                     |
| $R$                   | Radius of the mandrel [m]                             |
| $V_c$                 | Carriage velocity [m/s]                               |

$V_{\text{surface}}$  Surface velocity of the mandrel [m/s]

# Chapter 1

## Introduction

This chapter describes the specific problem that this thesis addresses, the context of the problem, and finally presents the goals of the thesis, ending with an outline of the structure of the following chapters.

### 1.1 Background

Polymer matrix fiber composites such as **Carbon Fiber (CF)** are used extensively in the aerospace industry due to their high strength to weight ratios. Specifically in small commercial and hobby rockets, the main body, composed of several segments, a nose, as well as the fins, can be made with **CF** [1]. For smaller applications, the manufacturing process is, however, quite cost-, time- and labor intensive, as it is often done by hand due to lack of tooling and machinery.

In the student rocketry organization **ÆSIR** [2], the airframe of rockets is currently manufactured using manual layup techniques. While this approach requires relatively simple equipment, it introduces several limitations related to efficiency and consistency. The lead time of a single **CF** tube can take up to three hours, excluding post-processing, which significantly constrains production capacity and extends project timelines. For a typical rocket, such as the ongoing project **Freyja** [3], this process must be repeated for each of the four airframe segments. In addition to time-related inefficiencies, manual manufacturing results in considerable variability in tube quality. This variability arises from the process being highly dependent on operator skill, making it more like a craft than a controlled engineering process. As a result,

inconsistencies in fiber placement and material properties may occur, leading to uncertainty in structural integrity and potentially compromising mission reliability.

In industry, these issues are practically solved by automating the manufacturing process with **Computer Numerical Control (CNC)** machines. Being highly sophisticated and built for manufacturing complex shapes, they are far too expensive and beyond the scope of a student organization where its only purpose would be manufacturing **CF** tubes. These machines, called filament winders, use many thousands of continuous fibers which are bundled together into thin flat tapes or strips, called tow, to wrap around a mandrel in several layers. These **CNC** machines standardize the manufacturing process and allow the quality and strength of the finished product to be tailored to each application. There is a fundamental difference in how the fibers are layered in manually rolled tubes compared to tow wound. In tow-wound tubes, the angle of the tow is directly controlled by the **CNC** machine, while for hand-rolled tube sheets of prewoven **CF** are wrapped around a mandrel giving less customizability. While requiring simpler tools it is more labor intensive and ultimately ends up being more expensive in the long run than filament winding. Therefore, there is a need for **ÆSIR** to develop a budget friendly filament winder capable of improving standardization and quality while reducing material waste.

## 1.2 Problem

The fabrication of hand rolled **CF** tubes is a laborious task and highly prone to errors. Filament winding machines are known to cut costs dramatically, but can be far too expensive to warrant the acquisition of a small hobby organization. A smaller, budget-friendly alternative is needed to improve quality and standardization, specifically by determining whether a low-cost, easy-to-use **CF** filament winding machine can reduce the time, labor, and skill required to produce **CF** tubes. The problem is to reduce the initial cost of the machine while maintaining quality at an acceptable level. The engineering challenge for this project will be to create a **CNC** machine that avoids unnecessary expenses but retains functionality. Commercial software is far too expensive, so a program for the generation of G-code instructions will have to be developed. Another challenge is to have the machine consistently follow the instructions without wasting time as the epoxy resin used to coat the fibers has a short working phase before becoming too viscous. The question

is how to balance the conflicting requirements of low-cost, ease of use, and consistent product quality in the design of a filament winding machine.

### 1.2.1 Original problem and definition

- What is the maximum operating speed of a low-cost filament winder at which consistent fiber placement and acceptable tube quality are maintained?

### 1.2.2 Scientific and engineering issues

- What is the simplest possible machine architecture that still achieves acceptable precision?
- What components contribute most to cost, and where can simplifications be made?
- What parameters ensure that the filament is wound consistently?
- How can material waste be limited?
- What is the relationship between winding speed and fiber placement accuracy?
- How can the machine be calibrated to ensure repeatability between runs?
- How can user input (e.g., desired winding angle) be translated into an intuitive interface?
- How can the necessary winding parameters be translated into G-code instructions?

## 1.3 Purpose

The purpose of this thesis is to contribute to the more accessible and standardized manufacturing of **CF** tubes for hobby rocket applications. This is achieved by investigating how filament winding technology limited to expensive industrial systems can be adapted into a simpler and more cost-effective solution without compromising essential quality and consistency.

The work aims to explore the feasibility of reducing the reliance on manual labor through automation, while addressing key engineering challenges related to process control, material handling, and system integration. The project is

carried out within the course MF133X at KTH Royal Institute of Technology (KTH) and involves the development of a mechatronic system that integrates mechanical, electrical, and computational components.

## 1.4 Goals

The goal of this project is to find a low-cost, user friendly and alternative to modern filament winding machines capable of keeping quality and consistency necessary for small-scale manufacturing. This has been divided into the following sub-goals:

1. Reduce the manual labor required to manufacture CF tubes by designing and creating a filament winding machine.
2. Cut costs and simplify the machine compared to previous existing solutions in the area without reducing quality.
3. Design and optimize a self-made toolpath generation algorithm to allow stable and consistent winding while minimizing errors.
4. Develop a user-friendly Internet of Things (IoT)-based solution for generating, managing and executing the G-code instruction set when running the machine.

## 1.5 Research Methodology

Due to the broad scope of the problem, the project focuses on a selection of key challenges related to process consistency, cost, and usability. Research is conducted through the design and implementation of a three-axis filament winding machine, followed by an experimental evaluation of its performance in terms of manufacturing consistency and efficiency. In addition, the system is assessed from a cost and design perspective by comparing it to existing solutions, with particular emphasis on simplifying the machine architecture while maintaining essential functionality in order to reduce cost.

## 1.6 Delimitations

The scope of this project is limited to the design and implementation of a low-cost filament winding machine. Aspects relating to the composite-manufacturing process, such as resin impregnation or the mechanical

properties of a cured multilayered tube, will be excluded from the experimental investigation. However, they will still be taken into consideration since they represent requirements for the machine's end-use. Usability is another design objective of the project, but will not be formally investigated. A systematic usability study would broaden the scope beyond what is feasible for a bachelor's thesis in mechatronics and is therefore left out, though it still influences the general design architecture. Due to time constraints, only one filament winding scheme will be implemented. Alternative winding patterns and closure handling methods are excluded for the same reason. For the project to be deemed a success, it is sufficient to demonstrate that this single scheme works correctly. The primary goal is to show that the machine can follow winding instructions reliably, regardless of whether those instructions are optimal for a specific carbon-fiber tube application. By narrowing the focus to functional testing of lay-down consistency, this project aims to validate the machine's core winding capability without extending into adjacent manufacturing or human-factors domains.

## 1.7 Structure of the thesis

Chapter 2 presents relevant background information on CF filament winding and related previous works. Chapter 3 presents the research methodology leading to Chapter 4 where the implementation of the filament winder and design choices are presented and motivated. Chapter 5 present the results and analyses the data as necessary. Chapter 6 features the discussion of the results and attempts to answer the research questions and ultimately determine the success of the project given the goals. Finally Chapter 7 summarizes the work and mentions possible improvements for future work in the area.

# Chapter 2

## Theory

### 2.1 Composite Materials and Filament Winding

#### 2.1.1 Carbon Fiber

Composite materials, specifically polymer matrix fiber composites, are preferred in aerospace applications such as in hobby rocketry. This is thanks in part to their unique material properties such as a high strength to weight ratio, ability to handle high temperatures and stiffness [1]. One of the most commonly used composites is CF and can come in the form of continuous fiber rolls, which when bundled together is known as tow, or in prewoven fabrics usually 0/90 unidirectional, meaning that the fibers form a hatched pattern. In this pattern one layer is angled  $0^\circ$  and the other  $90^\circ$ , also commonly referred to as  $\pm 45^\circ$ . This theoretically gives the product equal strength in all directions even though strength is usually only in the direction of the fibers. For the process of manufacturing a resin-based CF product these strips of continuous fiber or unidirectional sheets are impregnated with an epoxy resin, either before, known as prepreg, or during placement, known as wet lay-up. The epoxy seeps in between the fibers and, when cured, makes the composite material strong while also lightweight making it perfect for aerospace applications [4].

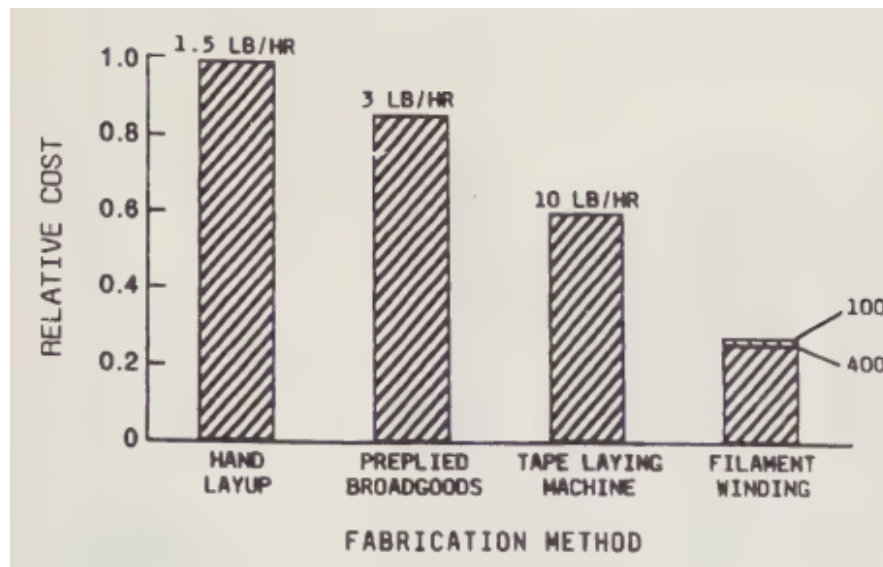


Figure 2.1: Relative costs and composite laydown rates for different manufacturing methods [5].

### 2.1.2 Filament Winding

CF composites are associated with high manufacturing costs, largely due to the price of both the fibers and the epoxy matrix [4]. Consequently, any reduction in material usage, whether in fiber or epoxy, can significantly improve cost efficiency. A cost analysis comparing material usage relative to manufacturing time [5] indicates that filament winding can reduce production costs by approximately 70% compared to manual lay-up methods as shown in Figure 2.1. This is the case for industrial manufacturing but for smaller batches it may not necessarily be as big of a difference.

Filament winding is performed using a CNC machine which winds fiber filament around a rotating mandrel with modern machines allowing for more complex asymmetric geometrical molds. The fibers follow a predetermined pattern in order to ensure thorough coverage, limiting gaps while avoiding overlap between the passes in order to achieve desired thickness and structural properties. In these patterns multiple parameters can be controlled including winding angle, feed rate and fiber tension [6].

Filament winders may operate across multiple axes. Modern industrial filament winding systems typically have up to six axes [6]. However, for simpler applications, such as the production of cylindrical airframe tubes, a two- or three-axis configuration is sufficient. In such systems, the primary

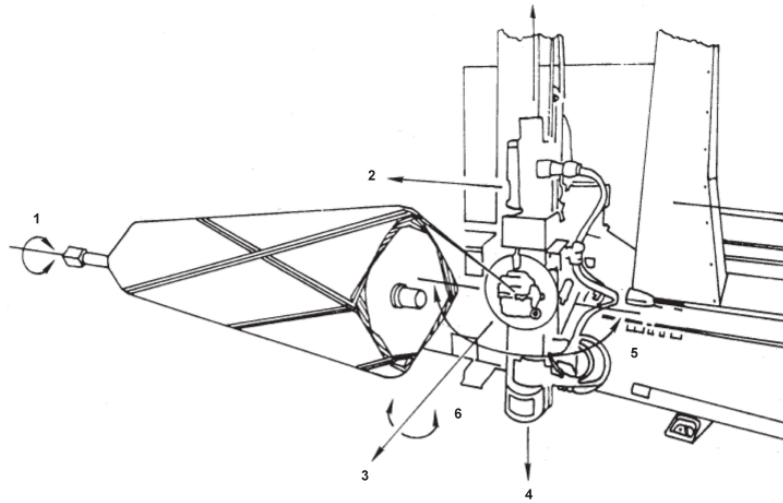


Figure 2.2: Schematic illustration of the possible axes of a filament winder [6].

axes correspond to mandrel rotation, carriage translation along the horizontal axis, and in the case of a third axis, rotation of the winding eye as shown by the first two axes and the sixth respectively in Figure 2.2.

### 2.1.3 Numerical control of filament winders

Modern filament winding machines are typically numerically controlled due to the complexity of the parameters required to produce consistent and repeatable composite structures [6]. In **Computer Aided Manufacturing (CAM)**, G-code, a standardized programming language used in **CNC** machining, is commonly employed to control machine motion. G-code specifies the toolpath, including position, movement speed, and trajectory, which the **CNC** controller translates into motor actions [7]. In addition, M-codes are used to control auxiliary machine functions such as spindle operation, tensioning systems, or other machine-specific features. Unlike G-code, M-codes are not fully standardized and may vary depending on the machine, control system and more specifically how many axes are controlled [8].

The numerical control of filament winders relies on mathematical relations to determine the desired tool-path prior to simulation and implementation. The specific formulation of these relationships depends on the number of machine axes and the selected process parameters, resulting in a range of applicable models [6]. For geometrically complex structures, numerical

methods and differential geometry are typically required. However, for simpler configurations, such as winding over a cylindrical mandrel, analytical solutions have been derived [9].

A key parameter influencing the structural performance of the wound composite is the winding angle,  $\theta$ . It is defined as the angle in degrees between the deposited filament and the longitudinal axis of rotation of the mandrel. The winding angle is directly proportional to the ratio between the carriage velocity,  $V_c$ , and the surface velocity of the mandrel,  $V_{surface}$ , according to [6]:

$$\theta = \tan \left( \frac{V_c}{V_{surface}} \right) \quad (2.1)$$

In the case of a cylindrical mandrel the surface speed can be described with a simple relation from classical mechanics where the surface speed can be calculated through the angular velocity at a certain radius,  $R$ , which allows for the relation to be rewritten as:

$$V_c = \omega R \tan(\theta) \quad (2.2)$$

Which is particularly suitable for numerical control applications, where the angular velocity of the mandrel is typically predetermined, and the winding angle is selected based on desired mechanical properties.

A problem in filament winding is the issue of coverage, when winding around a mandrel it must be ensured that the proper amount of laps are done to ensure a full coverage of the mandrel allowing for a decision to be made of the amount of layers specified for the product. As illustrated in Figure 2.3 effective coverage can be achieved in different layers but the motivation of the total coverage over the mandrels circumference. There is also the issue of rotation around the mandrel in order to make sure the tow does not unwind as the carriage switches direction. In the figure pattern 1 uses more material due to hoop winding almost a full rotation but ensures stability whereas pattern 2 limits material waste but needs more tension and friction in the tow to work consistently.

To quantify this mathematically, the effective coverage width is introduced:

$$b_{\text{eff}} = \frac{b}{\sin \theta} \quad (2.3)$$

Where  $b$  denotes the nominal tow width, and  $b_{\text{eff}}$  represents the projected width

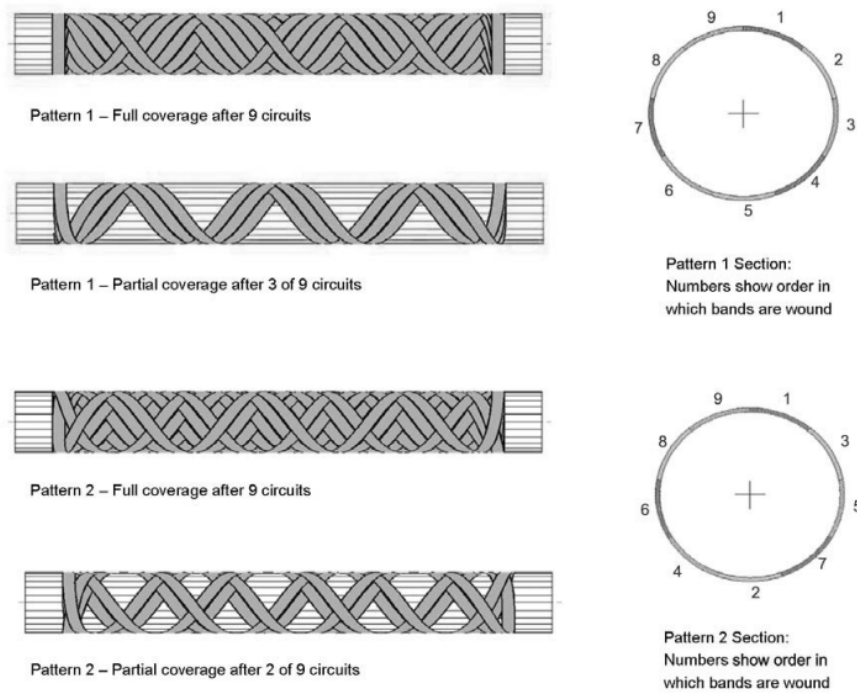


Figure 2.3: Illustration exemplifying possible band patterns showing effective coverage over the mandrel [6].

along the mandrel circumference [6].

The ideal number of circuits required per pass for full coverage in a single layer is then given by:

$$N_{\text{ideal}} = \frac{C}{b_{\text{eff}}} \quad (2.4)$$

Where C is the circumference given by the basic geometrical relation  $2\pi R$ .

If  $N_{\text{ideal}}$  is not a perfect integer, which it rarely is, the issue of closure arises. There are several methods to handle it which range in complexity and which parameters they change and should be chosen depending on what is most important. A straightforward method, particularly suitable when maintaining a constant winding angle is critical, involves introducing a controlled overlap between adjacent tows. This is simply calculated from basic geometry the ideal number of circuits is rounded upwards giving, N, and then a closure residual, e, is calculated as the difference between the circumference and the amount of rounded integer circuits times the effective coverage as following:

$$e = C - N \cdot b_{\text{eff}} \quad (2.5)$$

If  $N_{\text{ideal}}$  were not rounded upward this would instead cause a slight gap between the fibers which would require more resin to fill the gaps which in turn would make the the finished product weaker while also increasing both weight and material cost.

Then finally the overlap,  $\delta_u$ , can be calculated as following:

$$\delta_u = \frac{e}{N} \quad (2.6)$$

In order to avoid stacking all the errors in one place the overlap can be spread out over all the revolutions of the tow and for that a phase shift,  $\Delta A$ , can be calculated as:

$$\Delta A = 360^\circ \cdot \frac{\delta_u}{C} \quad (2.7)$$

For process planning and toolpath generation, it is also necessary to determine the number of mandrel revolutions per carriage traverse. This is obtained using the helical pitch, defined as [9]:

$$p = 2\pi R \tan \theta \quad (2.8)$$

The number of revolutions per traverse is then:

$$N_{rev} = \frac{L}{p} \quad (2.9)$$

where  $L$  is the axial length of the mandrel. Finally, the corresponding angular displacement of the rotational axis per traverse, expressed in degrees, is given by:

$$A_{traverse} = 360 \cdot \frac{L}{p} \quad (2.10)$$

## 2.2 Electrical components

### 2.2.1 ESP32-S3

The ESP32 is a low-cost, energy-efficient microcontroller developed by Espressif that integrates both Wi-Fi and Bluetooth, making it ideal for products involving Internet of Things. It features a dual-core processor and can be programmed using various environments. For this project an ESP32-S3 was used due to its extended 512 KB internal SRAM [10] and then programmed in the PlatformIO IDE which provides a unified framework for code development, library management, and hardware abstraction [11]. The firmware was then written in C and C++ with the web application being written in JavaScript, HTML and CSS.

### 2.2.2 Stepper motor and driver

Stepper motors are a type of brushless DC electric motors capable of precise position control without the need for external feedback sensors. This is achieved through their operation in discrete angular increments, referred to as steps, typically  $1.8^\circ$  per step. Stepper motors are most commonly used in precision applications such as CNC systems. Standardized frame sizes defined by the National Electrical Manufacturers Association are commonly used to classify stepper motors [12]. In this project two NEMA23 stepper motors capable of providing 1.26 NM of torque were used.

Control of stepper motors is achieved with specific driver circuits that receive digital signals from a microcontroller, commonly in the form of step and direction inputs. The driver regulates the supplied current to make the motor move as specified. Many modern drivers also support microstepping, where

each full step is subdivided into smaller increments, resulting in smoother motion and increased positional resolution [12]. For this project two TB6600 stepper drivers are utilized for their ability to handle higher current loads necessary to control the chosen stepper motors.

### 2.2.3 Servo motor

Servo motors are electromechanical actuator systems composed of a DC motor, a gear mechanism, an internal control circuit and a potentiometer enabling precise control of the motors angle at all times. The angle of the motor is continuously compared from the potentiometer and adjusted to the desired angle through a feedback loop achieving high precision control [13]. A commonly used low-cost servo motor, SG90, allows for movement between  $0^{\circ}$ - $180^{\circ}$  making them perfect for applications where high repeatability and angle accuracy are required such as this project.

Servo motors are directly controlled with **Pulse-Width Modulation (PWM)** signals from a microcontroller where the duty cycle of the input signal corresponds to a specific angular position within the servo's operating range. This eliminates the need for an external driver circuit such as with stepper motors [14]. However, servos often require more power than what a microcontroller can provide which necessitates an external power supply.

## 2.3 Related work

### 2.3.1 X-winder

X-winder is a manufacturer of a relatively low-cost four-axis "desktop winder" designed for hobby and smaller manufacturing applications. Initially marketed to be for less than \$5000 for the three-axis version the only current available four-axis has a price of around \$7,495.00 [15] positions it as one of the lowest prices for a commercial winder on the market. However, despite its comparatively lower cost within the commercial market, the system remains financially nonviable for smaller organizations and hobbyists operating under stricter budget constraints.

### 2.3.2 A Low-Cost Filament Winding Technology for University Laboratories and Startups

A study conducted by researchers at the University of Brasilia presents a cost-effective approach to the development of a four-axis filament winding system, including the implementation of custom control software. The solution could serve as a cheaper alternative to otherwise expensive industrial machines for university laboratory and start ups [16]. The resulting system detailed is similar to the X-winder but justifies its design choices from a financial perspective showing that there is still room for improvement on the electronics side. It can be used as an important stepping stone in making a three-axis winder optimized for low-cost.

### 2.3.3 The Contraption

There have been earlier attempts at making a hobby tow winder for smaller applications. One of these attempts is by Andrew Reilley. Through his website [17] he shares **Computer Aided Design (CAD)** files, software and some videos on his machine, named the Contraption, as open source and for others to replicate. Using three stepper motors the three-axis filament winder is proven to work given his configuration. This work will be crucial in the following work presented.

### 2.3.4 D.I.Winder

A printables project set up to give hobby enthusiasts a desktop tow winder for under \$500 called D.I.Winder successfully creates a simpler solution than the contraption at a possibly cheaper price due to less costly mechanical parts [18]. The electronics still remain the most expensive components as three stepper motors are used which shows there could be further improvement.

### 2.3.5 Summary of related work

All the above mentioned works have similar construction and electronic design solutions and whether they are three- or four-axis machines they still all use stepper motors even though they are usually quite expensive compared to servo motors. The mechanical parts are harder to make cheaper as it would come at the cost of stability but the electronical components can still be optimized. This motivates trying a cheap servo motor for the eyelet instead of a smaller

stepper motor which also requires a driver as this could cut costs and provide a simpler machine.

## Chapter 3

# Methodology

This chapter outlines the methodology used to answer the research questions and also covers the conceptual design choices for the filament winder. Investigating each of the requirements was deemed too wide for the scope of the project as stated in Section 1.6 therefore the most important goals were chosen to be researched.

### 3.1 Conceptual design

A three-axis filament winder machine will be built to answer the research questions. It will use two stepper motors, one for the carriage and one for the mandrel as well as a small servo motor for the eyelet. The machine will be controlled by a locally hosted website eliminating the need for a control panel and allowing for a combination of G-code generation, file management and control of the machine to one place with ample instruction for ease of usability.

### 3.2 Research methodology

The consistent lay-down of filament was deemed the most important factor in creating high quality and standardised CF tubes. The machine's ability to follow the G-code will be tested by mounting a pen through the eyelet in order to trace out the toolpath. Then the CF filament will be simulated with string which, due to being less wide than tow, shows the centerline of the filament winding path. The pen will show how well the machine follows the instructions

and the string will provide insight into potential issues in physical lay-down. The parameters measured will be tube length, winding angle, distance between neighbouring filament paths and the total time elapsed. These parameters can be compared to the theoretical desired values derived from the G-code generator program. In this the winding angle and the tube length will be inputs and the distance between neighbouring filaments can be extracted from the G-code. The G-code takes an input that is the measured tow width which will be put at a value higher than the strings width so the measurements can be done more easily and visually clear. The time will be compared to previous runs in order to establish a statistical basis for evaluating manufacturing consistency. This will be tested at different speeds to find the optimal lay-down feed-rate that still keeps the quality consistent for each layer ensuring a standardized product while avoiding time waste. The goal of reducing labor is solved by the construction of the machine in itself where steps will be taken to ensure ease of usability.

Another research goal is to find how the filament winder compares to previous work in terms of cost and simplicity. This aspect will be investigated with a simple cost analysis and component comparison which, although not exhaustive, will show how the filament winder differs and what makes it novel.

# Chapter 4

## Implementation

This chapter covers the design and construction of the three-axis filament winder along with accompanying software.

### 4.1 Hardware

A three-axis **CF** Filament Winder **CNC** machine was developed as shown in Figure 4.1. Following previous work, it aims to lower costs while maintaining stability. Many components are 3D-printed for ease of manufacturing from a hobby or "maker" perspective. The electronics that were chosen following this design philosophy leads to the most novel part of the hardware side of the machine, which is the use of only two NEMA23 stepper motors. Instead, an SG90 micro servo motor was used to control the third axis, which significantly lowered the total cost of the machine.

#### 4.1.1 Overall construction

The general construction can be divided into three main assemblies, the frame, the mandrel, and the carriage. The frame and carriage are mostly made of aluminum extrusions with either a T-slot or a V-slot profile. The main guide rail is a 1.5 m long 20x40 mm V-slot profile, while the two sidepieces are each 0.75 m long 30x30 mm T-slot profiles. The carriage uses a 35x35 mm T-slot profile because these were already available to build with. The mandrel is made of a 110 cm long, Ø 159 mm, 5 mm thick steel pipe, with a 3D-printed spur gear attached with four M8 screws and nuts.

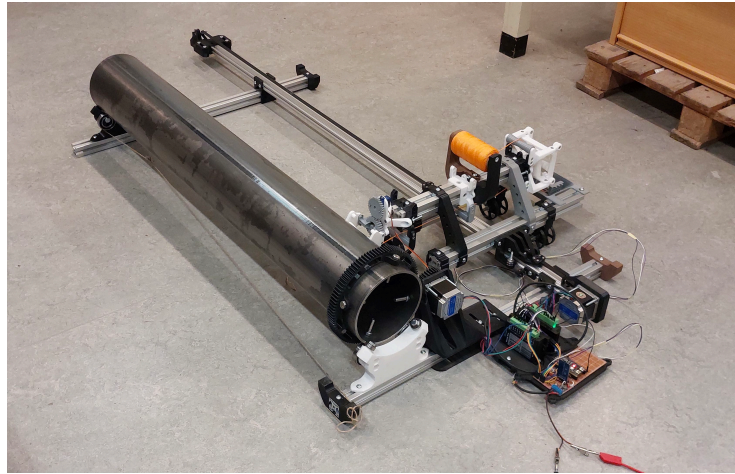


Figure 4.1: Photograph of the finished machine ready for testing.

#### 4.1.2 Mechanical movement of the carriage

Linear mechanical movement of the carriage is accomplished by attaching a 10 mm wide GT2 timing belt to both sides of the carriage. The belt is then routed along the length of the main guide rail of the machine, around a timing pulley, and back through the inside of the guide rail to get driven by one of the NEMA23 stepper motors. Since the guide rail has V-slots, it is possible for the carriage to ride on standard V-rollers used for 3D-printers, and therefore those rollers are used on this machine. Later, during testing, a realization was made that the carriage was unstable and able to pivot around the guide rail, and therefore supporting wheels that ran against the floor were also created. In order to prevent electrostatic discharge believed to arise from the pulley belt rubbing against the frame that was causing the problems, each of the motors was grounded to the aluminum extrusions with copper wire, which solved the problems.

#### 4.1.3 Mechanical movement of the mandrel

The rolling mechanical movement of the mandrel is accomplished by a set of two spur gears with a gear ratio and diametrical pitches of 200:80 and a module of 2 mm. The bearing assembly in Figure 4.2 that supports the steel tube mandrel is made up of four ball bearings, two SKF 608-2Z ball bearings, and two SKF 605-2RS ball bearings. All ball bearings are attached with M8 screws and nuts to a 3D-printed support that is screwed into the 30 mm side extrusion. A separate motor mount was also designed to allow for adjusting

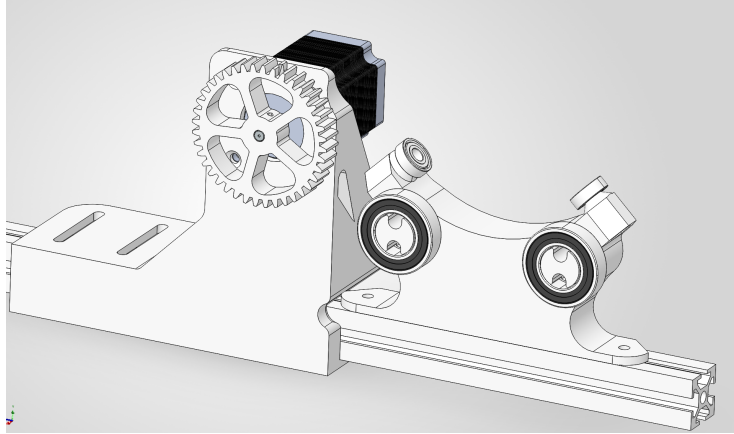


Figure 4.2: CAD model of the mandrel bearing assembly and mandrel stepper motor mount.

of the spacing between the gears and to be able to try out different gear ratios. This approach also ensures that the structural integrity of the bearing assembly is enough for the heavy steel mandrel being used.

#### 4.1.4 Tow roller bearings and components in contact with resin

The rollers carrying CF tow are designed with 3D-printed sliding bearings, as seen in Figure 4.3, to be able to easily be switched out in the case where the resin gets stuck in the bearings. The resin bowl also features sliding bearings for a roller and hooks to attach a strip of neoprene with a slit through it which will remove excess resin from the tow letting it drip back down into the bath, which can be seen in Figure 4.4. The bowl was specifically challenging to design because it needs to be easily reprinted on a 3D-printer since when the resin has cured in the bowl, the roller inside will be stuck. To make printing the bowl easy, much design went into using the plastic's natural elastic flexing to be able to fit a pin roller inside the bowl between two supports. To be able to print such a pin roller it had to be split into two identical parts with a plastic pin inside which can be seen in Figure 4.5.



Figure 4.3: An early version of the wind eyelet showing how the sliding bearings work.

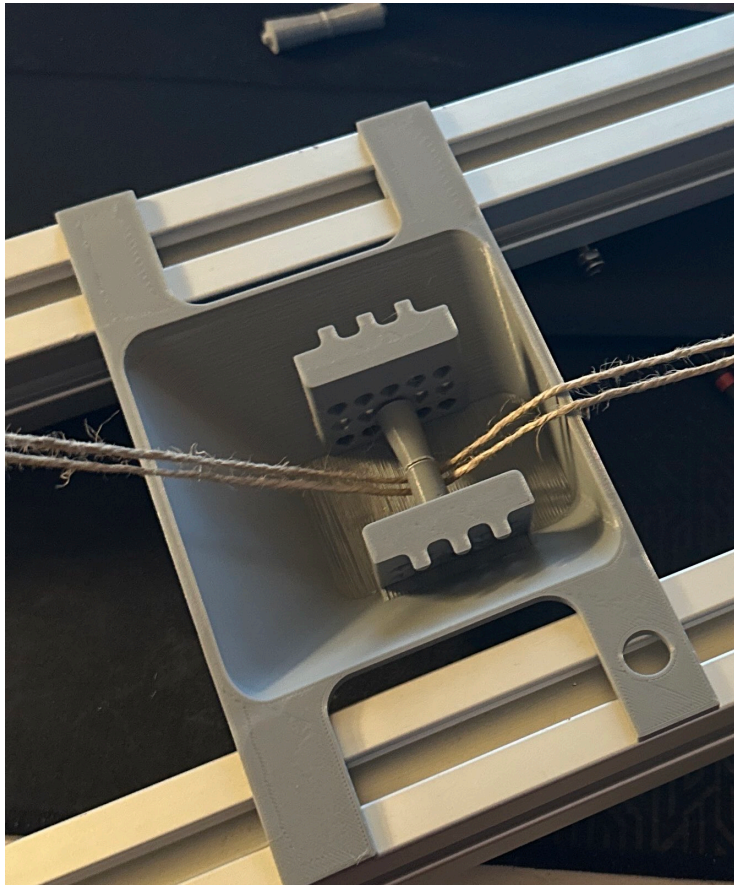


Figure 4.4: Photograph of the resin bath bowl with an integrated roller inside.

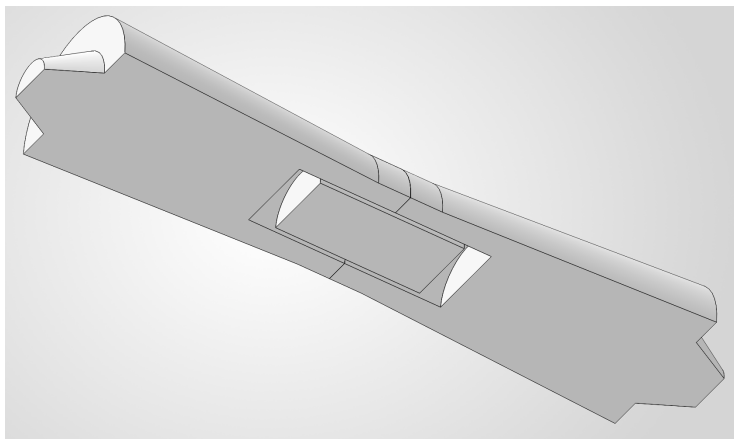


Figure 4.5: Cross-sectional view of the **CAD** model showing the roller inside the bath bowl.

#### 4.1.5 String distribution through the wind eyelet

To ensure precise placement of the string tow substitute onto the mandrel, a specialized wind eyelet is used. This component, seen in Figure 4.6, acts as the final guide point for the filament and is specifically designed for the current filament width used. Unlike the other axes, the eyelet is a round hole that allows the filament to move freely depending on how the mandrel and carriage move. Since the speed of the carriage compared to the mandrel is what determines the winding angle. In some way this makes the servo less necessary but it was still kept to ensure the holder does not risk coming in even more contact with epoxy.

When running CF filament through the machine, the eyelet can be redesigned or replaced with a roller to ensure a smoother filament distribution. When using a roller instead of a ring, the whole head of the eyelet assembly can be tilted to the desired winding angle with a servo motor through two spur gears. A servo was chosen because it is cheaper than a stepper motor used in similar constructions. Furthermore, a servo motor is, as stated in Section 2.2.2, simpler to use because it only requires a PWM signal as opposed to stepper motors, which need a separate driver circuit to function.

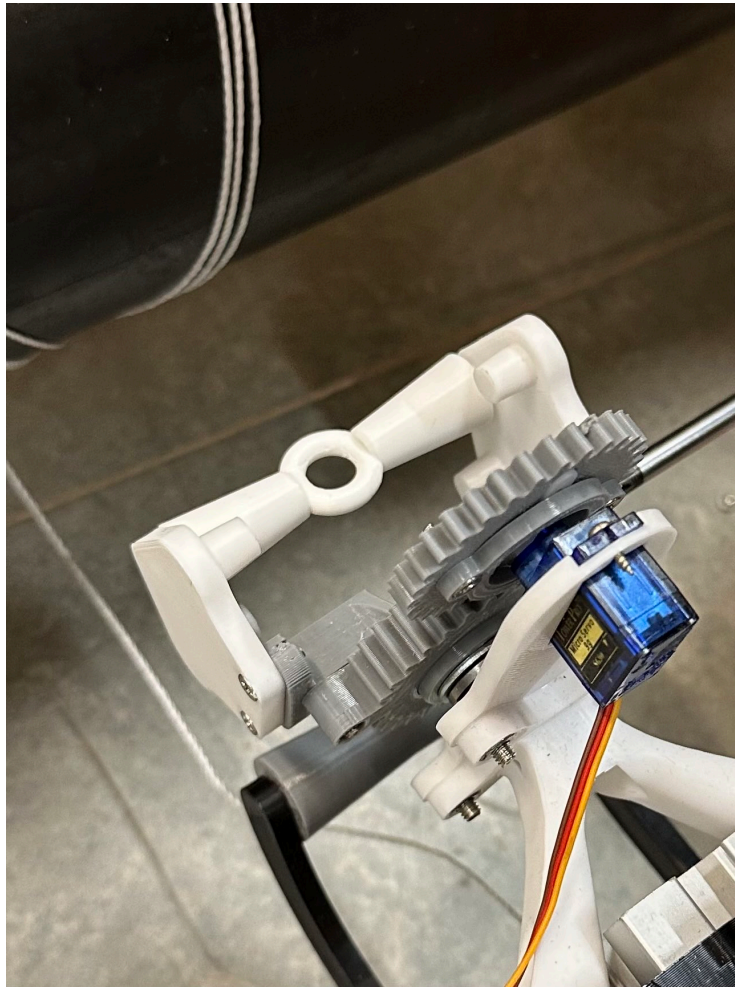


Figure 4.6: Photograph of the specialized winding eyelet used for winding string test filament.

## 4.2 Software

The software to control the tow winder has to both control the machine, and also include a G-code generator with necessary redundancy measures to make it robust to user error in order to fulfill the goal of making it easy to use in the perspective of a smaller hobby rocket organization. An IoT solution utilizing the ESP32's ability to host a website makes controlling the machine simpler and more user-friendly. The code can be accessed via the [project's GitHub repository](#).

The implementation of software is best explained by a flow chart in Figure 4.7 showing the components that make up the software. The main components are the web interface, the machine controller, the SD card interface, and the G-code interpreter, which are all separate tasks in FreeRTOS (the realtime operating system officially supported by Espressif for IoT development [19]).

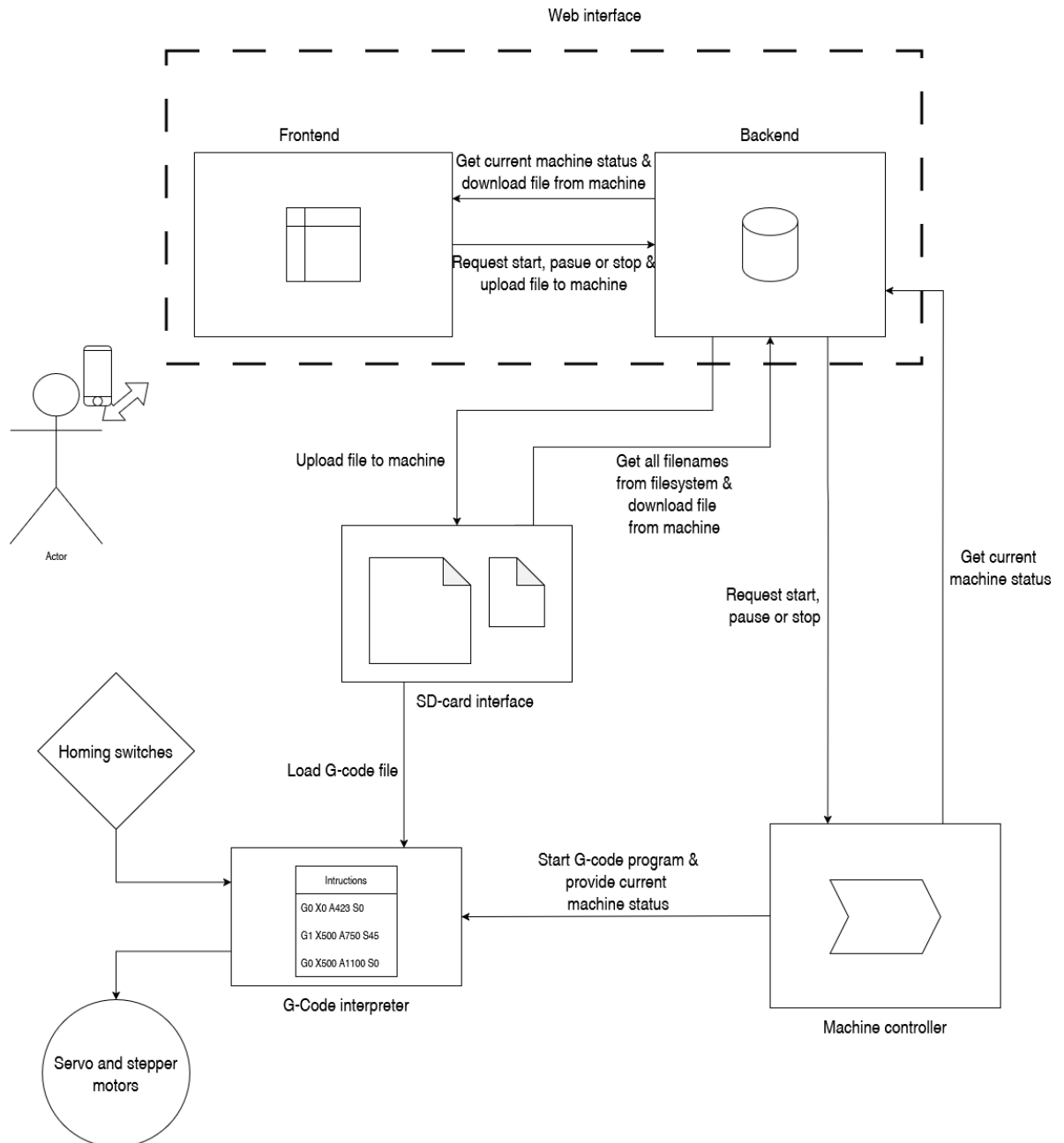


Figure 4.7: Flowchart showing how the machine's software is implemented.

### 4.2.1 Web interface

The web interface consists of two parts, the back-end and the front-end. The front-end is a simple HTML, CSS and JavaScript website which acts as a control panel for the machine and as a G-code generator. This solution was chosen because it was faster and cheaper to implement while reducing the electromechanical complexity of the machine because there is no need to construct a physical control panel which has a higher risk of malfunctioning. In addition to this, G-code can be generated from any browser through JavaScript which allows the user to simply use their smartphone's built in browser and in turn simplify the user experience.

The back-end part is a lightweight HTTP server, implemented using the ESP-IDF TCP/IP stack [19] which features a REST-like **Application Programming Interface (API)** to control the machine. The HTTP server also interfaces directly with the SD card interface to be able to provide website files or to write new G-code files to the SD card.

### 4.2.2 SD card interface

Although the ESP32-S3 was chosen for its relatively high SRAM and flash memory, it is still not enough to store a whole G-code file, therefore an external storage device was necessary. A micro SD card was chosen because it is easy to read and write to and there exist premade, cheap and easy to use hardware modules for connecting them to a microcontroller during prototyping. The module and SD card use the hardware **Serial Peripheral Interface (SPI)** communication protocol. When writing a new G-code file to the SD card, the body of an HTTP post request is read chunk for chunk and passed on to the SD card in the same fashion. The same happens in reverse when an HTTP get request is received for the front-end files that are stored on the SD card. In the code during the start of the program the SD card is mounted and **SPI** is initialized, and then it can be written to or read from using standard file commands in C.

### 4.2.3 Machine controller

The machine controller is a simple state machine with three states, running, paused, or stopped. It handles pause and resume logic while also allowing for emergency stopping by stopping all motor output and disabling the motor drivers which is necessary for safety reasons as with all moving machines there

are risks involved when running it such as hair or clothing getting caught or less immediate dangers such as epoxy spills.

#### **4.2.4 Toolpath simulation and G-code generation**

The G-code is generated on the client connected to the HTTP server, which allows for improved usability and avoids hard-coding solutions to make future development easier. Furthermore, in order to generate the G-code, the inputs need to be the diameter and length of the tube in mm, the desired winding angle, the width of the tow tape and the amount of desired layers. The program always starts with a homing sequence and then continues with the program specific instructions. The G-code (and M-code) commands used are taken from the LinuxCNC standard libraries and include commands for fast movement and slow movement of both carriage and mandrel, movement of the winding eyelet servo as well as machine commands for homing and coordinate system zeroing. From these inputs, all the necessary outputs can be generated using the equations in Section 2.1.3. Currently only one pattern can be generated but in the future more patterns can easily be added due to the modular nature of the code and all the necessary parameters already being correctly calculated.

#### **4.2.5 G-code interpretation and numerical control**

To be able to interpret the G-code, a new FreeRTOS task is created from the machine controller in which a data stream from a file on the SD card will be opened. Through the data stream, G-code commands will be fed to the interpreting part of the program to filter out comments and to recognize which G-code command is to be executed. The commands are then executed in separate functions and then fed into the motion planner.

The motion planner is a single function that synchronizes all motors in the time domain while simultaneously incorporating a trapezoidal or triangular speed profile to both stepper motors to ensure that the motors do not lose any steps during the acceleration or deceleration part. The motion planner then converts the speed profiles into actual steps for the stepper motors to take by utilizing the RMT peripheral in ESP-IDF.

Lastly, the homing and coordinate system zeroing commands are interpreted by moving the carriage slowly in small increments towards a small switch on the frame of the machine. When the machine detects the homing switch

press, it will back off a few centimeters and do the same procedure again in even smaller increments to get a really accurate homing position. The homing sequence is essential for calibration because it avoids manual calibration and in turn lowers the margin of error as well as ensuring a consistent result when the same program is run.

## Chapter 5

# Results and Analysis

This chapter presents the results of the project along with a short analysis of the data and its viability.

### 5.1 Toolpath tracing consistency

The toolpath was traced using a pen mounted in an eyelet with a suspended weight ensuring it presses against the mandrel with a constant force, giving a consistent toolpath trace against the mandrel. The tests were conducted at different feed rates using G-code generated for a 500 mm long tube with a diameter of 159 mm. With a tow width of 15 mm, the target spacing between passes was 14.72 mm in the normal direction after closure handling. The reported deviations correspond to the difference between the measured spacing and this target value. The feed-rates chosen were determined in steps/s for simplicity since in the code direct control of a stepper motor is determined in amount of steps. In Table 5.1 the chosen feed-rates are presented along with their corresponding feed-rates in mm/s.

Table 5.1: Conversion between feed rate in steps per second and linear feed rate

| Feed-rate<br>(steps/s) | Feed-rate<br>(mm/s) |
|------------------------|---------------------|
| 400                    | 357.6               |
| 800                    | 715.1               |
| 1 200                  | 1 072.7             |
| 1 400                  | 1 251.4             |

The main results are presented in Table 5.2, which summarizes the measured winding parameters and associated deviations for each feed rate. The average winding angle remains close to  $45^\circ$  for all tested feed-rates, indicating stable winding. However, the mean absolute deviation of the distance between passes varies significantly with feed-rate. Feed-rates above 1400 steps/s could not be evaluated due to hardware limitations, as the micro-controller encountered memory constraints while calculating the acceleration curve during motion planning.

Table 5.2: Measured consistency parameters at different feed rates

| Feed-rate<br>(steps/s) | Elapsed<br>time<br>(s) | Tube<br>length<br>(mm) | Average<br>winding<br>angle<br>(deg) | Mean abs.<br>deviation<br>between<br>passes<br>(mm) | Standard<br>deviation<br>between<br>passes<br>(mm) |
|------------------------|------------------------|------------------------|--------------------------------------|-----------------------------------------------------|----------------------------------------------------|
| 400                    | 575                    | 501                    | 45.2                                 | 1.632                                               | 1.274                                              |
| 800                    | 425                    | 501                    | 45.0                                 | 0.768                                               | 0.440                                              |
| 1 200                  | 435                    | 501                    | 45.0                                 | 0.721                                               | 0.494                                              |
| 1 400                  | 450                    | 502                    | 45.8                                 | 2.377                                               | 1.339                                              |

The measured tube length remains close to the target value of 500 mm for all feed rates, with a maximum deviation of 2 mm. The lowest deviations for adjacent pass spacing are observed at 800 and 1200 steps/s, with values below 0.8 mm, indicating good consistency relative to the target spacing. At 400 steps/s, the deviation increases to 1.63 mm, while at 1400 steps/s it rises further to 2.38 mm. A similar trend is observed in the standard deviation, which is lowest at intermediate feed rates and increases at both low and high feed rates.



Figure 5.1: A traced toolpath on the mandrel at a low speed showing imperfections clearly.

An example of the resulting pattern formed when the machine traced the G-code on the mandrel can be seen in Figure 5.1.

These results indicate a non-linear relationship between feed rate and winding consistency, with an optimal range at intermediate feed rates. Both low and high feed rates introduce increased variability in pass spacing.

## 5.2 Simulated filament lay-down consistency

The filament lay-down was simulated using a 2 mm diameter string, dry-wound onto the mandrel at different feed rates. During testing, significant issues related to low friction and inconsistent string behavior were observed, which affected the repeatability of the results. The obtained measurements are therefore subject to high variability, but are presented in Table 5.3 where the average winding parameters and corresponding deviations are summarized for the tested feed rates.

Table 5.3: Measured consistency parameters for repeated simulated tow trials at different feed rates

| Feed-rate<br>(steps/s) | Average<br>time<br>(s) | Average<br>tube<br>length<br>(mm) | Average<br>winding<br>angle<br>(deg) | Mean abs.<br>deviation<br>between<br>passes<br>(mm) | Standard<br>deviation<br>between<br>passes<br>(mm) |
|------------------------|------------------------|-----------------------------------|--------------------------------------|-----------------------------------------------------|----------------------------------------------------|
| 400                    | 582.0                  | 507                               | 48.30                                | 3.809                                               | 1.107                                              |
| 800                    | 428.5                  | 505                               | 47.65                                | 4.037                                               | 1.951                                              |

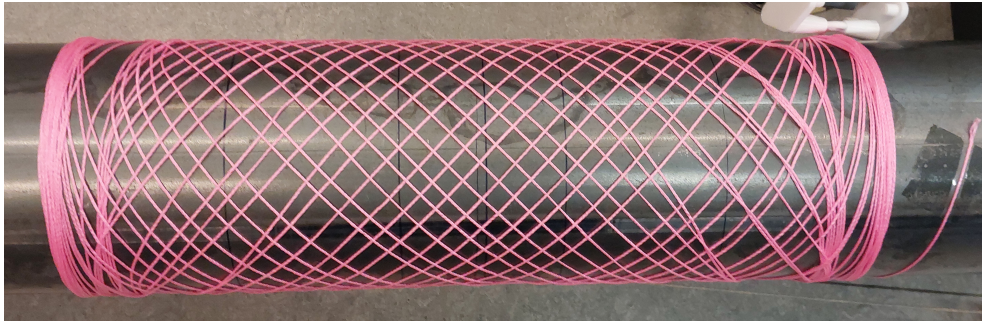


Figure 5.2: A simulated filament lay-down example highlighting the issues in consistency.

The results indicate that 400 steps/s produced slightly more consistent winding compared to 800 steps/s, as reflected by the lower standard deviation and mean deviation. However, both cases exhibit significantly higher deviations than those observed in previous tests, indicating poor overall consistency.

In addition to the averaged values shown in Table 5.3, spatial variations along the tube were observed. The winding angle was consistent in the central region of the tube, whereas larger deviations occurred near the edges where pass transitions took place.

The loss in consistency is attributed to insufficient friction between the dry-wound string and the mandrel surface. As a result, previously deposited passes were displaced by subsequent layers, leading to interactions between adjacent passes and aberrations in the helical winding paths as can be seen in Figure 5.2. After testing at 400 and 800 steps/s, further increases in feed-rate were deemed impractical, as the process became increasingly unstable rendering the results largely unusable. A few tests were relatively successful and looked similar to the traced toolpath from the first test such as in Figure 5.3 where the only difference was the test was done before the mandrel was washed clean of grease accumulated during cutting and preparation.



Figure 5.3: A relatively successful simulated filament lay-down example done at a medium speed with an unwashed mandrel.

Compared to pen-based tests, the simulated filament trials exhibit substantially larger deviations and variability. This highlights the importance of material interaction and friction in achieving a consistent lay-down.

# Chapter 6

## Discussion

This chapter analyzes and provides reflections based on the test data and presents the conclusions of the project.

### 6.1 Lay-down consistency

From the results of the pen-test it is clear that the two best feed-rates are 800 and 1200 steps/s. It is unsurprising that quality is lost as speed is increased but it is seemingly unintuitive that a lower speed results in the worst consistency of the tested speeds. It was noted during testing that the lower the speed the more clearly one could see the lines become more "squiggly" having a sort of wave like pattern as seen in Figure 5.1. This could be due to the stepper motor steps becoming more apparent as they move slower. Stepper motors move in discrete steps which at high speeds is barely noticeable but at too low speeds with low micro-stepping it can become clearly apparent. This results in the wavy lines and caps the lowest speed. Another issue could be insufficient pressure and fastening of the pen which could amplify these steps or even cause them from friction pressing against the mandrel as it rotates. Further testing would be required to understand the underlying cause.

For the application of carbon fiber filament winders the goal is to speed up the production rate so lower speeds are practically not considered. At too high feed-rates the motors risk jumping steps due to the higher torque required, this destroys consistency and was noticed in the 1400 steps/s trial. A stepper motor jumping a step causes the whole rest of the G-code program helical paths to be shifted and ends up causing closure issues especially noticeable

towards the end. The G-code generation and winding is very susceptible to small errors which, after enough passes, accumulate into large errors and can end up causing unexpected overlaps or gaps lowering quality significantly. Therefore intermediate speeds where the stepper motors discrete steps aren't noticed but not so high that the stepper motors risk jumping steps is optimal. There are a few other ways of overcoming these issues. Previous works either use smaller mandrels such as Reilley's Contraption and D.I.Winder, or simply use stronger motors such as X-Winder or the University of Brasilia low cost winding alternative as seen in Section 2.3.

Since most cost-effective epoxies used in hobby rocketry cure in room temperature there is always a time limit before the epoxy starts hardening and becomes too thick and unusable. This can happen any time between thirty minutes to one hour which is usually stated as the possible working time for an epoxy resin. This means any winding time that's quicker than 30 minutes is a basic requirement for a functional machine. Fortunately, all the tests finished in a timely manner so this never became an issue but is still worth noting.

## 6.2 Carbon Fiber Tow Simulation Issues

The results obtained from the string-based tests, intended to simulate carbon fiber filament winding, highlight several limitations of the chosen approach. Although the method provides qualitative information about the winding process, significant discrepancies exist between dry-wound string and actual carbon fiber tow.

The primary issue observed was insufficient friction between the string and the mandrel surface. This caused previously deposited passes to shift position despite the presence of an initial hoop layer before each pass partly intended to prevent unwinding. Subsequent layers were observed to displace earlier passes, leading to local accumulation of material and increased geometric inconsistency. These disturbances also negatively affected the placement of later passes as seen in Figure 5.2. In addition, the low friction resulted in reduced tension in the string during winding. In filament winding, tension is essential for maintaining tight contact between layers, as intersecting passes help constrain each underlying layer thus stabilizing the structure. When tension is insufficient, this stabilizing effect is diminished, resulting in a less uniform lay-down.

It was also observed that surface conditions of the mandrel significantly

influenced the results. Prior to cleaning, the mandrel surface contained residual grease from machining, which increased friction and improved winding consistency. Although limited data is available from these trials, photographic evidence such as Figure 5.3 indicates more stable lay-down under these conditions. In contrast to the dry-winding approach used in these tests, actual carbon fiber filament winding involves fibers impregnated with a viscous epoxy resin. This resin increases adhesion between layers and between the filament and the mandrel, thereby reducing the likelihood of slippage. Additional resin may also be applied to the mandrel surface to further improve bonding.

Another limitation of the simulation is the geometric difference between the string and carbon fiber tow. Carbon fiber tow typically has a flat, tape-like cross-section, whereas the string used in this study has a circular cross-section. This reduces the area of contact with the mandrel and consequently reduces friction, further exacerbating the observed problems.

To improve the validity of future simulations, alternative materials should be considered. For example, using a flat tape, such as a thin ribbon, or introducing controlled surface friction (e.g., through coatings or pre-treated materials) could better replicate the behavior of resin-impregnated carbon fiber tow. These findings demonstrate that accurate simulation of filament winding requires both appropriate material properties and surface conditions to replicate the interaction between fiber, resin, and mandrel. They also provide insight into the parameters that ensure consistent winding as well as potential fixes to increase consistency.

In previous work this lack of friction issue encountered in the preformed test does not seem to cause issues when actually laying down filament since it is never mentioned as an issue in related works. No measures are taken to avoid this and since their constructions are similar to the one proposed in this thesis it can be assumed that this is not an issue in actual lay-down. Further, possibly expensive, testing would be required to validate this statement.

## 6.3 Cost Analysis

A qualitative cost and complexity analysis was conducted to compare the developed filament winder with existing designs, specifically those included in Section 2.3. The comparison focuses on key cost-driving factors, including system architecture, actuator selection, motor drivers, and mechanical

construction.

The developed system employs a three-axis configuration, whereas two of the comparable designs, such as the X-winder [15] and the University of Brasilia [16] designs, utilize four axes. The additional axis increases system cost due to the requirement for an extra motor, driver, and associated control hardware. Even when disregarding this additional axis, the developed system remains comparatively cost-effective compared to the four-axis systems.

A major cost difference arises from the actuator used to control the eyelet. While most existing systems employ stepper motors (e.g., NEMA17 or NEMA23), the present design uses a low-cost servo motor. This choice significantly reduces system cost, as both the actuator and its control requirements are less expensive requiring no extra drivers or more power allocation. In contrast, the developed system utilizes higher-performance motor drivers capable of supplying up to 4 A per motor. Comparable systems, such as Reilley's Contraption [17], use CNC shield-based drivers with lower current limits (typically around 2 A per motor), which are more cost-effective. While sufficient for smaller-scale applications, such current limitations may pose challenges when driving larger mandrels, such as the 159 mm diameter steel pipe used in this work. Although the measured current consumption of the developed system rarely exceeds 3 A in total, the use of higher-rated drivers was chosen to reduce the risk of overheating and ensure reliable operation. From a mechanical perspective, the developed system relies heavily on 3D-printed components, similar to the D.I.Winder [18] design. In contrast, other systems make greater use of aluminum extrusions and custom-machined components, which increase manufacturing cost and reduce ease of replacement.

The total cost of the developed system is estimated to be around \$300, which is significantly lower than comparable alternatives. For example the four-axis X-winder costs \$7,495 with a now outdated three-axis version selling for below \$5000. The more comparable D.I.Winder and Reilley's contraption have costs of "less than \$500" which is similar to the final design presented in this report. This demonstrates that the design successfully meets the low-cost objective defined in Section 1.4 and addresses the first two engineering challenges identified in Section 1.2.2 regarding simplicity of design as well as answering which components contribute most to cost.

## 6.4 Ethical and Sustainability Considerations

It is worth commenting on the sustainability concerns inherent when working with CF products. So far, only the direct cost has been discussed as the main optimization goal, but environmental and ethical problems can still arise. In current CF manufacturing, there are considerable difficulties when recycling or reusing waste materials. This not only drives up costs but also creates significant sustainability problems, as the material cannot easily be reused or recycled, making the process inherently unsustainable. Therefore, minimizing waste materials is a high priority, not just for cost reasons but for environmental ones as well. According to Figure 2.1, filament winding reduces costs compared to other manufacturing methods. Additionally, filament winding enables weight and material optimizations that limit environmental impact. While the growing concern for a sustainable future may eventually lead to alternatives to CF products, until then, in applications where performance is critical, the only feasible action is to limit waste.

During tests where CF tow was simulated using ordinary string, several rolls were consumed. However, care was taken to remove the string without damaging it, allowing for potential reuse. Although no reused or rewound string was actually used in this project, future testing could limit waste by reusing string after it has been wound once.

Working with epoxy and composites involves significant risks, as these materials are toxic and can cause serious, not immediately apparent, health issues if handled improperly. The necessary precautions must therefore be taken when working with them. Regarding machine safety, a safety stop and the ability to pause the machine were added as part of improving ease of use. Any machine with moving parts can be dangerous, so it is assumed that all necessary precautions are taken by the user.

## Chapter 7

# Conclusions and Future work

This chapter presents the conclusions of the project determining its success as well as possible future work left on the prototype and in the low-cost filament winding area in general.

### 7.1 Conclusions

In summary, the developed **CF** filament winder addresses the objectives outlined in Section 1.4 and demonstrates a largely successful design. Although the system has not been evaluated using actual filament winding with resin-impregnated tow, its performance under the tested conditions indicates strong potential for successful implementation in such applications. The issues encountered during testing, particularly in the string-based simulation of filament winding, are primarily attributed to the differences in material properties between the string and carbon fiber tow. These limitations are expected to be less apparent when using resin-impregnated tow, where increased adhesion and friction contribute to improved lay-down stability.

From a cost and manufacturing perspective, the proposed solution offers advantages over traditional wet lay-up methods by reducing both production time and overall cost. Furthermore, the system is competitive with existing low-cost filament winding solutions while maintaining adequate performance. A dedicated toolpath generation algorithm and G-code generator were successfully developed, enabling customizable layer configurations. The integration of an IoT-based interface further enhances usability, contributing to a more accessible and user-friendly system. Experimental results indicate that

an optimal operating range between 800 and 1200 steps/s provides a favorable balance between production efficiency and winding consistency. However, further work is required to improve robustness and ensure reliable operation under a wider range of conditions. Finally, while the achieved consistency is promising, even minor deviations in filament placement may have significant effects in applications such as rocketry, where components are subjected to high dynamic loads and temperature variations. Continued refinement of the system is therefore necessary to achieve the level of precision required for such demanding applications.

## 7.2 Future work

Due to the scope of the problem, as well as time and budget constraints, it was not possible to investigate all aspects of the project in full detail. The most significant limitation is the lack of testing involving actual filament winding with epoxy and CF. Consequently, certain design modifications may be required once such conditions are evaluated, for example, in cases where tow tension is sufficiently high to introduce structural challenges that could not be assessed within the present work. If composite tubes produced using CF were manufactured, a comparison of their mechanical properties and overall quality with manually manufactured tubes could provide a quantitative assessment of the improvements achieved, or alternatively reveal limitations in the proposed method.

In addition, the associated software platform could be further evaluated in terms of usability and extended to support a wider range of filament winding patterns and configurations for different applications. A further potential development is the introduction of a fourth axis, which would enable the fabrication of more complex geometries. This would be particularly relevant for applications such as pressure vessels, where higher geometric complexity and stricter consistency requirements are necessary, as well as being a less researched area when it comes to low-cost winders.

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