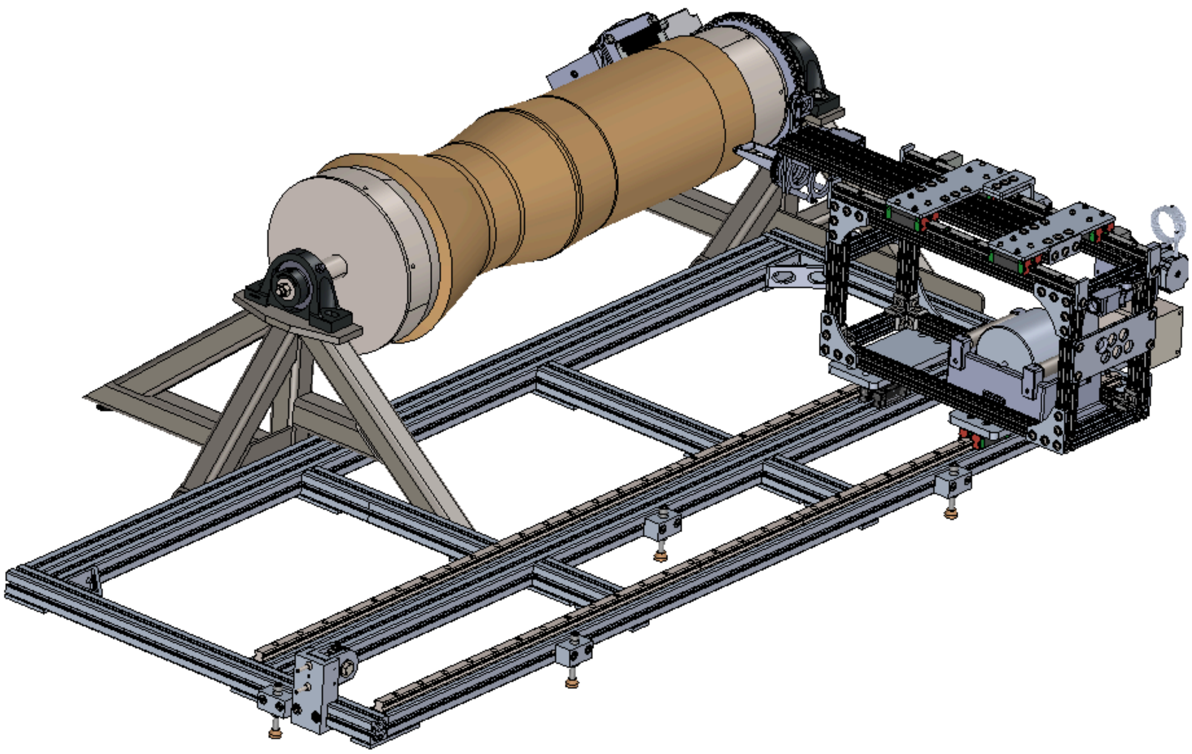
Carbon Fiber Filament Winding Machine



Operations Manual and Procedures

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0.0 Prelude:

This machine was designed and constructed by Capstone Team 25 in 2025, in collaboration with Space Concordia Rocketry Division. A special thank you to Oleg Khalimonov, Michael Rembacz, Alexis Gosselin, Henri Takahashi-Massicotte, Andy Shin-Pong, Syn Furuli, Erik Huang, and Serguey Palacio for their help and guidance.

Please contact us when you send our stuff to space!

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1.0 Safety

Operation of this machine must comply with all applicable Concordia University Environmental Health & Safety (EHS) protocols. Personnel must complete all required safety training and adhere to personal protective equipment (PPE) standards. Unauthorized use of the machine is strictly prohibited.

1.1 DISCLAIMER ON THE SCOPE OF THE FOLLOWING SAFETY PROTOCOLS

The safety protocols outlined in this manual are specific to the dry use, operation, and modification of the filament winding machine. They do not encompass the full range of safety considerations required during wet winding processes or the actual manufacturing of composite parts, which involve hazardous materials such as epoxy resins and hardeners.
Working with these substances introduces significant risks including, but not limited to:

- Eye and skin irritation
- Skin sensitization
- Inhalation of hazardous fumes
- Flammability and potential ignition hazards

These activities are governed by separate process safety documentation, which address material handling, ventilation requirements, and exposure mitigation strategies for the specific materials used. All personnel must consult the Safety Supervisor or Team Lead before engaging in any wet winding or composite manufacturing procedures. Appropriate Standard Operating Procedures (SOPs), Personal Protective Equipment (PPE), and certified training are mandatory for such work.

1.2 Required Training

Before operating or working near the machine, personnel must have successfully completed the following training modules:

1. WHMIS for Laboratory Personnel
2. Hazardous Waste Disposal for Laboratory Personnel
3. Corrosive Substances
4. Safe Handling of Nanomaterials

Training completion must be verified by the designated Safety Supervisor or Team Lead. Training details are available through the Concordia Chemical Safety webpage or via email at ehs@concordia.ca.

1.3 Personal Protective Equipment (PPE)

Always required:

- CSA-approved eye protection (ANSI Z94.3 rated).

Required during specific operations:

- Insulated gloves when working with or near live electrical components.
- Steel-toe boots when handling loads exceeding 50 lbs (e.g., mandrel loading/unloading).

Recommended:

- Work gloves (general handling).
- Lab coats or coveralls.
- Respiratory protection during prolonged epoxy resin exposure (as specified in SOPs)

Clothing requirements:

- Long hair must be tied back securely.
- Loose clothing, jewelry, or accessories that may become entangled must not be worn.

1.4 Operational Safety

1. A minimum of two trained individuals must be present during machine operation or heavy lifting activities.
2. The machine must be used on a stable, ground-level surface to prevent tipping and reduce the risk of falling parts.
3. The working zone must be free from tripping hazards, loose tools, and unnecessary personnel.
4. Use proper lifting techniques. For components exceeding 50 lbs, lifting must be conducted by two people or with mechanical assistance.
5. When working near electrical components, ensure all circuits are de-energized prior to handling.
6. All resins, hardeners, and solvents must be handled in accordance with their respective Material Safety Data Sheets (MSDS) and stored in designated containers.

2.0 Machine overview

The machine is composed of 6 subassemblies. The following will describe their overview and purposes. Figure 2.0.1 Shows the overall assembly with the labeled subsystems.

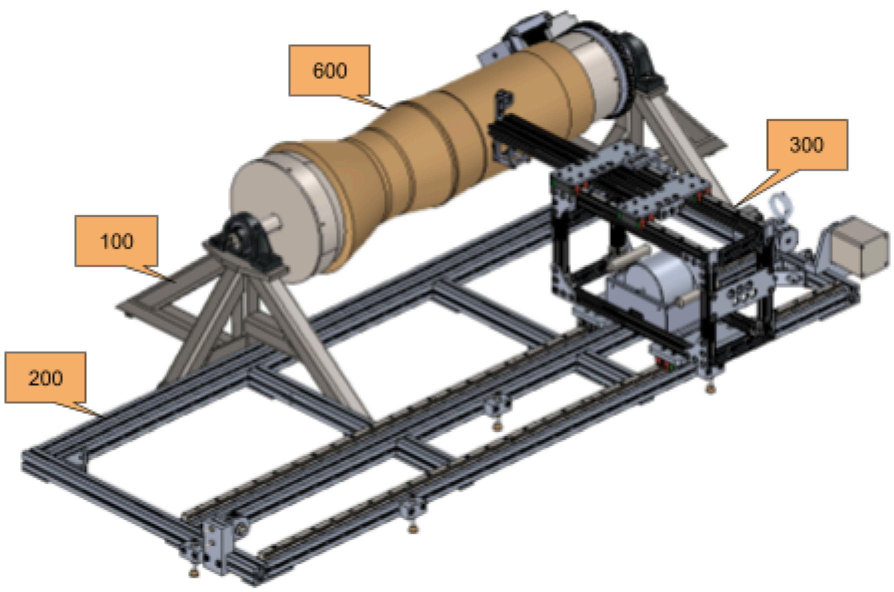


Figure 2.0.1 Overall assembly with subsystems

Figures 2.0.2 and 2.0.3 show the 400 and 500 subsystems which are the Creel (Tow management system) and the tensioning system respectively. Note that the 2025 Capstone team who developed this machine did not reach the point of editing or refining the creel or tensioning system.

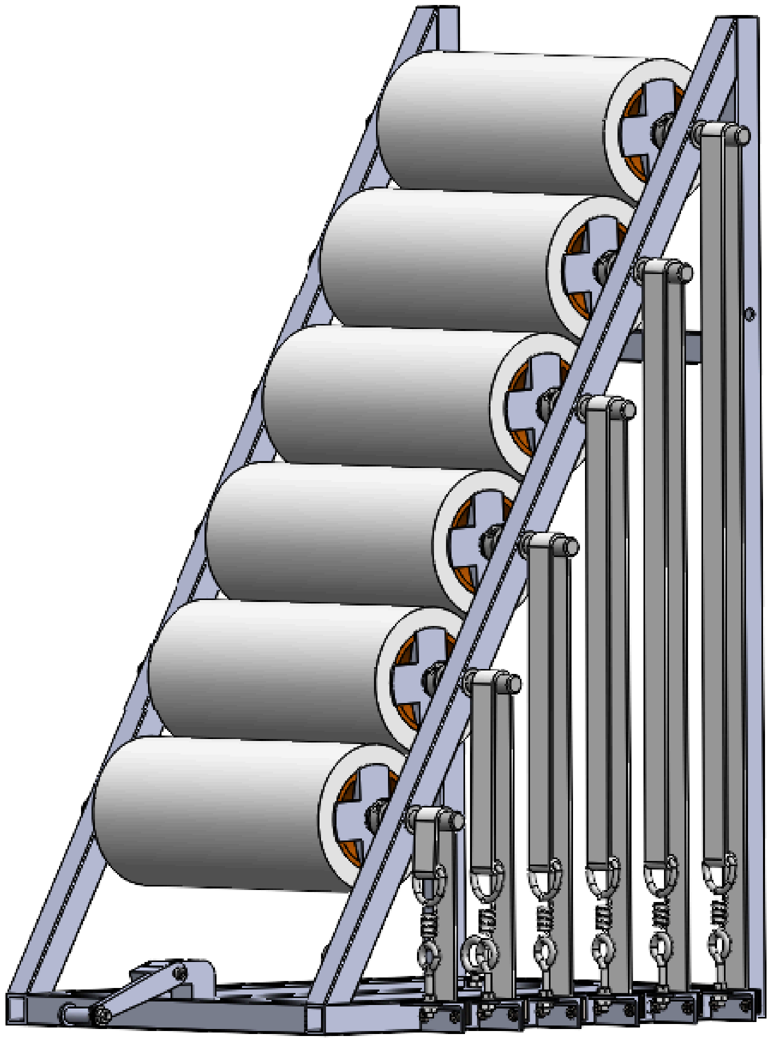
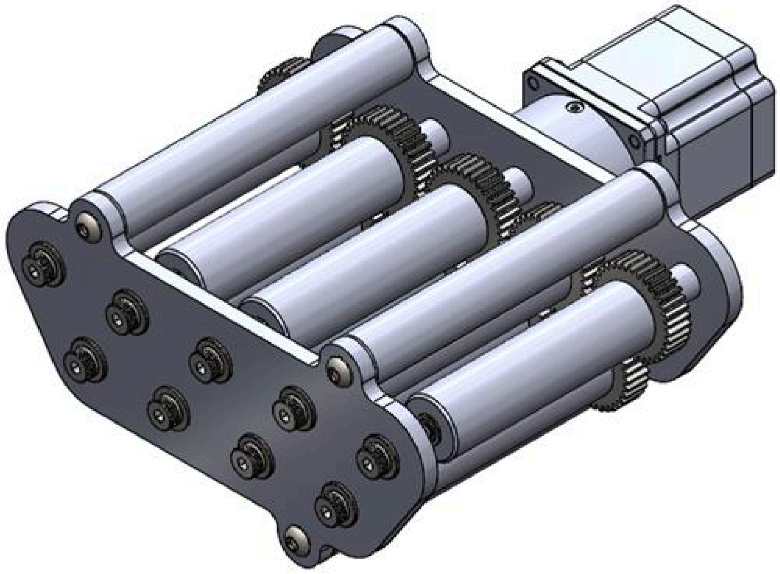
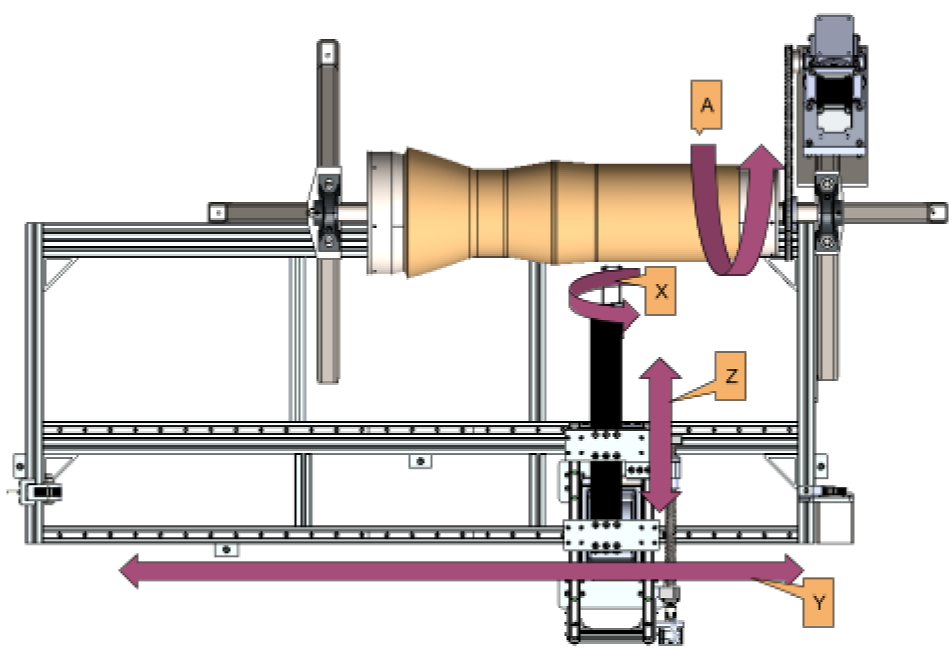


Figure 2.0.2 Creel assembly

The tensioning system was designed as our research revealed it would probably be needed for the winding process of complex geometries. Upon researching this it was realized that the analysis, research, design and manufacturing of this sub assembly would constitute its own capstone project. Regardless it was designed so that future teams could develop it and implement it should they determine it's required.



2.0.3 Tensioning System



2.0.4 Axis definition

Note that the axes defined here are relevant in the software portion of this manual. There exist a number of different possible axis definitions for filament winding machines or other, similar mechanisms. However these definitions were chosen as they are most similar to the cartesian machines for which the firmware being used (GRBL) was developed.

2.1 Mandrel Frame:

This subassembly is prefixed by '1xx_' in CAD. The purpose of the mandrel frame is to support the weight of the mandrel. It is composed of two independent steel 'feet' which are designed to reduce the probability of tipping. The foot which holds the motor and gearbox is called the motor foot (12x_ in CAD).

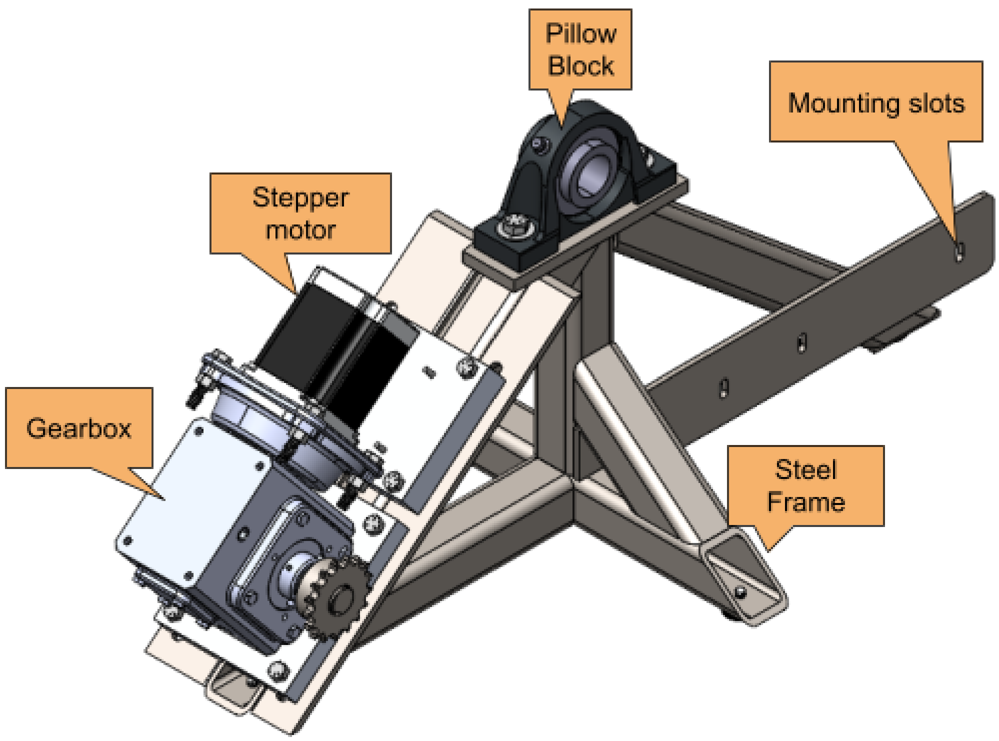


Figure 2.1.1 120_MotorFoot assembly

The motor foot houses the motor which drives the mandrel through a chain. The slots allow the motor foot to be mounted to the extrusion frame in assembly and removed for transport. They also allow adjustability during the leveling process. Note that a larger, NEMA 56 servo motor (CPM-MCVC-N0564P-RLN) was specified for this assembly but budget constraints meant that a NEMA 34 was used instead. A mounting pad for the aforementioned NEMA 56 (with mounting feet accessory) is provided with the machine, should the motor be purchased. The NEMA 34 can be used for smaller and slower operation but extended use will require a larger stepper motor. In code this motor is referred to as the A-axis.

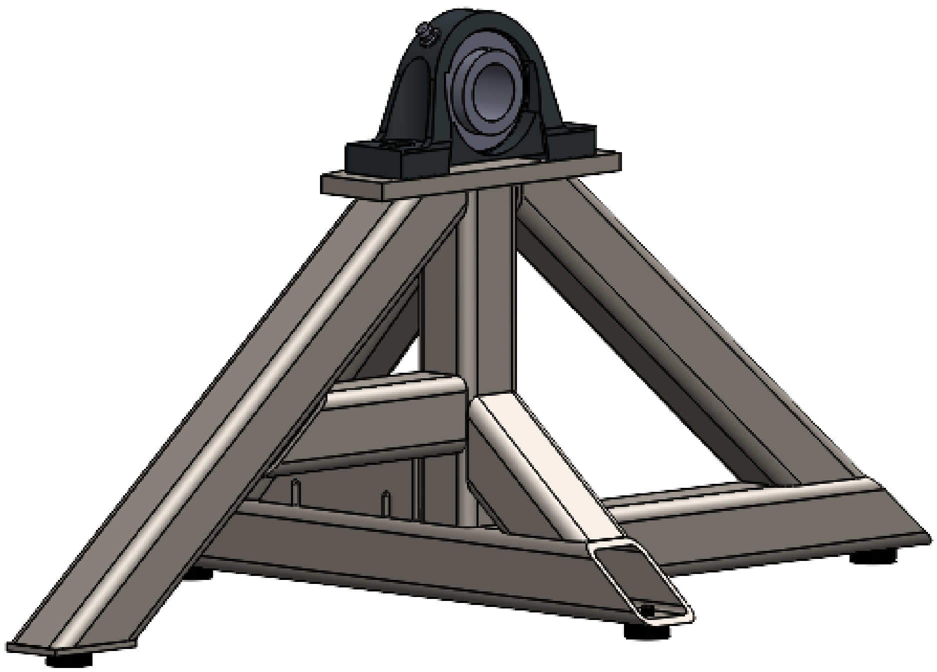


Figure 2.1.2 110_MovingFoot assembly

The moving food is simpler. It also has slots so that it can move along the extrusion frame to accommodate different mandrel lengths.

2.2 Extrusion Frame:

While the mandrel frame supports the mass of the mandrel and has the necessary rigidity to accommodate the mandrel's accelerations, the extrusion frame houses the more intricate machinery. This mainly involves the carriage. The purpose of this subassembly is to remain square and trammed and be adjustable so that the carriage can run smoothly along it and remain parallel to the mandrel.

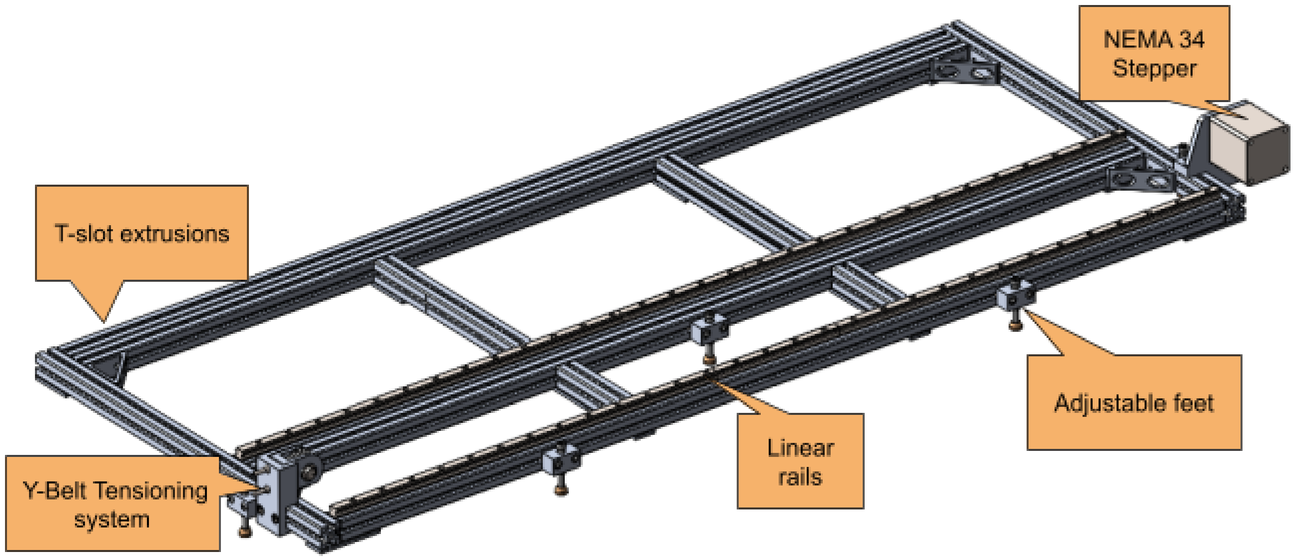


Figure 2.2.0 200_ExtrusionFrame Assembly

The T-slot extrusion means that the mandrel feet can move along the extrusion frame. It is highly adjustable so that it can be made square, trammed and level before operation. The motor, rails and belt tensioning system here are what comprise the Y-axis of the machine.

2.3 Carriage

The carriage is the most intricate and complex subassembly. It houses the X-axis and Z-axis. These being the rotation of the delivery head and extensions of the delivery arm respectively. This subassembly runs along the Y axis which is parallel to the mandrel.

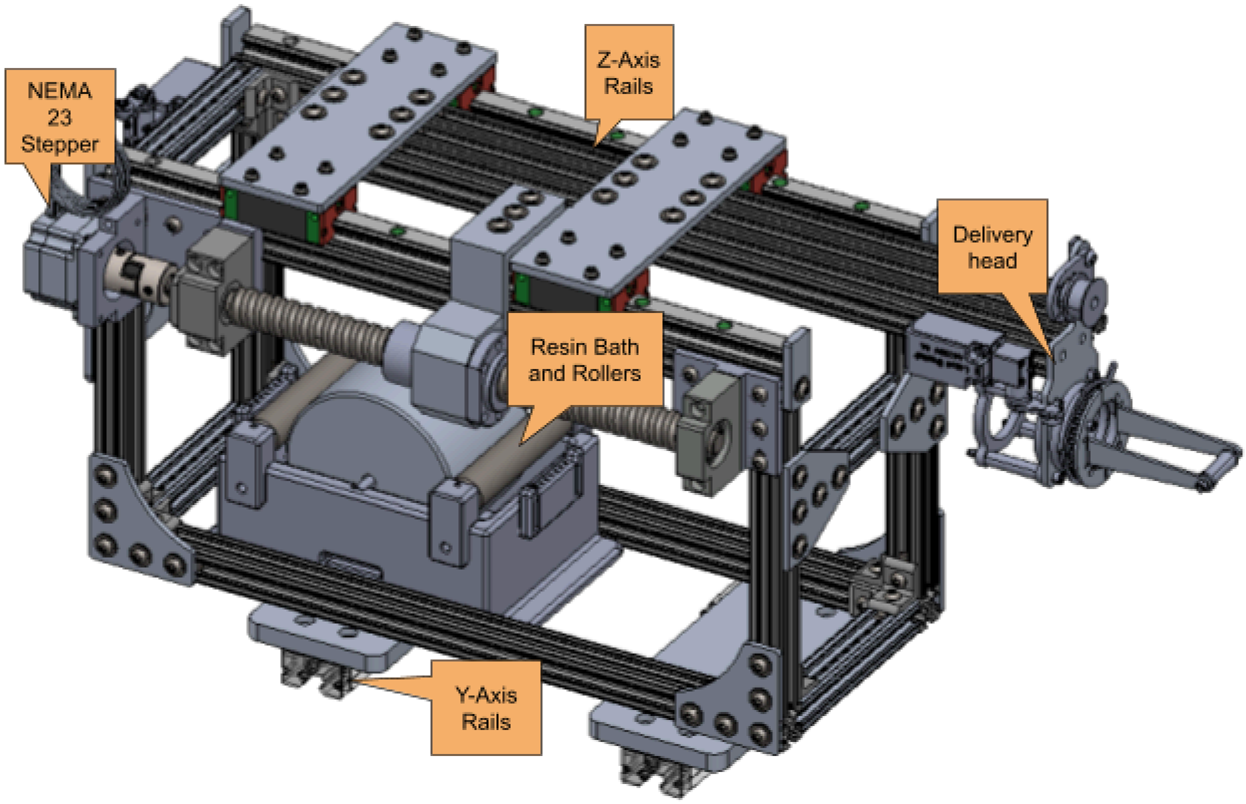
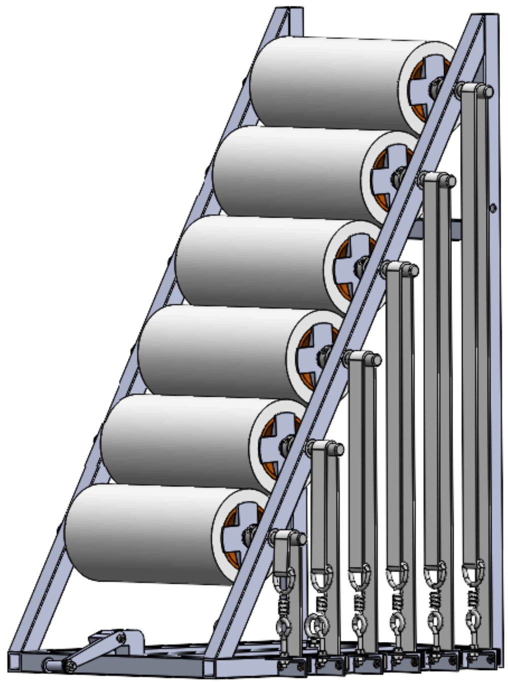


Figure 2.3.0 300_Carriage Assembly

This subassembly also houses the tensioning system. Note that the tensioning system was designed but not developed by the 2025 capstone team.

2.4 CREEL

This subassembly was inherited from SCRD. The only modification made was the replacement of springs to increase tension. Based on analysis, we believe an active tensioning mechanism will be required in winding. However, for preliminary testing and the winding of non complex shapes, the existing belt tensioning system can be used.



2.4.1 400_Creel Assembly

2.5 Tensioning system

The 2025 capstone team realized the need for active tensioning in winding complex geometries. This means adjusting the tension of the tows based on the part of the mandrel being wound. This is a difficult concept and constitutes the workload of an entire capstone in itself. Andrea Devulder of the 2025 capstone team developed a preliminary design based on months of research and discussion with industry specialists. This was not yet prototyped.

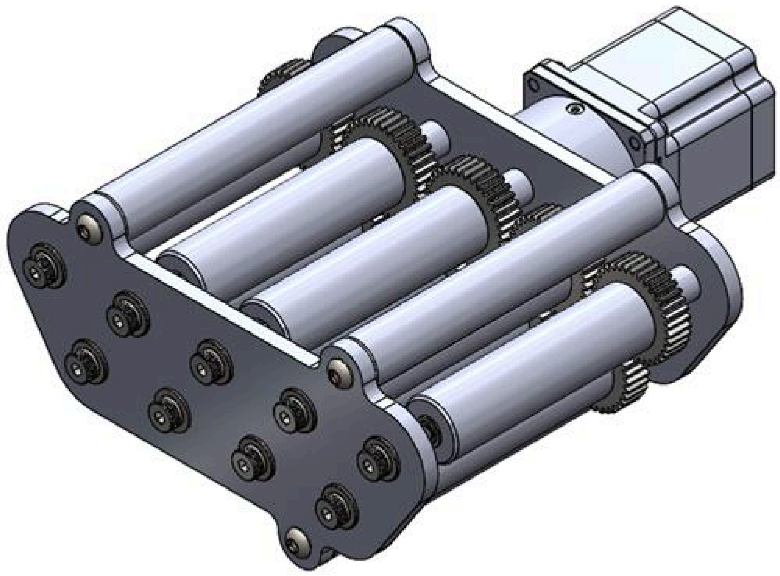


Figure 2.5.0 Tensioning system

2.6 Mandrel

This Subbassembly was also inherited from SCRD, with an added sprocket. The mandrel in question is the combustion chamber, however this machine was developed to handle any mandrel that fits in the specifications outlined in section 3.0.

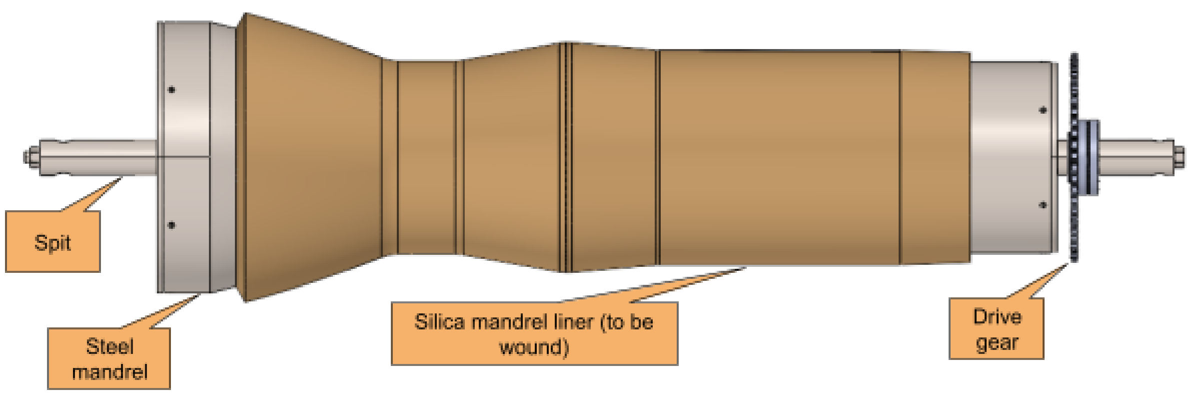


Figure 2.6.0 600_Mandrel Assembly

3.0 Intended Purpose and Use

This machine is intended to be used for winding filaments onto mandrels. These filaments can be passed through a filled resin bath if required. This machine can also be used with pre-impregnated filaments (pre-preg).

3.1 Intended specifications:

The following are specifications to be respected for operating the machine in its current state. Some portions of the machine may be capable of handling increased inputs, but this will require the augmentation of other subsystems. For example, the mandrel feet can handle more than 150 kg, but the motor will not be able to stop it in a reasonable amount of time. It is imperative that a user conducts all relevant analysis and modifications before surpassing the following specifications.

Specification	Value	Description	Limiting Feature
Max. mandrel mass	150 kg	The sum of the mass of the mandrel. This is defined as the culmination of the mass on the mandrel feet. This includes all the added mass during the winding process	The mandrel motor is only capable of halting a mandrel of this size safely. A larger mandrel would require analysis of the stopping capability of the mandrel motor.
Max. mandrel length	1.5 m	The distance from the beginning to the end of the winding path (the mandrel spit may be longer without issue as long as the mandrel feet are secured to the extrusion frame.	The travel of the carriage. The current linear rails have an extra 25 cm. The long extrusions in the extrusion frame can be extended to capitalize on this length.
Max. mandrel diameter	0.5 m	The diameter of the longest part of the mandrel	The height of the mandrel center axis and the maximum displacement of

			the carriage.
Max. tension (all tows combined)	240 N	The maximum tension of all the tows passing through the carriage.	Limited by a number of components in the carriage and Y axis.
Max. number of tows	6 tows	The number of individualized groups of fiber entering the carriage at once.	Limited solely by the RFS and number of eyelets.
Operating accelerations	X: 69 mm/s^2 Y: 100 mm/s^2 Z: 100 mm/s^2 A: 200 mm/s^2	These are the speeds at which the GCODEs were developed, however the machine runs comfortably at around 3 times these accelerations.	Limited by the vibrations of the frames, motor torques and safety concerns.
Operating speeds	X: 140 mm/s Y: 280 mm/s Z: 169 mm/s A: 280 mm/s	These are the speeds at which the GCODEs were developed, however the machine runs comfortably at around 3 times these speeds.	Limited by safety concerns, motor torques and the vibrations of the frames.

Table 3.1.0 Machine Specifications

4.0 Transport and portability

This machine was intended to be partially disassembled and moved to a location where winding carbon fiber is approved (CONCOM). Then disassembled and returned to storage. The machine breaks up into different manageable parts. The machine can be disassembled into the following components:

1) The motor foot (with motor and gearbox)
2) The moving foot
3) The extrusion frame
4) The creel
5) The carriage
6) The electronics box

The heaviest of the non-rolling components being the motor foot which can safely be moved and carried by two people. Not forgetting that steel toed boots should be worn as explained in section 1.0.

This section will outline the procedure and considerations for transporting the machine. The tools Required for the assembly and disassembly of the machine are the following.

Hex wrenches or sockets:

- 19mm / 3/4"
- 7/16"

Allen keys:

- 4mm
- 5mm
- 3/16"
- 5/16"

4.1 Assembly for Winding.

Assuming the machine is being taken out of storage and transported to be assembled in a winding area. If any components are dusty or damaged, clean or repair them before proceeding.

1) Start by placing the mandrel feet on the ground in their approximate locations
    a) Space the bearing blocks by approximately the length of the spit
    b) Remove the bearing blocks from the feet and place them to the side.
2) Place the extrusion frame on the ground in position at the base of the mandrel feet.
3) Lift the moving foot and place it over the extrusion frame.

4) Raise the extrusion frame and attach the bolts through the slots in the mandrel feet into the extrusion frame. Use Twist in T-nuts for convenience and washers on the mandrel foot side.
    a) Note that it is easier to install the screw and Twist in T-nuts into the mandrel feet before aligning and inserting them into the extrusion frame.

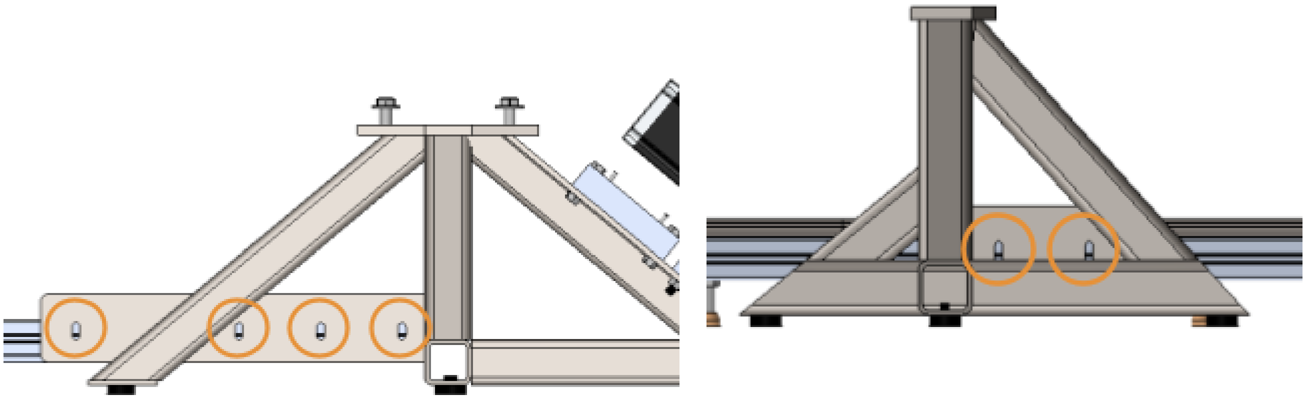


Figure 4.1.0 Mandrel Feet Bolt Slots

5) Once the extrusion frame is secured to the mandrel feet it is time to square, tram, and level the frame.
    a) Use a spirit level or alternative across both axes of the extrusion frame and adjust the adjustable feet or slot positions as necessary
    b) Measure diagonals and assure the frame is square
    c) Tram the linear rails of the y axis by placing a dial indicator on one block and running it across the length of the rail

Figure 4.1.1 Rail tramming

6) Once the frames are in position the carriage can be added to the linear rails by sliding it on from the end of the rail.
7) Attach the belt tensioner to the extrusion frame and connect it so that it has room to tension the belt.

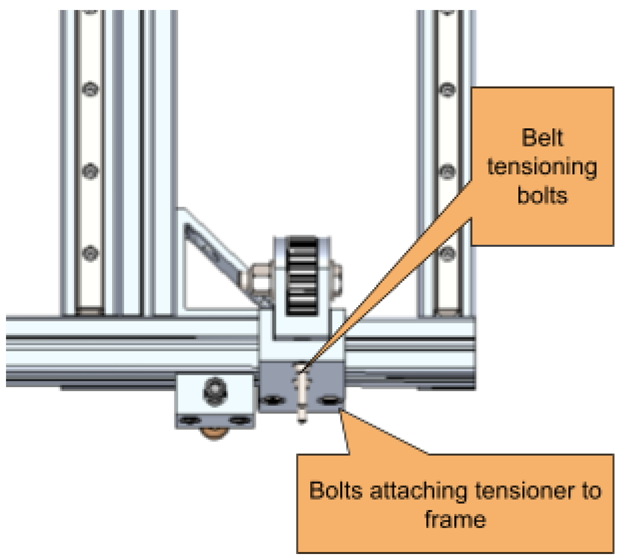


Figure 4.1.2 Belt tensioning bolts.

8) The belt can be mounted by securing the belt clamps as such:

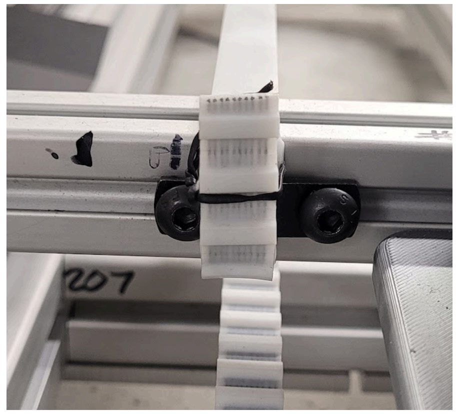


Figure 4.1.3: Belt Clamp

9) Tighten the 'belt tensioning bolts' until the belt is taut. Then secure the lock nuts and three locking grub screws.
10) The motors can now be plugged in and the machine is ready for setup

4.2 Disassembly for storage:

It is preferable to store all motors, electronics, and linear rails in an area where they will not accumulate dust. For this section refer to the images in section 3.1 for clarifications.

1) First disconnect all the motors and limit switches and pack the electronics in a bin where they will not get damaged. Note that the included PC can be stored with the electronics, but the machine can be operated with any computer.
2) Remove the pillow blocks from the mandrel feet and place them with the mandrel in storage.
3) De-tension and remove the belt from the carriage. Remove the belt tensioning system to allow the carriage to come off the rail.
4) Slide the carriage off the rails and carefully onto the included black carriage block inserts. These are used to stop the ball bearings from falling out of the carriage blocks.

Figure 4.2.0 Linear rail block ball restrainer (image source)

5) Secure these inserts in the blocks using tape. Place the entire carriage in a bag or bin to avoid dust accumulating on the ball screws and rails. Place the carriage in storage.
6) The extrusion frame can now be released from the mandrel feet by loosening the screws shown in figure 4.1.0.
7) Finally the mandrel feet and extrusion frame can be placed in storage. The extrusion frame can be disassembled for space constraints but this will require more assembly time during the next wind.

5.0 Electronics and wiring

The electronics configurations for the machine is based on an arduino microcontroller. The software implications of this are described in section six. This section will discuss the physical electronics components specifically to aid in troubleshooting and modification. The following figure shows the overall wiring diagram.

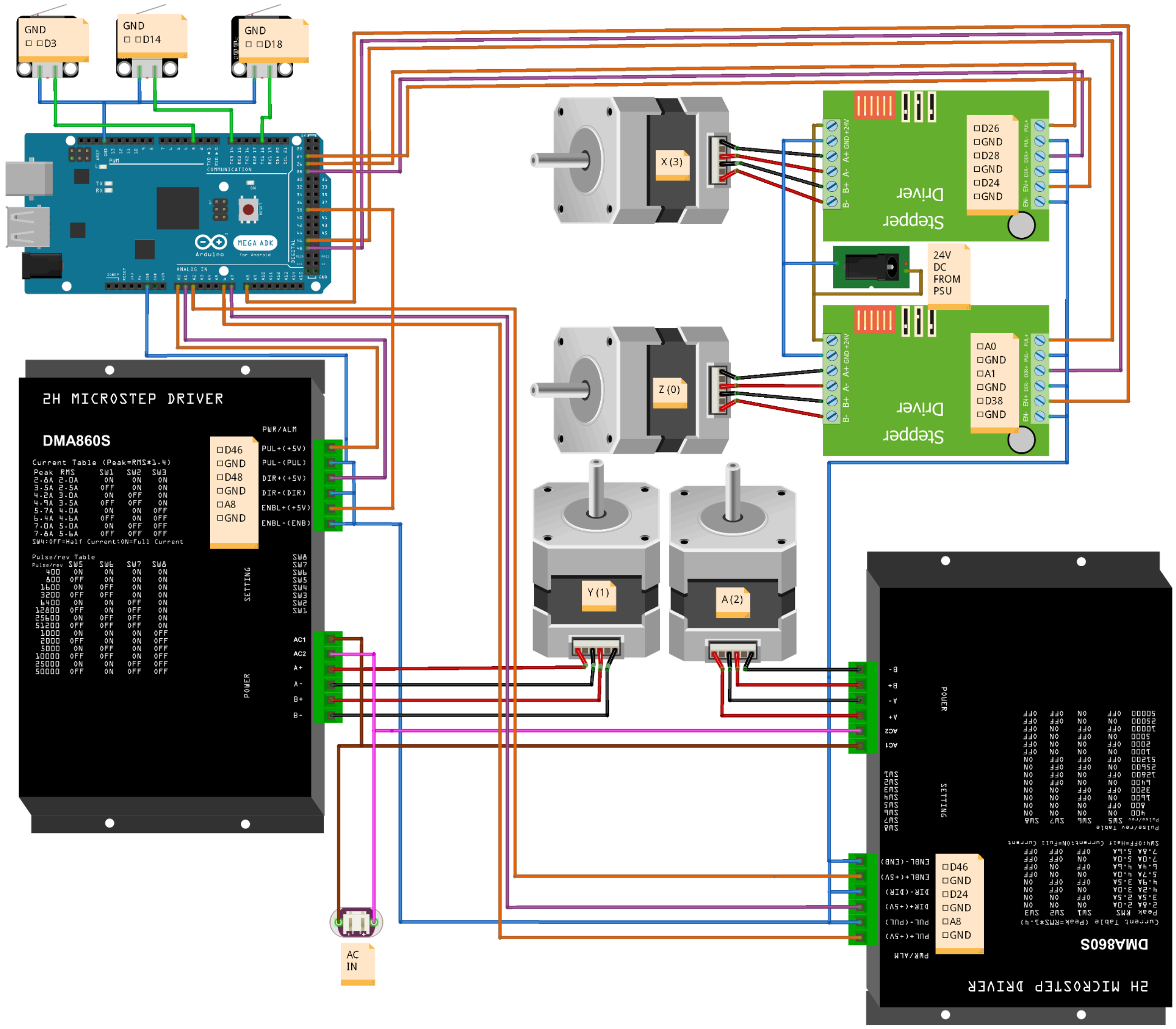


Figure 5.0.0 Wiring diagram

This arduino is fed information from a small windows computer through serial communication (USB - 115200 Baud rate). The actual configuration of the electronics has a breakout board to facilitate the connections to the drivers and increase the durability and reliability of the connections (when compared to jumper wires). Figure 5.0.1 shows this board and its configurations.

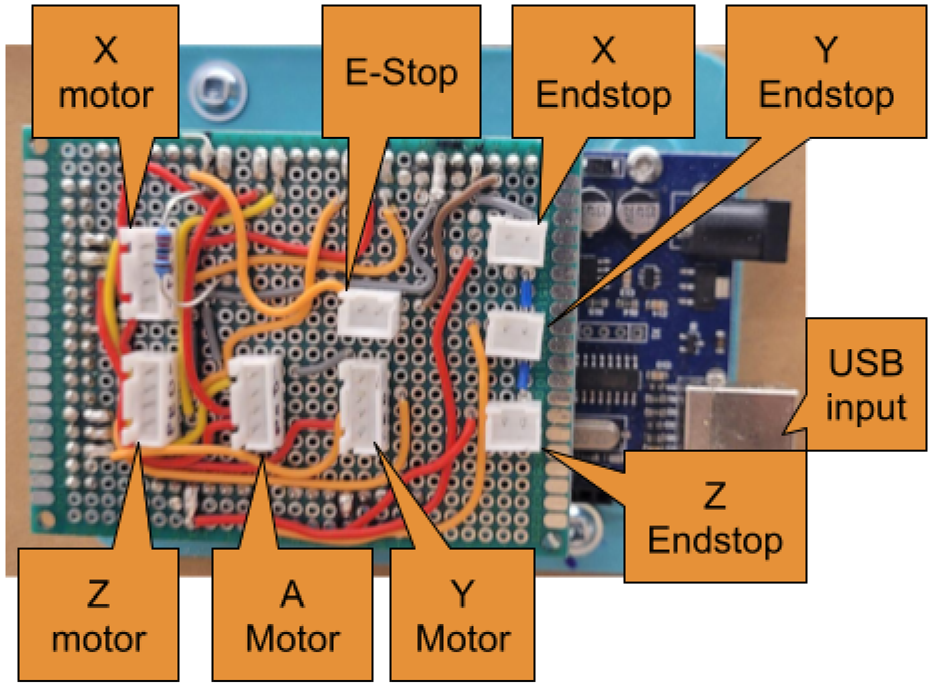


Figure 5.0.1 Pinout for Arduino Breakout board

These motor connectors have 4 pins: Ground, Pull (+), Eng (+), Dir(+). These go to the motor drivers input signals, and the negative signal is shared at the (-ve) side of each of the pull, eng, and dir ports. The endstops are simply connected to ground and when pressed send a ground signal to a digital arduino pin. These pins have built in (physical and software based) pullup resistors within the arduino which are activated by default through GRBL. This should be noted if any pin reassignment is necessary. The Estop port has a 22KΩ pullup resistor, and goes to a digital reset pin within GRBL. This was selected over an estop on the power to the machine for two reasons. The first is that the DC power supply has large capacitors which can continue to provide power to motors after AC power is cut. The second is that the system's inertia will allow it to continue to move even when power is cut. The software based E-stop will hold the motors which will provide active braking power against movement.

6.0 Software and control

This machine uses a fork of GRBL. The repository for this software can be found here:
https://github.com/fra589/grbl-Mega-5X

Although alternative GRBL versions can be used (such as GRBL HAL), this machine elected to use this as an Arduino Mega 2560 was on hand and this was a simple option.

6.1 What is GRBL and how do I use it?

GRBL is a firmware which runs on the arduino. It reads commands or 'G-code' directly and translates them to a series of signals sent to pre-defined pins on the arduino. These pins are then sent to motor drivers which translate the signals into a series of amplified pulses on each motor's sets of coils.

GRBL can run on a variety of processors. It was conceived for small, low power, cartesian machines, and is meant to run on an Arduino Uno. The version of GRBL being used on this machine is slightly more powerful and can control more motors since it uses the Arduino Mega's ATMEGA2560 chip rather than the Arduino Uno's ATMEGA328P chip.

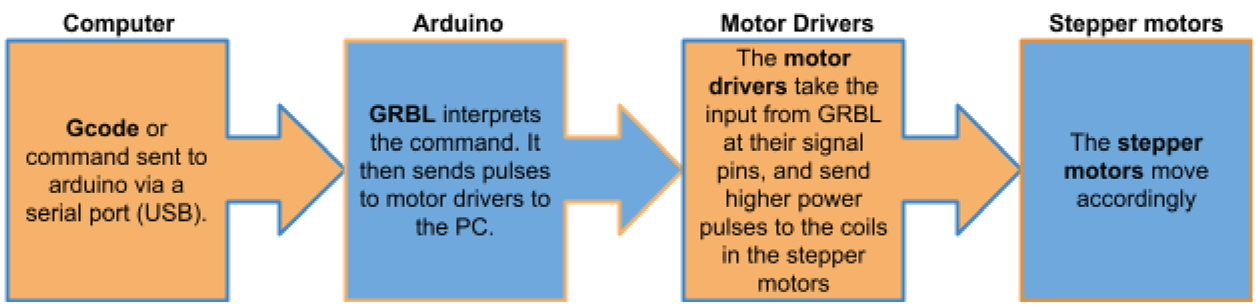


Figure 6.1.0 flow chart for signal transmission

6.2 How do I communicate with GRBL?

There are two distinct types of commands you can send to GRBL. Both require communication through a serial port. A 'G-code sender' can be used for ease as they often include macros which allow jogging of axes and testing of limit switches/e-stops. This project used a free program called Universal G-code Sender or UGS to send code, although one could use the arduino IDE serial port.

The first type of command one can send to GRBL is the obvious one: G-code. G-code is a simple way of communicating motion to the machine. An example of what G-code can look like is as follows.

G1	X	0	Y	0	Z	0	A	0	F	6000
G1	X	125	Y	20	Z	200	A	0	F	6000

Here the G1 states that the machine should move all axes at the defined feed rate in the F command rather than as fast as it can. The X,Y,Z, and A values define the location the machine is being asked to move to, on their respective axes. The F value is the aforementioned feedrate.

Not all G-codes are created equal. This machine interprets a very generic type of G-code, whereas other machines may require specific codes for some tasks. These machines would require an additional post processor to decipher the codes. The version of GRBL being used on this machine understands the following commands.

- Non-Modal Commands: G4, G10L2, G10L20, G28, G30, G28.1, G30.1, G53, G92, G92.1
- Motion Modes: G0, G1, G2, G3, G38.2, G38.3, G38.4, G38.5, G80
- Feed Rate Modes: G93, G94
- Unit Modes: G20, G21
- Distance Modes: G90, G91
- Arc IJK Distance Modes: G91.1
- Plane Select Modes: G17, G18, G19
- Tool Length Offset Modes: G43.1, G49
- Cutter Compensation Modes: G40
- Coordinate System Modes: G54, G55, G56, G57, G58, G59
- Control Modes: G61
- Program Flow: M0, M1, M2, M30*
- Coolant Control: M7*, M8, M9
- Spindle Control: M3, M4, M5
- Valid Non-Command Words: F, I, J, K, L, N, P, R, S, T, X, Y, Z, A, B, C

Notice there are some which will never apply to the winding machine such as spindle or coolant control as these (and GRBL itself) are more tailored to subtractive CNC machines.Some of the more common G-codes which you might choose to include in your toolpaths would be the following.

G0	This command is used to move the machine's tool to a specified position at the maximum speed (rapid motion) without regard for cutting operations. It's typically used for repositioning the tool between operations.
G1	G1 allows the machine to move in a straight line to a specified position at a controlled feed rate, typically used for actual cutting operations where precise movement is required.
G28	This command instructs the machine to return to its predefined home position (usually the machine's reference or origin point). It's often used as part of the setup or for safety during operation.
G30	Similar to G28, but the machine will return to an alternate home position (secondary home) instead of the primary home position. This can be useful for different tooling or safety requirements.
G54	G54 activates the first work coordinate system. This is used to define the "home" position relative to the part you're working on. There are other work coordinate systems (G55, G56, etc.) for different setups or parts.
G21	This sets the machine to interpret all distances and coordinates in millimeters (metric system). It's a key command for setting the proper units when programming in different systems of measurement.
G92	G92 allows you to set the current position of the machine as a specific value (like zero or a reference point). This is useful when you're not starting from the machine's home position and want to redefine the current position as a reference.

Table 6.2.0 Common G CODE commands

Sending G-code can be done by uploading it to a G-code sender or by sending it as text through the arduino IDE

The second type of code that can be sent are command and setting codes. GRBL recognizes a variety of such codes and this is a good way of adjusting settings without having to re-upload the firmware several times. Refer to the github for more complete documentation on these commands, but some relevant ones are as follows.

$$	Sends the list of modifiable settings such as steps per mm and others, this list should

	be periodically copied to a text document to preserve settings.
$HX	Homes the X direction. Can be used in conjunction with any other axis such as $HY for Y axis. Otherwise $H will initiate the homing feature which homes X, Y and Z.
$!	Feed hold. Stops the movement of all motors
$?	Query endstops
$X	Unlocks the axis if they were not yet homed
$	Help

Table 6.2.1 Common GRBL commands

6.3 Uploading and modifying firmware

There will certainly be a time when modifications to the firmware are required. Luckily this process is simple. Grbl is separated into a number of files. These can be edited to achieve different functions. The existing version of GRBL CAN NOT BE RECOVERED from the arduino. Therefore it is imperative that the most recent firmware version be kept so that no one needs to start from scratch if an arduino dies or changes are needed. Of the files in GRBL, the ones most commonly edited are the following:

Config.h	The majority of the settings on the machine are edited here. These include axis naming, homing sequences, and limit switches. This config file can also be transferred to a different version of GRBL and will work on different CPUs
cpu_map.h	This essentially ties the commands to the specific pins on the ATMEGA2560 processor. This is all register level programming,
defaults.h	This stores the default machine parameters such as speeds and feeds. Though they are also stored in EEPROM, when a long term change is made it's best to include it here.

Table 6.3.0 Common GRBL files to modify

Uploading GBL to the arduino is relatively simple once the edits have been made to the files on your local computer, follow these steps to upload them.

1) Connect the arduino via USB
    a) Make sure the processor is an ATMEGA 2560 or this will not work

2) Open the arduino IDE, and add a new library from the ZIP file.
3) Compress the GRBL folder to a zip.
    a) The other folders which are in the files you download when getting GRBL from the github are just documentation and don't need to be on the arduino. Only zip the file called 'grbl'
4) Select the zipped GRBL file to add it as an arduino library.
    a) If you have uploaded a GRBL before this will give you an error as you can't reupload the same library twice. To fix this:
        i) Documents > arduino > libraries then manually delete the old GRBL library
        ii) Restart the IDE and go back to step 2
5) Then go to the examples tab and there will be a new option under 'grbl' called 'GRBL upload'. Open this example
6) Upload the example to the arduino.
7) The new GRBL is now running on the arduino. Proceed as normal.

6.4 Writing GCODE:

The 2025 capstone team did not develop the winding process itself. The development of the winding process will require the development and use of softwares capable of generating complex GCODEs for different geometries. However, to prove the useability of the machine, this team did develop a preliminary parametric cylinder winding GCODE generator. Figure 6.4.0 shows the input portion of this page.

Motor Side position	Y	0	Mandrel spin degrees at ends	Deg:	690
Far Side position	Y	870	Mandrel spin degrees along length	Deg:	1500
Z position Outside:	Z	92			
Z position inside:	Z	150			
X position while moving to motor	X	45			
X position while moving from motor	X	180			
Feed speed:	F	20000			

Figure 6.4.0 parameters for spreadsheet based cylinder winding GCODE generator

The parameters here can be set through experimentation. The Y and Z coordinates can be set by moving the machine to the extremities of the cylinder and registering its coordinates. Then input them into the spreadsheet which will generate a winding pattern. This was used to wind the 3d printed mandrel liner (a 1:1 scale 3D printed replica of the combustion chamber and nozzle), and it was wound with modest success. A more complicated tool path would be needed for better winding. Once the parameters are set, the processed GCODE can be copied and pasted into UGS and should be preceded by the following three statements.

G28 – return to home position (moves Z first)

G90 – absolute coordinates

G20 – set units to mm

	A	B	C	D	E	F	G	H	I	J	K
1	G1	X	180	Y	0	Z	0	A	0	F	20000
2	G1	X	180	Y	0	Z	92	A	0	F	20000
3	G1	X	180	Y	870	Z	92	A	1500	F	20000
4	G1	X	180	Y	870	Z	150	A	1500	F	20000
5	G1	X	45	Y	870	Z	150	A	2190	F	20000
6	G1	X	45	Y	870	Z	92	A	2190	F	20000
7	G1	X	45	Y	0	Z	92	A	3690	F	20000
8	G1	X	45	Y	0	Z	150	A	3690	F	20000
9	G1	X	180	Y	0	Z	150	A	4380	F	20000
10	G1	X	180	Y	0	Z	92	A	4380	F	20000
11	G1	X	180	Y	870	Z	92	A	5880	F	20000
12	G1	X	180	Y	870	Z	150	A	5880	F	20000
13	G1	X	45	Y	870	Z	150	A	6570	F	20000
14	G1	X	45	Y	870	Z	92	A	6570	F	20000
15	G1	X	45	Y	0	Z	92	A	8070	F	20000
16	G1	X	45	Y	0	Z	150	A	8070	F	20000

Figure 6.4.1 Example of Spreadsheet generated GCODE

6.5 Default Configuration

Should the configuration be lost or a new version of GRBL be installed, the default parameters may not be retained. The following are the parameters tested to be functional. These can be modified, but should serve as a baseline. Note that this is the response to the '$$' prompt.

```
$0 = 10         (Step pulse time, microseconds)
$1 = 254        (Step idle delay, milliseconds)
$2 = 0 (Step pulse invert, mask)
$3 = 2 (Step direction invert, mask)
$4 = 0 (Invert step enable pin, boolean)
$5 = 0 (Invert limit pins, boolean)
$6 = 0 (Invert probe pin, boolean)
$10 = 0         (Status report options, mask)
$11 = 0.020     (Junction deviation, millimeters)
$12 = 0.002     (Arc tolerance, millimeters)
$13 = 0         (Report in inches, boolean)
$20 = 0         (Soft limits enable, boolean)
$21 = 1         (Hard limits enable, boolean)
$22 = 1         (Homing cycle enable, boolean)
$23 = 7         (Homing direction invert, mask)
$24 = 200.000           (Homing locate feed rate, mm/min)
$25 = 1690.000          (Homing search seek rate, mm/min)
$26 = 250       (Homing switch debounce delay, milliseconds)
$27 = 20.000    (Homing switch pull-off distance, millimeters)
$30 = 12000     (Maximum spindle speed, RPM)
$31 = 550       (Minimum spindle speed, RPM)
$32 = 0         (Laser-mode enable, boolean)
$100 = 230.000          (X-axis travel resolution, step/mm)
$101 = 42.000           (Y-axis travel resolution, step/mm)
$102 = 168.070          (Z-axis travel resolution, step/mm)
$103 = 74.000
$110 = 8500.000         (X-axis maximum rate, mm/min)
$111 = 16900.000        (Y-axis maximum rate, mm/min)
$112 = 10000.000        (Z-axis maximum rate, mm/min)
$113 = 16900.000
$120 = 69.000           (X-axis acceleration, mm/sec^2)
$121 = 100.000          (Y-axis acceleration, mm/sec^2)
$122 = 100.000          (Z-axis acceleration, mm/sec^2)
$123 = 200.000
$130 = 360.000          (X-axis maximum travel, millimeters)
$131 = 1420.000         (Y-axis maximum travel, millimeters)
$132 = 220.000          (Z-axis maximum travel, millimeters)
$133 = 2147483.648
```

7.0 Operations procedures

The machine is complex and requires vigilance to ensure safety and proper operation. Although this team did not get to the point of wet winding, the machine operation will be as follows:

1) Assemble the machine as per section 3.0.
2) Jog the axis and home the machine before starting to make sure everything behaves as expected
3) Confirm the G CODE intended for use is operational by uploading a small amount and examining the behaviour
4) Use '$$' to verify that the hard and soft limits are enabled and that the G CODE will not send the machine out of bounds.
5) Run the carbon fiber tow through the eyelets, through the tensioning system and out the delivery head. Secure it to the spit.
6) Add mixed resin to the resin bath.
7) Start the G-code making sure the e-stop is accessible at all times in case of emergency.
8) Begin the winding process, pausing whenever manual adjustments are needed.