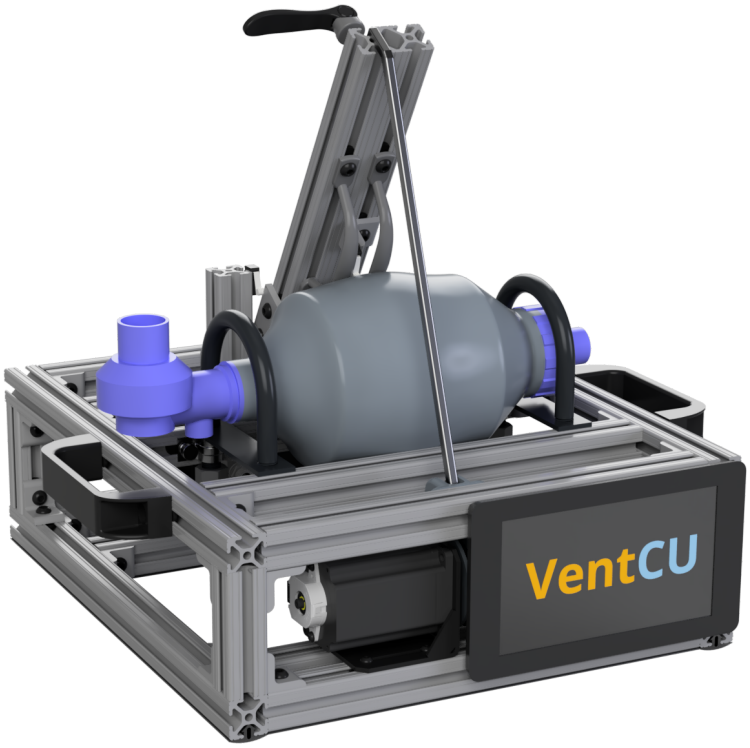
VENTCU

USER MANUAL



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Intended Use

VentCU functions by automating the compression of an Ambu-bag manual resuscitator (which are widely available and stocked in medical facilities). Built from a rigid 80/20 aluminum extrusion frame, a sprung arm is pulled down by a simple rope and pulley system to compress the Ambu-bag. Breaths per minute, tidal volume and inspiration to expiration ratio are set and monitored on a user friendly touch screen controlled by a Raspberry Pi. The system is designed to operate as reliably and safely as possible, including sensing capabilities for alarm condition detection.

Assuming all parts are bought new, a fully functional device costs under $1,000, a fraction of the cost of any ventilator currently available on the market, allowing for rapid production and mass adoption. All components are immediately available from multiple vendors in large quantities. Furthermore, these components are likely in stock in many hobbyist, hardware store, and student robotics team inventories, and such local organizations can be engaged to help provide hardware, skilled labor, and troubleshooting capabilities.

VentCU is fully open source and built to be as modular and modifiable as possible to accommodate a wide range of use cases and available components.

VentCU does not hope to replace conventional ventilators available on the market; it aims to meet the direct requests of medical professionals who may be struggling to find ventilators. This device is intended for use in **emergency** situations as a **temporary** solution.

Features

Device Frame

VentCU, with its compression arm folded down, occupies a footprint of 14" x 15.5" x 6" and weighs approximately 14 pounds. The frame of the ventilator is designed entirely from 80/20 aluminum extrusion. This robust and versatile material is commonly available to buy in large quantities, and can easily be substituted with other extrusion types that support T-nuts. The entire frame is assembled with angle brackets and hex head bolts, allowing construction with a single Allen key. The Ambu-bag slots between two beams of 80/20 extrusion, 4" apart, and is secured using two U-bolts that can easily be raised and lowered with thumbscrews to switch bags. The U-bolts can be adjusted back and forth, as well as up and down, to ensure a secure fit for a variety of Ambu-bags. Two handles on the sides allow for easy transportation.

Compression Arm

The hinged compression arm consists of an 80/20 aluminum extrusion and is pulled down using a rope to compress the Ambu-bag. An eyebolt at the bottom of the arm secures the end of the rope in position.

The end effector of the arm approximates a crescent shape to compress the Ambu-bag without sharp edges, mimicking compression by a human hand as to avoid shortening the lifespan of the bag. This is accomplished with a set of two eccentrically crescent-shaped door handles. An extension spring attached between the back of the arm and the frame of the device allows the arm to passively hinge back to its original position.

This design, centered around a single moving arm, was chosen because it delivered tidal volume most consistently (close to linear), was easily integrated into a COTS solution, and maximized mechanical advantage.

The compression arm is able to fully hinge horizontally, compressing the Ambu-bag completely. This easily accomplishes the desired amplitude range of 0 to 6 inches of compression, as well as the tidal volume requirement of 200 to 800 mL specified by consulting medical professionals.

Motor Selection

VentCU's actuation is powered by a bipolar NEMA 23 stepper motor with a built-in encoder, 1.95 N-m (276 oz-in) of holding torque, 1.8° step angle, and 200 steps per revolution. It draws 2.8 A under full load and is rated to run at 12 V, producing up to 34 W of power. To safely ensure that the motor does not fail under continuous usage, this amount of power is 6W greater than the required amount of 28W. A timing pulley with a pitch diameter of 1.5" is affixed to its output shaft, providing an output tension force of 200 N (45 lbf) on the rope pulling down the arm.

Though our selected stepper motor meets the calculated specifications (which can be found here: https://coda.io/@maker/ventcu/mechanical-specifications-9), and is widely available in large quantities, many other motors which meet the power and torque requirement along with a mounting bracket can replace the motor. The simplicity of the mechanical system means a DC gear motor, a high powered servo, or an alternative stepper motor could be easily retrofitted to the design.

Control Panel

VentCU has three primary parameters that can be set by an attending clinician via the control panel:

1. Breaths per minute (BPM)
2. Tidal volume (TV)
3. Inspiration to expiration ratio (I:E)

The control panel consists of a touch screen that connects via ribbon cable from the screen to a Raspberry Pi microcontroller. This means no soldering is required on this connection. Both the Raspberry Pi and touch screen are available in mass.

The clinician can then set the BPM, TV and I:E parameters via the screen with a simple user interface. The parameters are then shown on the touch screen along with live readouts of Peak Inspiratory Pressure, Plateau Pressure, and PEEP. The touch screen allows more parameters, more complex flow profile control, or more detailed sensor readouts to be added later if desired.

Power Supply

A 12V 5A power supply is used to power the device. The Raspberry Pi can be powered with a step down voltage converter or a simple USB wall adapter.

Alarms

There is a need for loud alarms when patients occupy isolated rooms. In the event of a fault, an alarm will be triggered alerting attending personnel. We utilize an alarm that can reach 85 decibels, so help can be notified quickly. Additionally, the touchscreen displays "ALARM", and corresponding information to the specific alarm condition. The alarm can be silenced by tapping and confirming a corresponding button on the touch screen.

The following chart shows the alarm conditions, how they are detected, and the response taken by the device.

Alarm Condition	Condition Detected	Response
LOW PRESSURE	Pressure lower than expected (possible airway disconnect)	Maintain operation and sound auditory alarm. Error cleared with onscreen confirmation.

HIGH PRESSURE	Pressure above tolerable threshold (when Ambu-bag pressure release valve opens)	Maintain operation and sound auditory alarm. Error cleared with onscreen confirmation
POSITION ERROR	Stepper driver error or unexpected position/velocity value reported (possible sensor fault or mechanical interference)	Trigger Rehoming procedure on next Expiratory Pause. If error persists, sound auditory alarm. Error cleared with onscreen confirmation and successful Rehoming
SYSTEM FAULT	Erroneous behavior detected with controller, stepper driver or sensors (possible electrical fault, overheat, etc.)	"System Fault" message is displayed with specific fault information and sound auditory alarm sounds. Error cleared with onscreen confirmation and correction of fault
HOMING FAULT	Homing or Rehoming procedure fails (i.e. unexpected limit switch or position values)	System re-attempts Homing procedure. "Homing Fault" message displayed upon subsequent failure with auditory alarm. Error cleared with onscreen confirmation and successful Rehoming.

The alarm will sound for a variety of error and alarm conditions such as leak detection or lack of confirmation for parameter changes, and more detailed descriptions can be found in the ‘User Interface’ section.

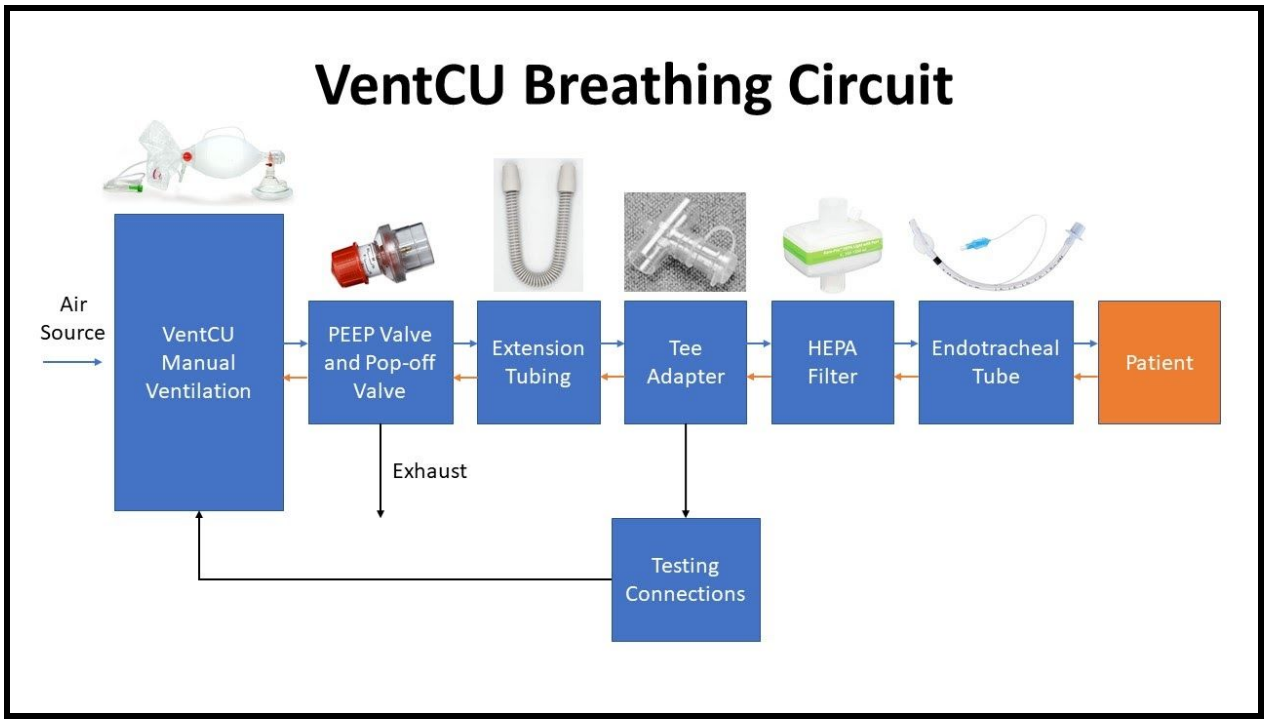
Sensing Capabilities

- **Encoder:** The encoder measures motor position for accurate control of Ambu-bag compression.
- **Absolute Limit Switch:** A limit switch is positioned on the ventilator frame, and is activated when the hinged arm reaches its uppermost position. The arm reaches a maximum angle corresponding to an Ambu-bag size diameter of 7.5'', so that even very large bags are compatible with the design.
- **Contact Limit Switch:** A second limit switch is stationed on the compression arm so that it is activated when in contact with the Ambu-bag.
- **Pressure Transducer:** The transducer measures the pressure and flow rate of the system.

The clinician can modify ventilation by specifying respiration rate, inspiratory:expiratory ratio, and tidal volume. Peak pressure, plateau pressure and PEEP are detected throughout the breathing cycle by the pressure transducer. Both limit switches are used when homing the ventilator to set it’s absolute position, and the contact limit switch is used to verify the homing over time to ensure that encoder readings maintain accuracy.

Plumbing and Gas Connections

The plumbing of VentCU is fully composed of common breathing connectors, many of which are interchangeable with other similar parts. This device is meant to run completely off of room air, meaning that no oxygen source is required to supply the patient. However, it is capable of using a gas source if such resources are available. The following diagram provides an overview of our recommended breathing circuit setup.



Basic Diagram of the Breathing Circuit

- The first connection starts with a **PEEP Valve** and **Pop-off Valve**, which are typically included with a standard Ambu-bag.
- **CPAP extension tubing** is then used to lengthen the distance between the device and the patient.
- A suitable **tee adapter** is then used to connect the extension tubing and HEPA filter, as well as to provide an opening for testing connections. In our case, we connected a **pressure sensor** on the testing end of the tee adapter.
- After the HEPA filter is connected to the end of the tee adapter, an **endotracheal tube** is directly attached from the filter to the patient. This is the general order in which VentCU's breathing circuit is arranged.

Depending on the sizing of each individual connection, fittings may be required to couple each section together. This is especially relevant for the testing connection, which can vary based on the pressure/flow sensor used.

Safety Precautions

VentCU is controlled in an intelligent manner to best mitigate three basic causes of lung trauma (oxygen trauma cannot be accounted for with VentCU's current design):

1. **Volume Trauma:** the correct volume of air must be delivered to the lungs within a small range of precision to avoid exceeding the lung's intrinsic capacity (which can and does change rapidly throughout COVID-19's progression)
2. **Pressure Trauma:** the delivered breaths must not exceed some pressure, determined by the lung's current compliance, which can damage the lung, so the speed of delivered inhalations must be finely adjustable
3. **Pneumothorax (collapse of the lung):** positive end-expiratory pressure (PEEP) must be maintained as to avoid the collapse of the lung's alveoli

This device's design is able to avoid these dangers with fine control of the three aforementioned flow profile parameters: breaths per minute (BPM), tidal volume (TV), and inspiration to expiration ratio (I:E) in combination with the Ambu-bag's inbuilt PEEP and pop off valves. Some medical facilities may not have access to gas mixing equipment, and in these cases, running the ventilator off of room air is adequate in an emergency situation.

The primary method of leak detection is via a pressure sensor, connected between the Raspberry Pi and the Ambu-bag's sensing port within the airflow, preferably as close to the patient as possible. If plateau pressure falls below a predefined, controllable value (such as 5 cm H2O), the alarm will be triggered. This device currently only supports continuous mandatory ventilation (CMV), in which an ambu-bag is compressed in order to supply air to a fully sedated, intubated patient. Ventilation parameters are fixed and do not adjust according to the patient's condition or intention to inspire or expire manually.

VentCU is meant for use with an endotracheal tube, which is directly connected to the patient's airway. VentCU is not designed for operation via a face mask**.**

Transport

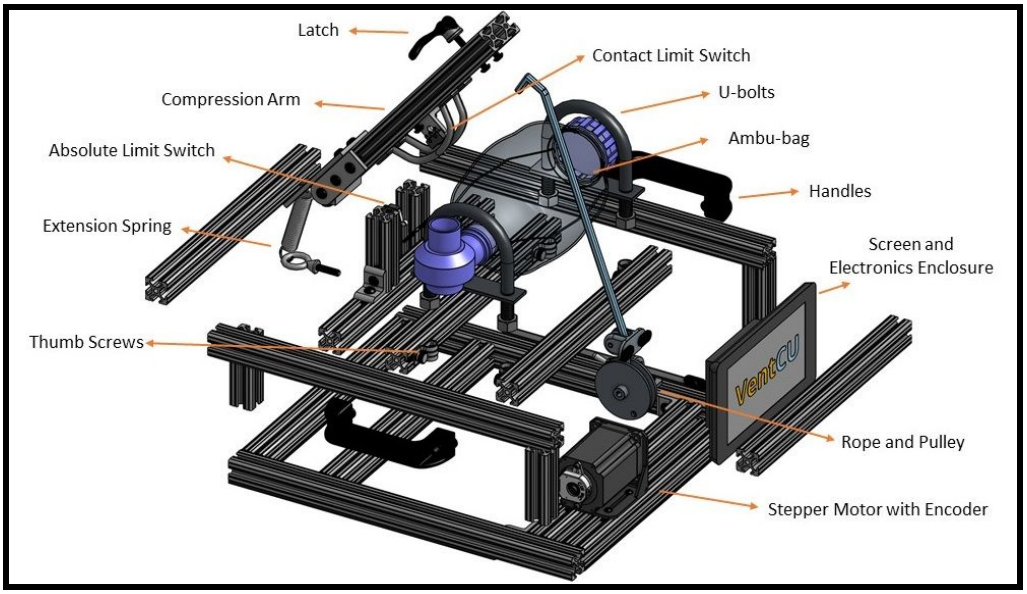
When transporting VentCU, the device should ONLY be held by the two handles on the sides. Do not hold it by the aluminum extrusion frame, U-bolts, or compression arm.

Power Supply

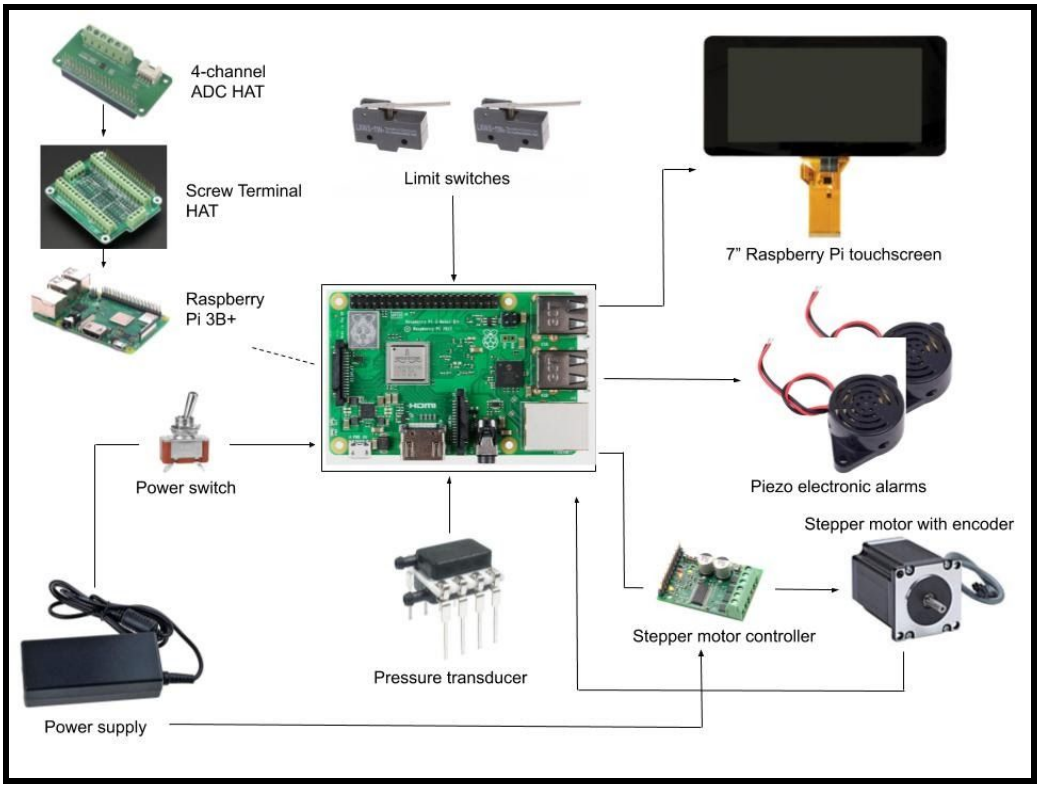
This device is only meant to connect to a standard US 120VAC/60Hz outlet. Using this device with any other power source can cause the device to malfunction or become damaged.

Always pull the power cord from any AC outlet by the plug itself. Place the power cord so that nobody can step on it or trip over it, as this can cause damage to both the device and its surroundings.

Technical Specifications



Exploded Mechanical Diagram



Basic Electrical Diagram

Physical Characteristics

Max Footprint (L,W.H): 14" x 15.5" x 17" / 356 x 394 x 432 mm
Touch Screen Size: 6.1” x 3.4” / 155 x 86 mm
Weight: 14 pounds / 6.4 kg
Noise Level: 60-70dB (Operating) / 85dB (Alarm)
Supported Languages: English

Operational Specifications

Respiratory Rate: Up to 25 BPM for 1:1 I:E Ratio, 17 BPM for 1:2, 13 BPM for 1:3, and 10 BPM for 1:4
Tidal Volume Range: 200 to 800 mL
I:E Ratios: 1:1, 1:2, 1:3, 1:4
Inspiratory Pressure (PI): Maximum 60 cmH_2O
Positive End Expiratory Pressure (PEEP): 5-20 cmH_2O
Compatible Ambu-bag sizes: 4 - 8” / 102 - 203 mm

What’s Needed to Run the Ventilator

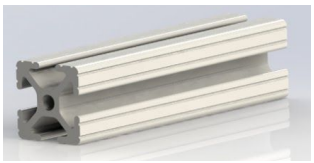
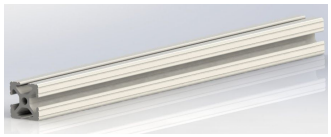
Rated For and Tested With 120V 60Hz Standard US Input
Compatible Ambu Bag
Oxygen Source (Optional)
Internet Connection for Device Setup (Optional)

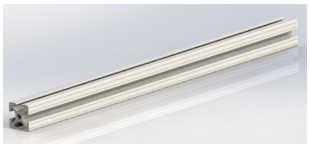
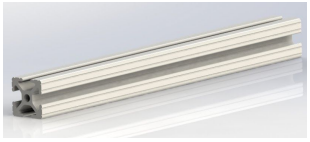
Tools Required

Tool Name	Reference
⅛” Allen Key	
Soldering Iron	
Double-Sided Tape	
Flat-head Screwdriver	

Tool Name	Reference
Ruler	
Scissors	
Power Drill with 3/32 to 1/4 Drill Bit	

Mechanical Components

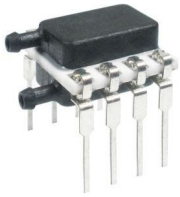
Part Code	Part Name	Quantity	Reference
M-1	80/20 Extrusion (4”)	5	
M-3	80/20 Extrusion (12”)	8	
M-5	¼-20 Button Head Screw 0.500” and T-Nut	25	
M-7	#10-32 Button Head Screw 0.375”	100	
M-9	#8-32 Button Head Screw 0.375” and T-Nut	15	
M-11	6’ T-Slot Antislip Cover	5	
M-13	¼-20 x 0.500” FHSCS and Roll-In T-Nut with Flex Handle	4	

Part Code	Part Name	Quantity	Reference
M-2	80/20 Extrusion (15.5”)	4	
M-4	80/20 Extrusion (10.5”)	1	
M-6	#10-32 T-Nut	100	
M-8	Frame L-Bracket	50	
M-10	T-Slot Plastic Handles	2	
M-12	Stainless Steel Hinge	1	
M-14	Pivot for Double 80/20 Rail	1	

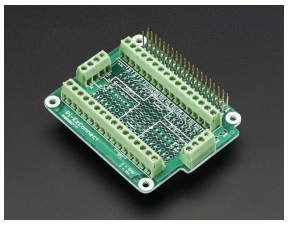
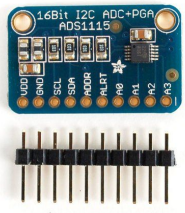
M-15	Door Handle	2	
M-17	#8-32 Flared Knurled Thumb Screw	4	
M-19	0.500” ID Routing Clamp	50	
M-21	Steel Eyebolt with Shoulder	2	
M-23	Power Switch Mounting Bracket	1	
M-25	Alloy Steel Socket Head Screw 3-48, 0.500” Long	100	
M-27	1.9mm Spectra Rope	1	

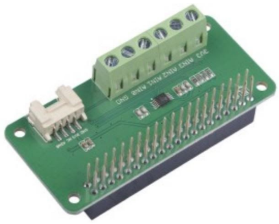
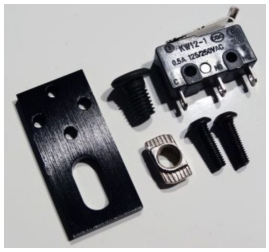
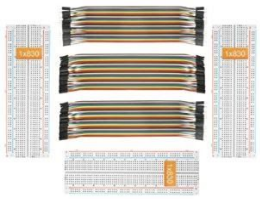
M-16	3” Extension Spring	3	
M-18	U-Bolt with Mounting Plate	2	
M-20	22T XL Acetal Timing Pulley	1	
M-22	8” Zip Tie	100	
M-24	T-Slotted Framing	1	
M-26	Zinc-Plated Steel Hex Nut 3-48	100	
M-28	NEMA 23 Steel L-Bracket (With 4 M4 Screws and Nuts)	1	

Electrical Components

Part Code	Part Name	Quantity	Reference
E-1	Stepper Motor Controller	1	
E-3	Pressure Transducer	1	
E-5	Screen Enclosure	1	
E-7	Stepper Motor with Encoder	1	
E-9	Raspberry Pi 3B+	1	
E-11	Alarm	2	

Part Code	Part Name	Quantity	Reference
E-2	Power Switch	1	
E-4	7” Touchscreen (and included add-ons)	1	
E-6	Micro-USB to USB-A	2	
E-8	Encoder Cable	1	
E-10	Assorted Wire	N/A	
E-12	12V Power Supply	1	

E-13	Breakout HAT	1	
E-15	18AWG Wire	1	
E-17	12V to Micro USB Power Source	1	
E-19	USB-A Male to Female	1	
E-21	ADS1115 4-channel ADC with header	1	

E-14	Power Splitter	1	
E-16	16GB MicroSD Card	1	
E-18	16-Bit ADC for Raspberry Pi	1	
E-20	Limit Switches and Brackets	2	
E-22	Breadboard with Connectors	1	

Plumbing Components

Part Code	Part Name	Quantity	Reference
P-1	CPAP Extension Tube	1	
P-3	Ambu-Bag with PEEP Valve (4”-8” diameter)	1	

Part Code	Part Name	Quantity	Reference
P-2	Sensing Tube	1	

Assembly Instructions

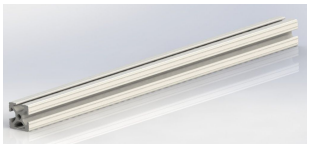
Step 0: Pre-assembling Bracket Assemblies

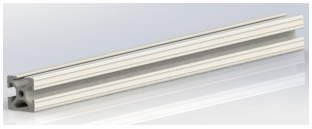
Part Code	Part Name	Quantity	Reference
M-7	#10-32 Button Head Screw 0.375”	22	
M-6	#10-32 T-Nut	22	

Part Code	Part Name	Quantity	Reference
M-8	Frame L-Bracket	18	

0.1) 40 **bracket assemblies** are required to fasten the assembly. Each “bracket assembly” has an L-bracket (Digikey 4337 __), two #10-32 bolts, and two #10-32 T-Nuts. Insert bolts on the inward facing sides of the L-bracket and loosely fasten nuts on the outward facing sides. See the image below for an example of a bracket assembly.

Step 1: Bottom Frame Assembly

Part Code	Part Name	Quantity	Reference
M-2	80/20 Extrusion (15.5”)	2	
M-5	¼-20 T-Nut	1	
M-7	#10-32 Button Head Screw 0.375”	22	
M-9	#8-32 Button Head Screw 0.375” and T-Nut	4	

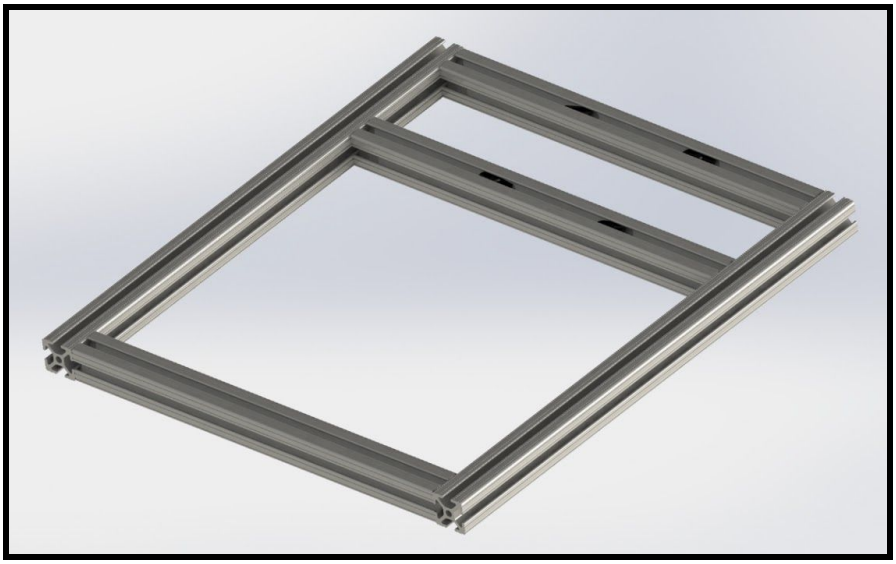
Part Code	Part Name	Quantity	Reference
M-3	80/20 Extrusion (12”)	4	
M-6	#10-32 T-Nut	23	
M-8	Frame L-Bracket	18	
M-21	Steel Eyebolt with Shoulder	2	

1.1) Align the 2x 15.5” extrusion pieces lengthwise and 3x 12” extrusion pieces perpendicular to and in between the long pieces.

1.2) On the first 12” piece facing you, insert 2x #8-32 T-Nuts on the up-facing side, and on the second 12” piece, insert 2x bracket assemblies **but modified with #8-32 hardware**, meaning that the #10-32 button head screw and t-nut are replaced with #8-32 sized parts.

1.3) On the last 12” piece , insert a ¼-20 T-Nut on the side facing forwards.

1.4) Insert a #10-32 T-Nut on the left 15.5” extrusion piece to prepare for switch mounting at a later step.



1.5) Fasten 2x bracket assemblies at each corner of the frame, so that a 1” x 1” space is left open for the uprights to be inserted. The side of the bracket assemblies with a T-Nut should be facing inwards, towards the open space. Fasten the bracket assemblies to hand tightness, just so that they stay in place. For reference, see the following image:

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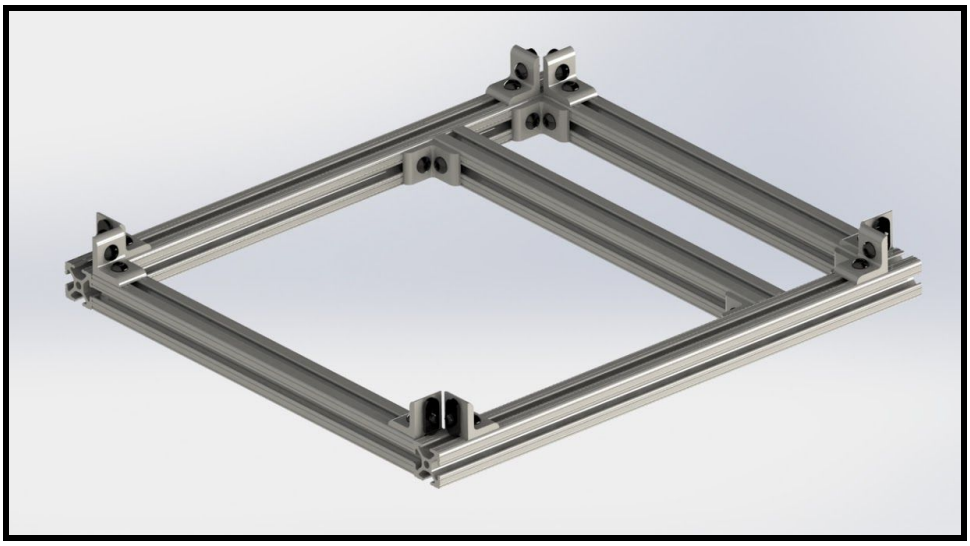
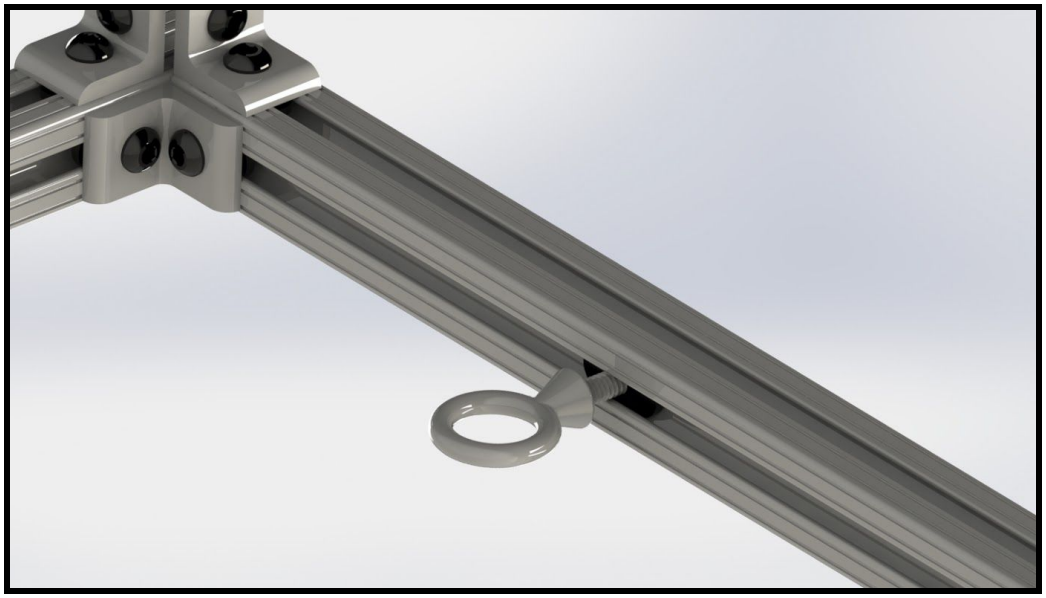


1.6) Attach eyebolt to the ¼”-20 T-Nut in the last 12” extrusion piece.



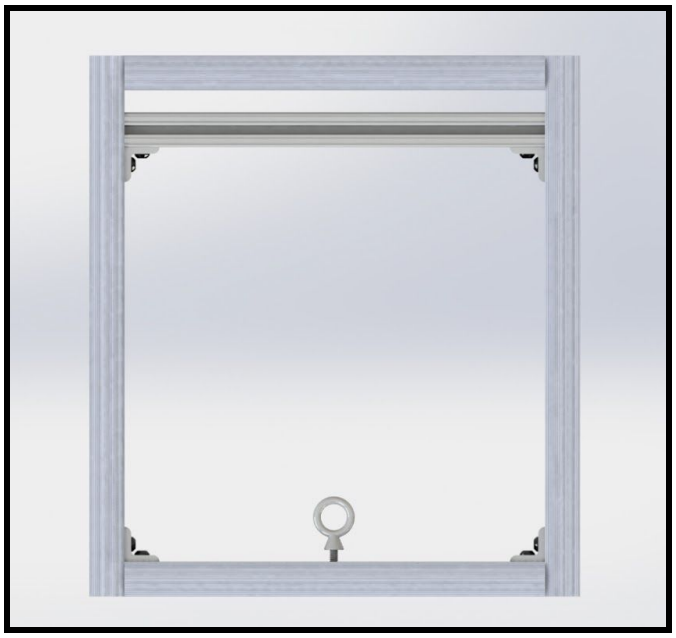
Step 2: Rubber Tread Attachment

Part Code	Part Name	Quantity	Reference
M-11	6’ T-Slot Antislip Cover	5	

2.1) Measure and cut out 2x 12” strips (Combine multiple strips if necessary).

2.2) Measure and cut out 2x 15.5” strips.

2.3) Insert the strips into the bottom of the outer 4 perimeter pieces of the bottom frame.



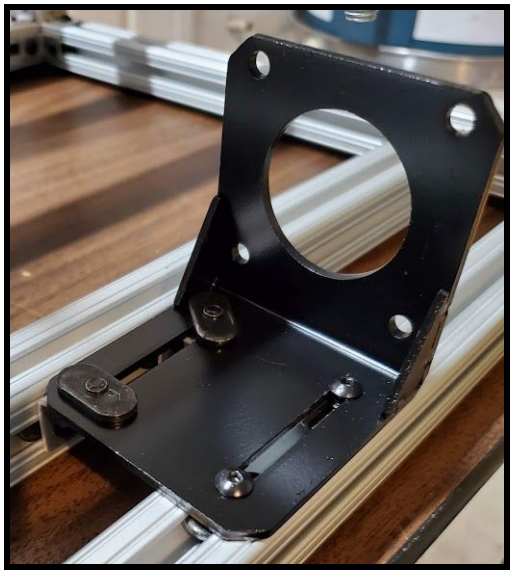
Step 3: Motor Mounting

Part Code	Part Name	Quantity	Reference
M-9	#8-32 Button Head Screw 0.375” and T-Nut	3	
E-7	Stepper Motor with Encoder	1	

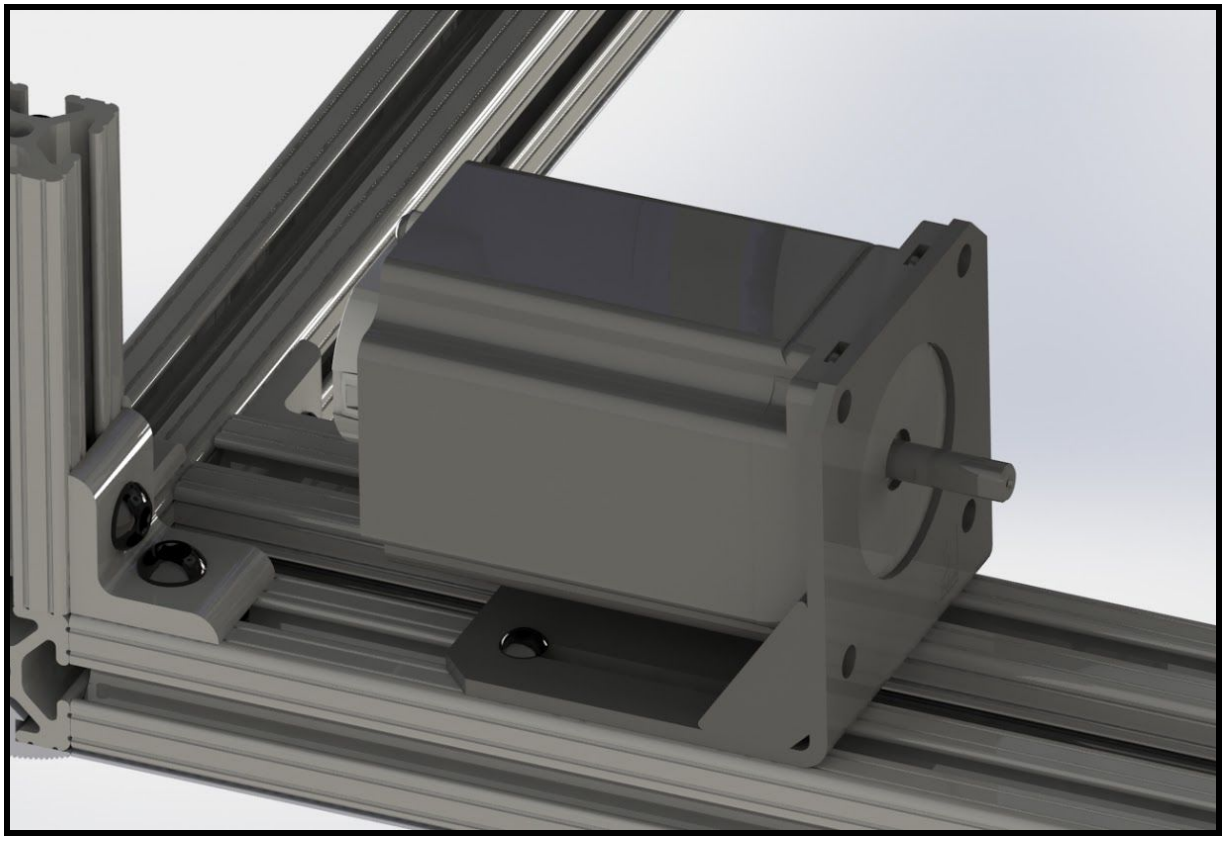
Part Code	Part Name	Quantity	Reference
M-28	NEMA 23 Steel L-Bracket (With 4 M4 Screws and Nuts)	1	

3.1) Screw bracket in place with 4x #8-32 bolts. On the first 12” Extrusion Piece screw 2x #8-32 bolts through the ends of the first slot of the NEMA 23 L-Bracket into the #8-32 T-Nuts previously placed in the extrusion.

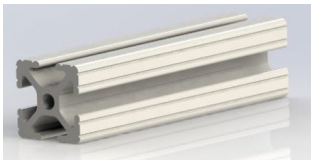
3.2) Screw #8-32 bolts through the second slot of the NEMA 23 L-Bracket into the previously attached #8-32 modified L-bracket assemblies, on the other 12” Extrusion Piece. The following image shows how the motor bracket was secured.



3.3) Screw motor in place with M4 nuts and bolts.

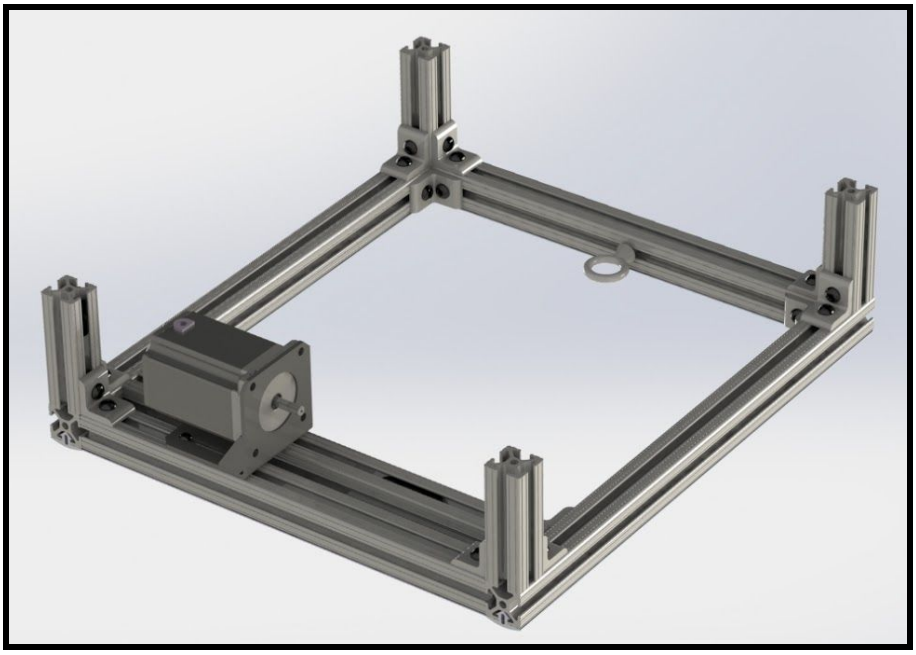


Step 4: Uprights

Part Code	Part Name	Quantity	Reference
M-1	80/20 Extrusion (4”)	4	
M-7	#10-32 Button Head Screw 0.375”	16	

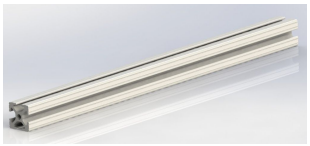
Part Code	Part Name	Quantity	Reference
M-6	#10-32 T-Nut	16	

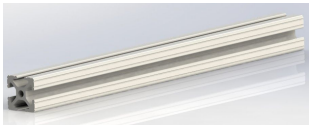
4.1) Slide the 4” extrusion pieces vertically through the T-Nuts of the bracket assemblies at the four corners of the frame, so that there is standing piece at each corner of the frame. Ensure that the 4” extrusion pieces are aligned with the frame. Then, fasten the #10-32 screws. See image for reference.



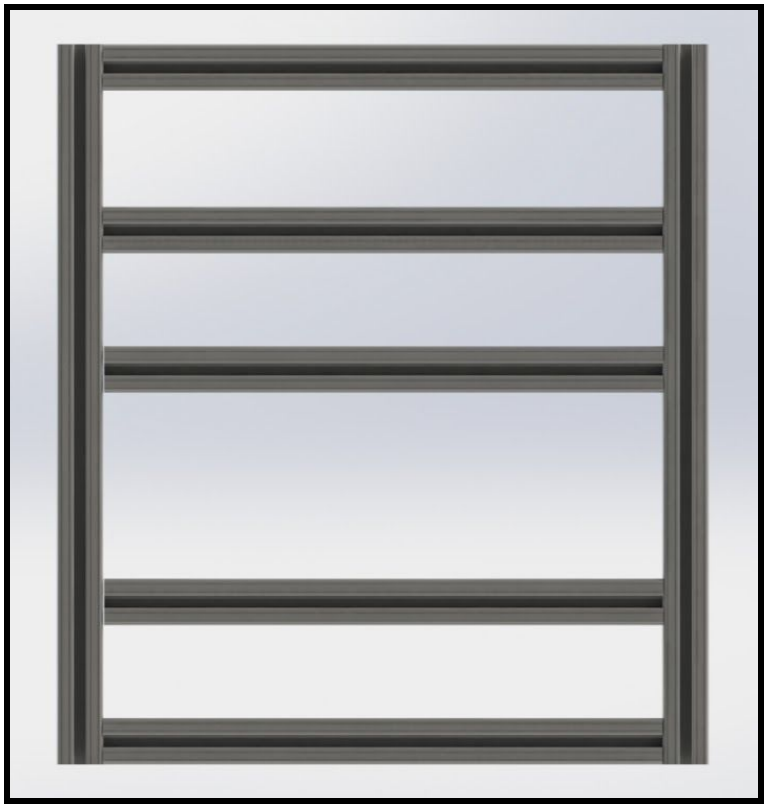
4.2) To prepare for connection with the top, slide a bracket assembly down each of the two inward-facing sides of each 4” extrusion piece.

Step 5: Top Assembly and Connection

Part Code	Part Name	Quantity	Reference
M-2	80/20 Extrusion (15.5”)	2	
M-5	¼-20 Button Head Screw 0.500” and T-Nut	4	
M-7	#10-32 Button Head Screw 0.375”	47	
M-9	#8-32 Button Head Screw 0.375” and T-Nut	6 T-Nuts and 2 Screws	
M-17	#8-32 Flared Knurled Thumb Screw	4	
M-20	22T XL Acetal Timing Pulley	1	

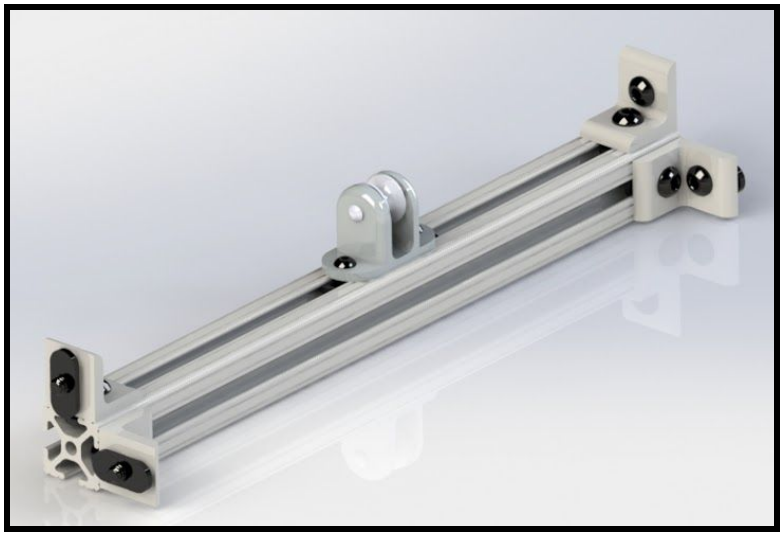
Part Code	Part Name	Quantity	Reference
M-5	80/20 Extrusion (12”)	8	
M-6	#10-32 T-Nut	47	
M-8	Frame L-Bracket	8	
M-10	T-Slot Plastic Handles	2	
M-19	0.500” ID Routing Clamp	4	

5.1) To prepare for assembly of the top frame, set up 2x 15.5” side extrusion pieces, like the top frame. Then, lay 5x 12” extrusion pieces in between. Each of these 12” extrusion pieces will require some isolated assembly before putting the whole top frame together.

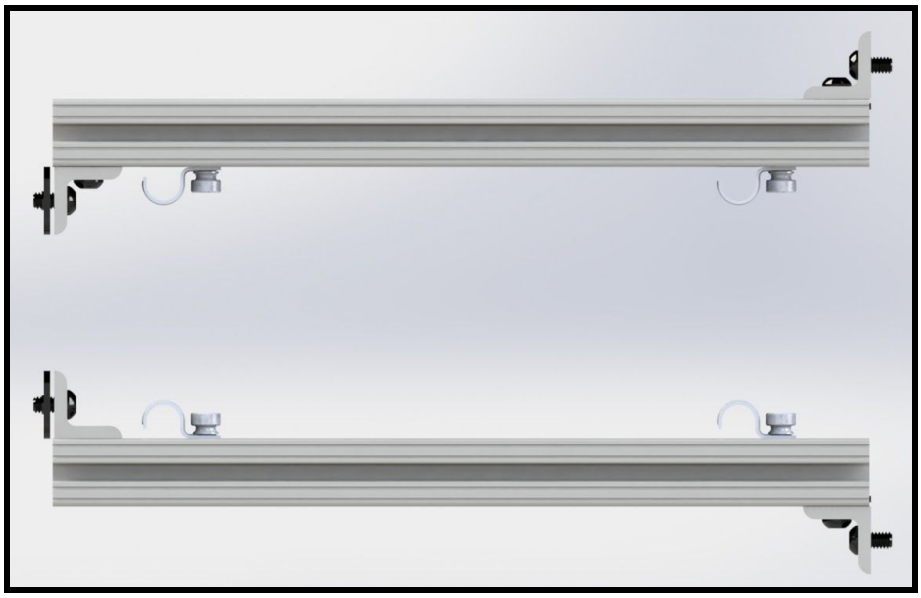


5.2) Slide in 2x ¼”-20 T-Nuts down each of the outward facing sides of the 15.5” long pieces. Fasten the Plastic Handles with ¼”-20 bolts (bolt head may be a tight fit through the counterbore, press firmly to get through), and keep the handles centered at around 7.75”.

5.3) On the first extrusion piece facing you, loosely fasten 2x bracket assemblies: one on each end, on the inward facing side (away from you).

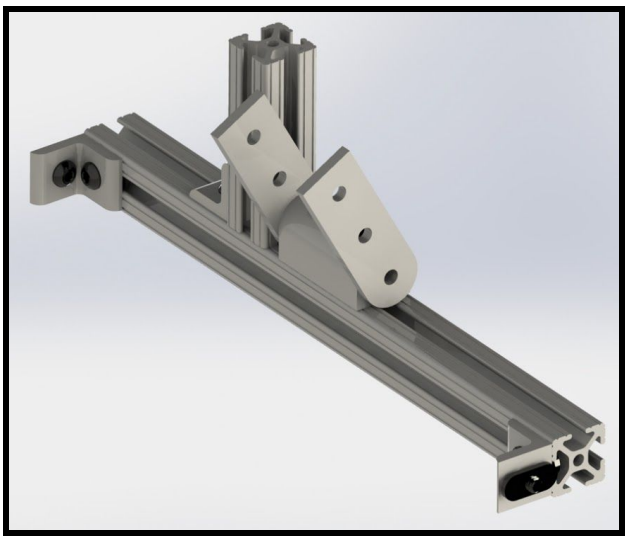


5.4) For the 2nd and 3rd 12” extrusion pieces facing you, slide 2x #8-32 T-Nuts down the sides of the 12” Extrusion such that the T-Nuts, within the extrusion faces, are facing each other. Then fasten the routing clamps with knurled thumbscrews to the #8-32 T-Nuts, as shown in the picture. Their exact locations are not critical, but keep them close to either end. Then attach bracket assemblies as shown in the image: 2x on each extrusion; one facing inward (away from you) and one facing outward (towards you).

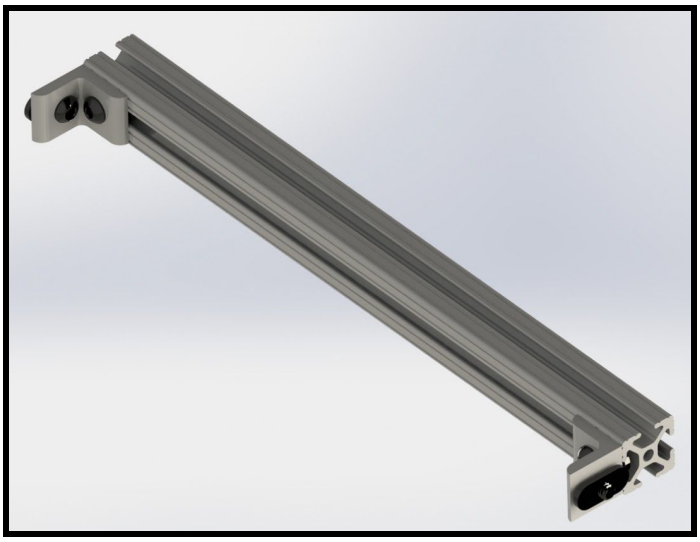


5.5) On the second-to-last 12” extrusion, slide in 2x ¼”-20 T-Nuts on the front facing side (toward you) and one bracket assembly on the top facing side. Attach the pivot as shown under step 5.6).

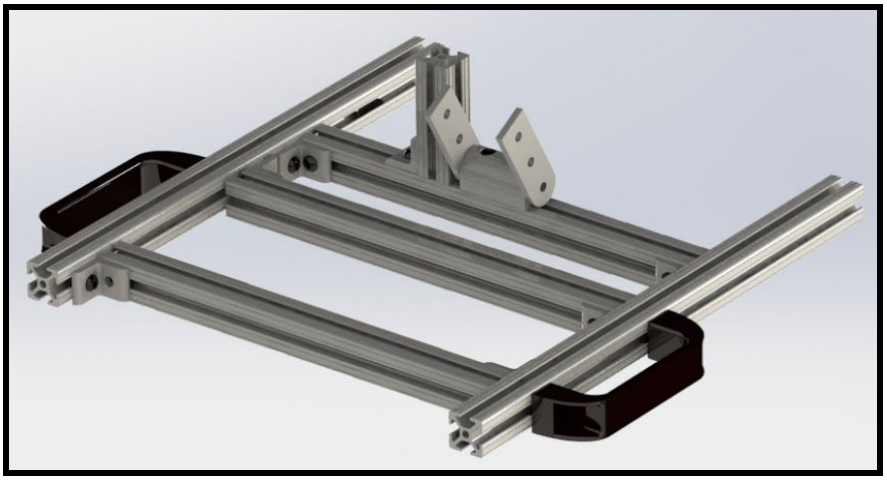
5.6) Then with the bracket assembly, attach the 4” extrusion piece as close as possible on the left side of the pivot, so that the arm when actuated up will barely miss the 4” extrusion. Then attach the bracket assemblies: 4x on the extrusion piece, 2x on each end; one facing inward (away from you) and one facing outward (towards you).



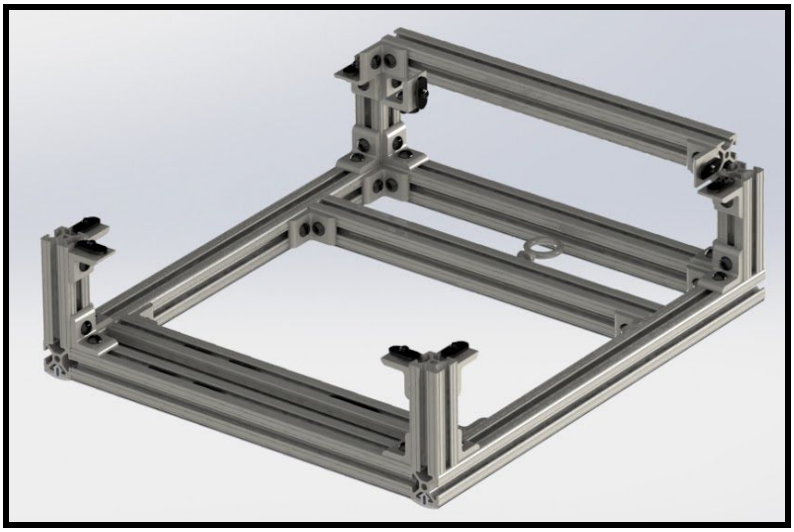
5.7) On the last 12” extrusion piece, loosely fasten 2x bracket assemblies: one on each end, on the inward facing side (towards you).



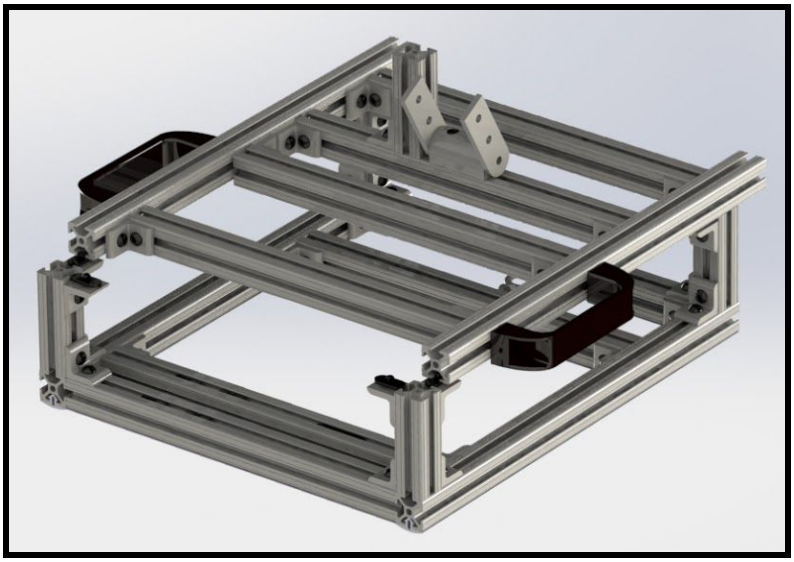
5.8) Put the whole top frame together; the first and last 12” Extrusion Pieces should not be attached.



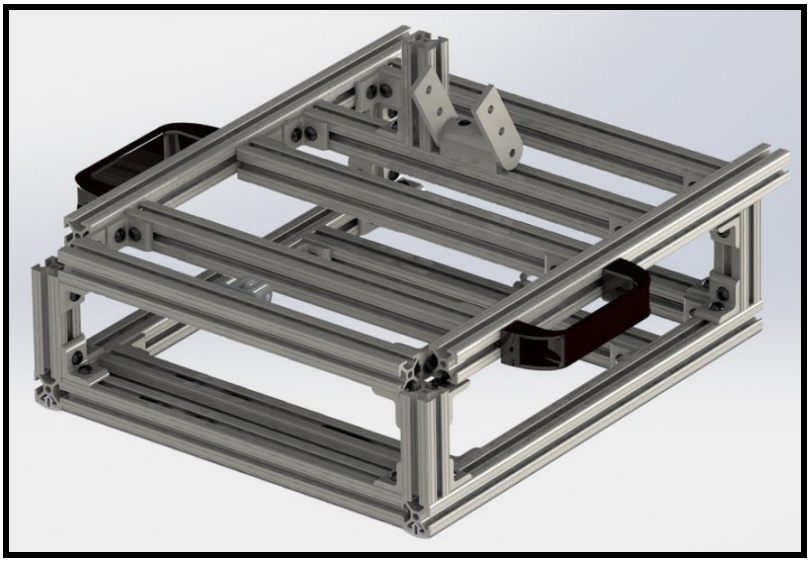
5.9) First slide on the back most piece down the back two vertical standoffs, keep it loosely in place.



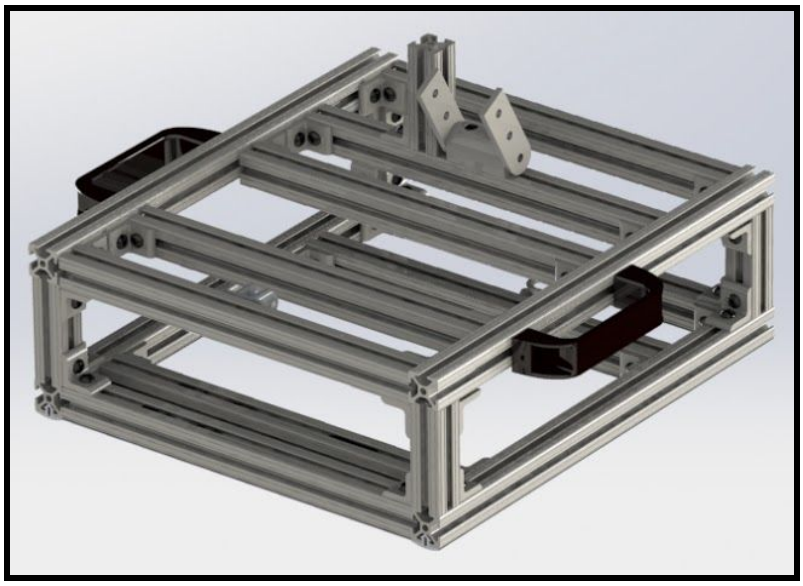
5.10) Then slide the next 12” Extrusion Pieces down the 15.5” Extrusion Pieces. Shimmy the T-Nuts in through the long 15.5” parallel pieces. Slide the 15.5” Extrusion Pieces, with 12” Extrusion Pieces attached, onto the vertical uprights such that it is resting 1” past the front vertical uprights. Ensure the L-brackets attached to the 12” sides are not poking out past, or else the entire assembly will be too wide.



5.11) Place a 12” Extrusion Piece onto the front two standoffs, with L-brackets attached.

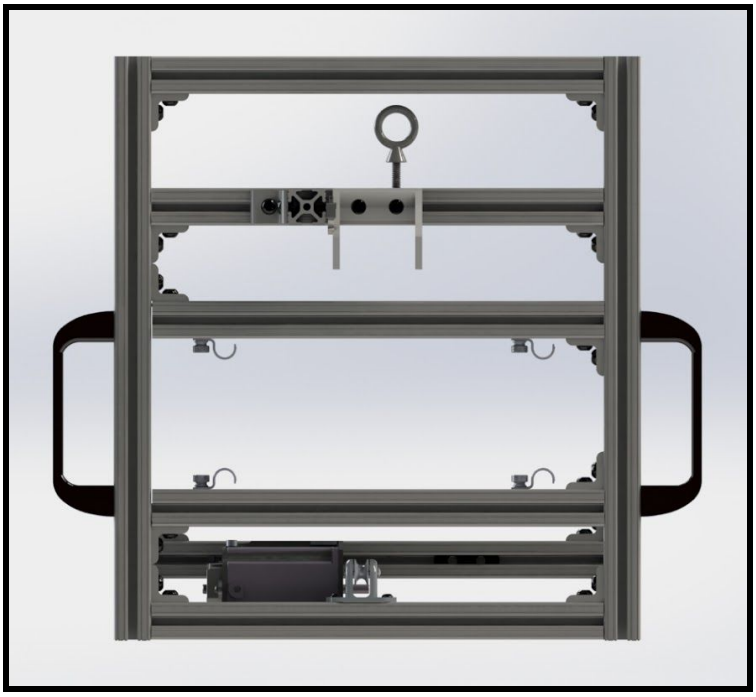


5.12) Slide the 15.5” Extrusion Pieces on the top frame forward into place, so that the ends are flush with the vertical uprights.

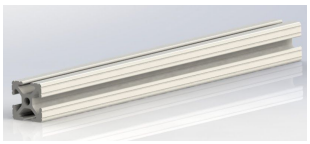


5.13) After every piece is through, tighten the start and end pieces. The arm extrusion piece should have a 1.5” gap between its back face and the front face of the end piece. Keep the U-Bolt extrusion pieces loosely fastened, but not loose enough that they swing out.

5.14) Note the first 12” extrusion is hanging over the table because of the two bottom attached L-bracket assemblies. The back 12” piece does not have attached L-bracket assemblies only because then it would not rest flat on a table. The following image shows a top-down view of the completed top frame for reference.

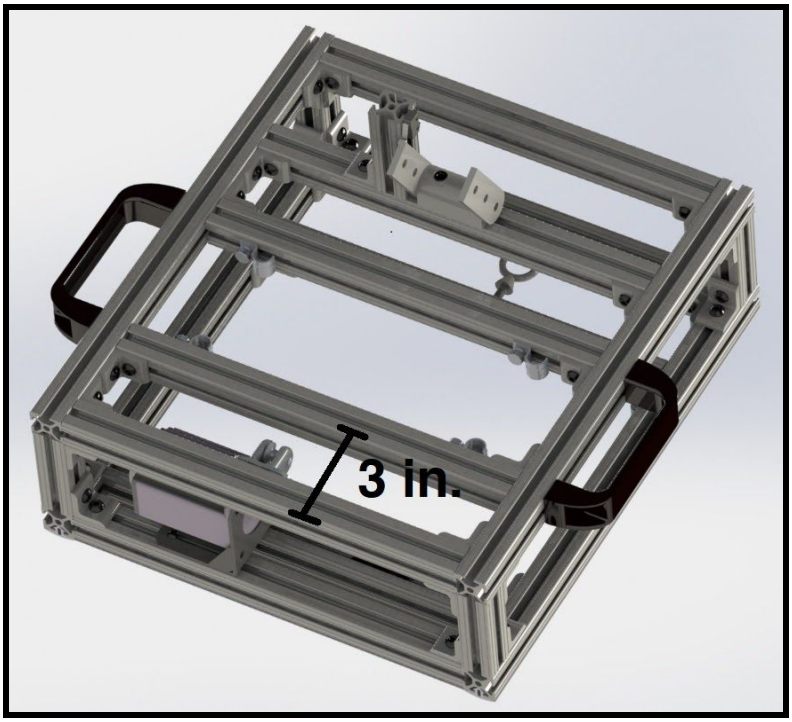


Step 6: Connecting Top with Bottom, Arm

Part Code	Part Name	Quantity	Reference
M-4	80/20 Extrusion (10.5”)	1	
M-6	#10-32 T-Nut	4	
M-8	Frame L-Bracket	8	
M-18	U-Bolt with Mounting Plate	2	
M-24	T-Slotted Framing	1	

Part Code	Part Name	Quantity	Reference
M-5	¼-20 Button Head Screw 0.500” and T-Nut	6	
M-7	#10-32 Button Head Screw 0.375”	16	
M-16	3” Extension 12”Spring	1	
M-21	Steel Eyebolt with Shoulder	2	

6.1) Now, attach the U-Bolts. Take off the nuts and insert each U-Bolt through the 2x routing clamps on the ends of the 2nd and 3rd Extrusion Pieces. Keep the U-Bolts around 1.5” from the inward facing sides of the 15.5” Extrusion Pieces. They should fit easily since the 12” extrusion pieces are loose. Once U-Bolts can slide up and down easily, tighten 12” extrusion pieces in place such that the front face (toward you) of the 2nd 12” Extrusion Piece is 3” away from the front face (toward you) of the 1st 12” Extrusion piece.

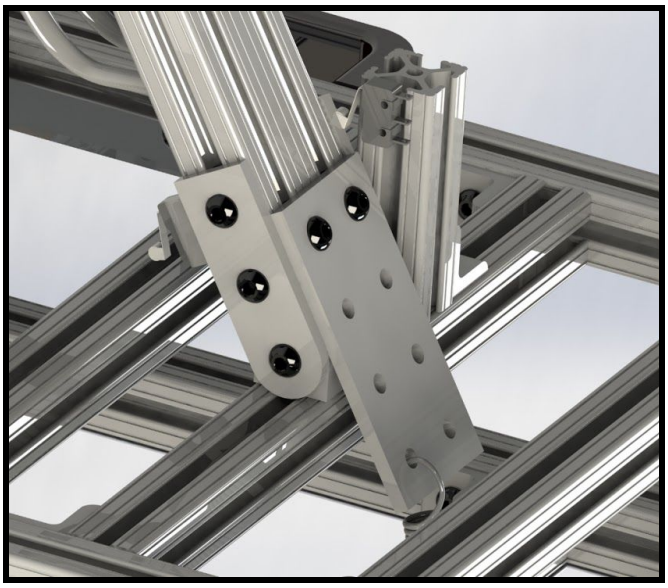


6.2) Slide 4x ¼”-20 T-Nuts down the 2” wide, 10.5” long extrusion piece, placing two in each slot of a single side. Attach 2x Door Handles on the 10.5” extrusion piece by bolting down each handle vertically along the long side of the extrusion; the first T-Nut and bolt in each slot should be fastened 2.5” from the top of the extrusion. The door handles should be perfectly parallel and aligned at their centers. See picture below for reference:

6.3) Fasten the 10.5” extrusion piece to the hinge. With the hinge facing you, add a bracket on the outside face of the frontmost hole on the left side, acting as a hardstop for the eventual limit switches. Slide 2x ¼”-20 T-Nuts down the bottom-facing side and fasten 2x ¼”-20 bolts through hinge holes through T-Nuts.

6.4) With the compression arm pointing towards you, use a ¼”-20 T-Nut to attach an eyebolt in the left T-slot, an inch into the arm. Make sure that when the arm is completely down, the eyebolt rests in the middle of the first and second 12” extrusion pieces on the top.

6.5) Slide 2x ¼”-20 T-Nuts down top-facing side of 10.5” extrusion and attach T-Slotted Framing Plate at its top two holes. The framing plate should be sticking off the end of the 10.5” extrusion by around 1.5”.



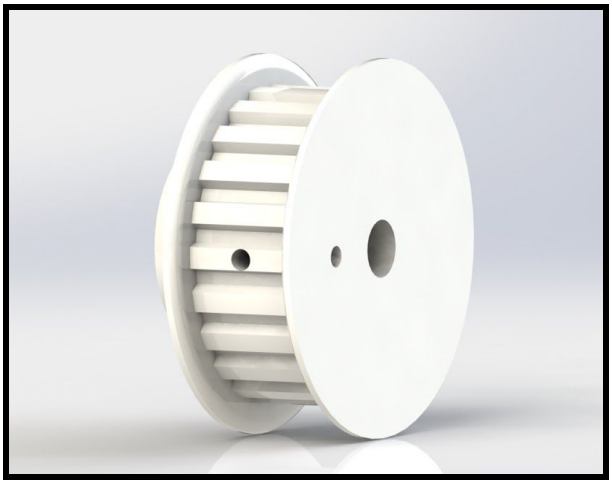
6.6) Attach the 3” spring hook to one of two bottom holes of the plate. Unscrew the eyebolt on the bottom frame, attach the other hook of the spring to the eyebolt, and re-fasten the eyebolt to the T-Nut.

Step 7: Pulley Mounting

Part Code	Part Name	Quantity	Reference
M-20	22T XL Acetal Timing Pulley	1	

7.1) Drill a 7/64” hole normal to the teeth of the pulley (into the pulley) about 0.5”.

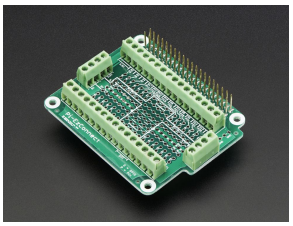
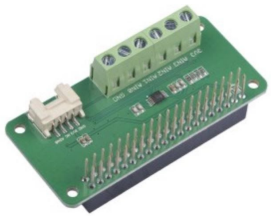
7.2) On the axis of the shaft, drill a 7/64” through-hole through the pulley perpendicular to the first hole. This hole should be situated between the metal collar and the thicker rim portion. See the image below for an example of how the holes should be drilled:



7.3) Melt the tip of the rope to make it easier to work with. Guide the rope through the pulley as shown below; when facing the pulley on the side opposite the motor, ensure that the compression arm goes down when the pulley is rotated counterclockwise.

Step 8: HAT Connection

Part Code	Part Name	Quantity	Reference
E-9	Raspberry Pi 3B+	1	
E-16	16GB MicroSD Card	1	

Part Code	Part Name	Quantity	Reference
E-13	Breakout HAT	1	
E-18	16-bit ADC HAT	1	

8.1) Orient the Screw Terminal HAT so that its GPIO header is the same orientation as the Raspberry Pi GPIO header.

8.2) Carefully plug the Raspberry Pi header into the bottom of the Screw Terminal HAT through the header, ensuring all pins are aligned. The four holes at the corners of the Screw Terminal HAT and the Raspberry Pi now line up. If more stability is needed, use tape to create another point of contact between the HAT and the Pi - mounting tape on top of the HDMI port works well. See Figure 8.1 for how this should look.

If the ADC HAT is being used.
8.3) Orient the ADC HAT above the Screw Terminal HAT so that their GPIO headers line up. The body of the ADC should be contained above the Screw Terminal HAT -- in other words, the ADC should not protrude outside the limits of the Screw Terminal HAT.

8.4) Plug the ADC into the Screw Terminal HAT via the GPIO header.

8.5) Flash the microSD card and insert it into the Raspberry Pi. See Software Details for more information about this.

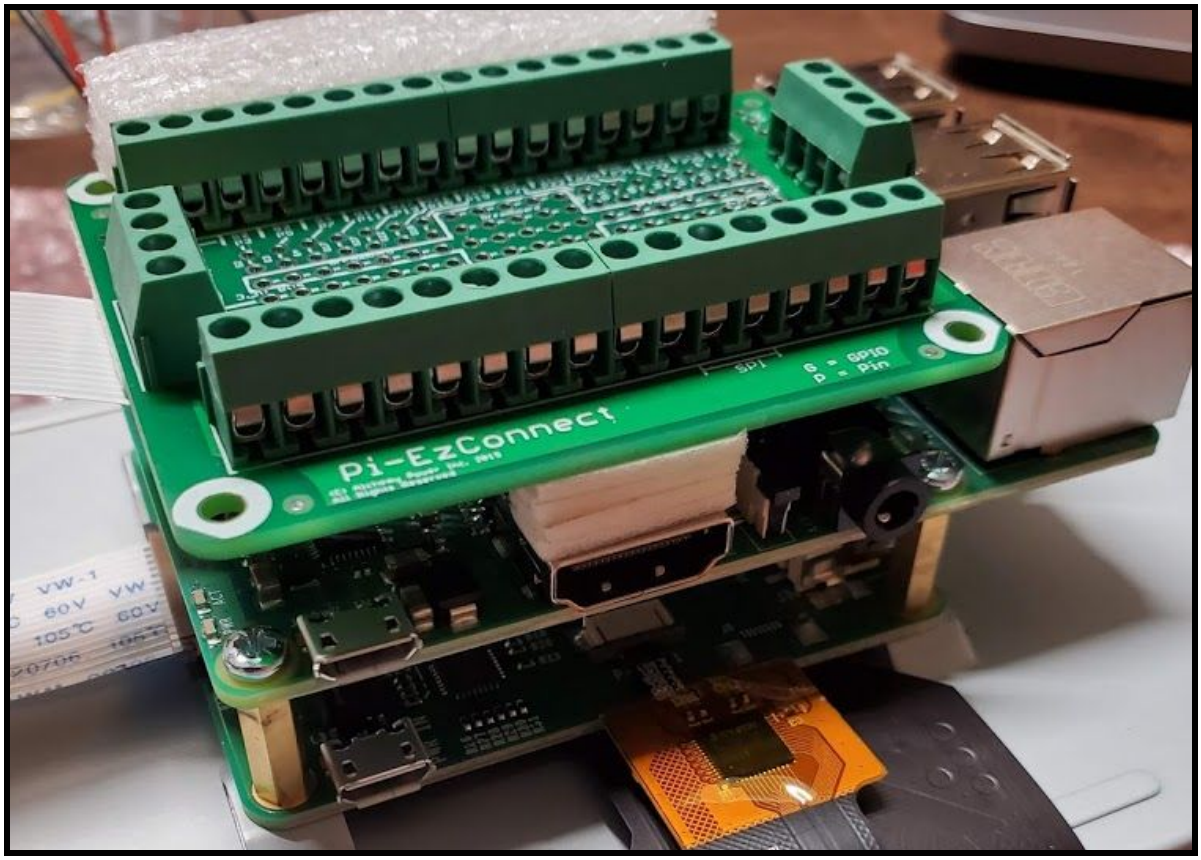
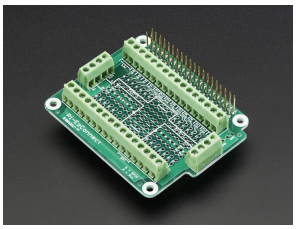


Figure 8.1 Screw Terminal HAT mounted on the Raspberry Pi. The topmost board is the Screw Terminal HAT, and the second board is the Raspberry Pi. Tape was mounted on the Raspberry Pi's HDMI port to secure the Screw Terminal HAT.

Step 9: Routing Power to Motor

Part Code	Part Name	Quantity	Reference
E-1	Stepper Motor Controller	1	
E-7	Stepper Motor with Encoder	1	
E-9	Raspberry Pi 3B+	1	
E-12	12V Power Supply	1	
E-14	Power Splitter	1	

Part Code	Part Name	Quantity	Reference
E-6	Micro-USB to USB-A	1	
E-8	Encoder Cable	1	
E-10	Assorted Wire	N/A	
E-13	Breakout HAT	1	

9.1) Plug the 12V power supply into the power splitter.

9.2) Ensure all components of the 12V power supply are attached, including the barrel-to-wire adapter at the end.

9.3) Attach two wires to the end of the wire adapter on the power supply and tighten the screw terminal with the screwdriver to secure them.

9.4) Connect the POWER wire from the power supply to the VIN screw terminal of the motor controller and tighten the terminal. Refer to Figure 9.1 to find VIN.

9.5) Connect the GROUND wire from the power supply to the GND screw terminal of the motor controller and tighten the terminal. Refer to Figure 9.1 to find GND.

9.6) The wire ends of the encoder cable are colored. Connect wire 4 (BLACK wire with RED stripe) to a GND terminal on the Breakout HAT. Connect wire 6 (RED wire with BLACK stripe) to a 5V terminal on the Breakout HAT. Connect wires 8 (GREEN wire with BLACK stripe) to GPIO 18 and wire 10 (WHITE wire with BLACK stripe) to GPIO 16. Refer to Figure 9.2 to find the terminals on the Breakout HAT (GPIO mappings start with G).

9.7) Plug the motor directly into the open port of the power splitter.

9.8) Cut open the 4-pin molex adapter attached to the motor, and strip down the wire leads. Connect the RED wire to the A1 screw terminal on the motor controller. Connect the WHITE wire to the A2 terminal. Connect the GREEN wire to the B1 terminal. Connect the BLACK wire to B2 terminal. *Note: If the motor fails to start or is non-functional after electrical wiring is completed, the first step to debug (after checking the power is on and everything is connected) should be to ensure all the wires are connected to the correct terminals.*

9.9) Use double-sided tape to attach the motor controller to the back of the motor.

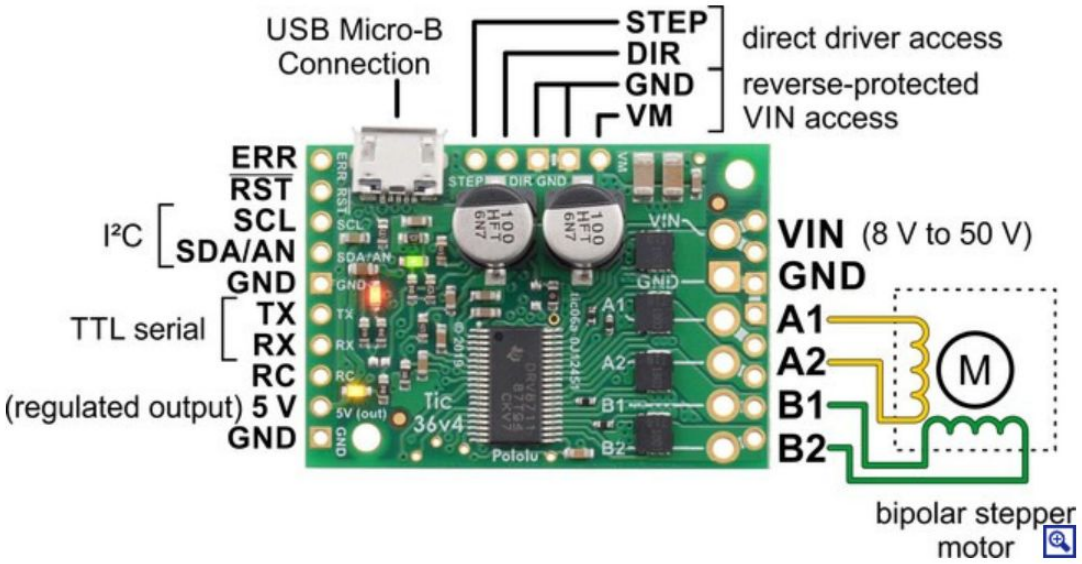
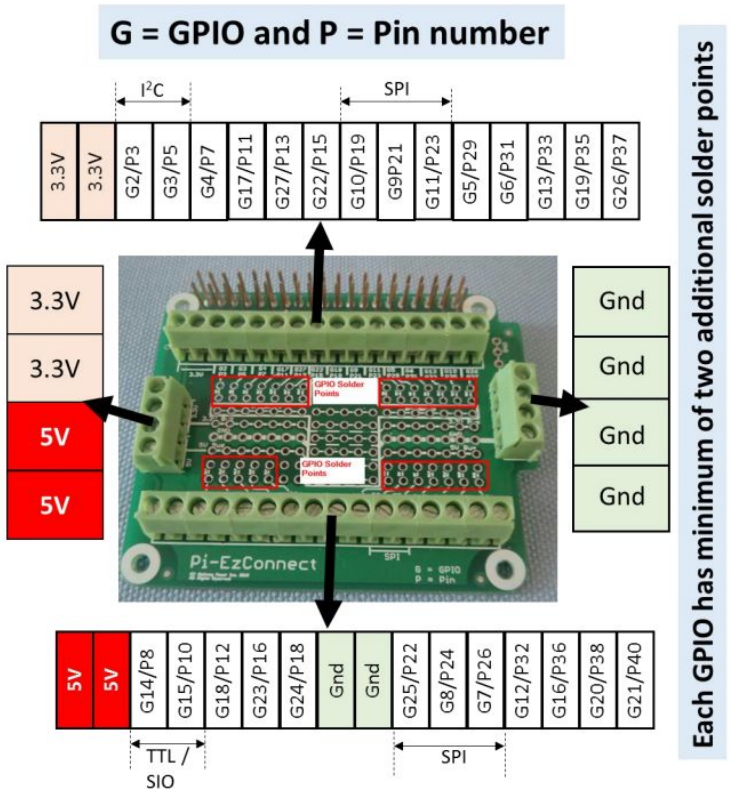


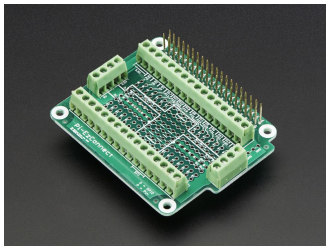
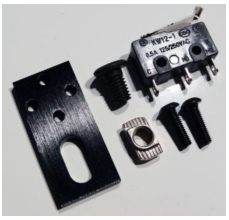
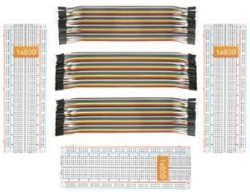
Figure 9.1 Pinout Diagram for TIC 36v4 Motor Controller. The VIN and GND terminals are both on the RIGHT side of the board, where the screw terminals are.

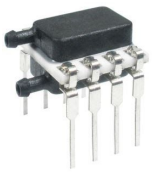
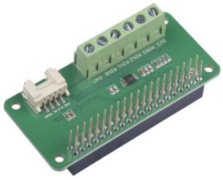
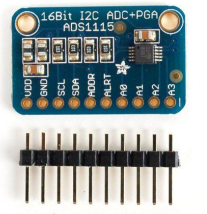


Pin out configuration details for Pi-EzConnect. The GPIO solder points are also shown in the picture.

Figure 9.2 Pinout Diagram for Screw Terminal Breakout HAT.

Step 10: Routing Power to Remaining Sensors

Part Code	Part Name	Quantity	Reference
E-2	Power Switch	1	
E-9	Raspberry Pi 3B+	1	
E-13	Breakout HAT	1	
E-20	Limit Switches and Brackets	2	
E-22	Breadboard with Connectors	1	
M-7	#10-32 Button Head Screw 0.375”	1	

Part Code	Part Name	Quantity	Reference
E-3	Pressure Transducer	1	
E-11	Alarm	2	
E-18	16-Bit ADC for Raspberry Pi	1	
E-21	ADS1115 4-channel ADC with header	1	
M-6	#10-32 T-Nut	1	
M-23	Power Switch Mounting Bracket	1	

10.1) Plug the pressure transducer into the top edge of the breadboard, making sure the ports are completely outside the breadboard AND the pressure transducer sits over the middle gap in the breadboard (the pins are on the two sides). Refer to Figure 10.1 to see how the transducer should be placed in the breadboard. *Note: A perfboard can also be used here, in which the components may be soldered on.*

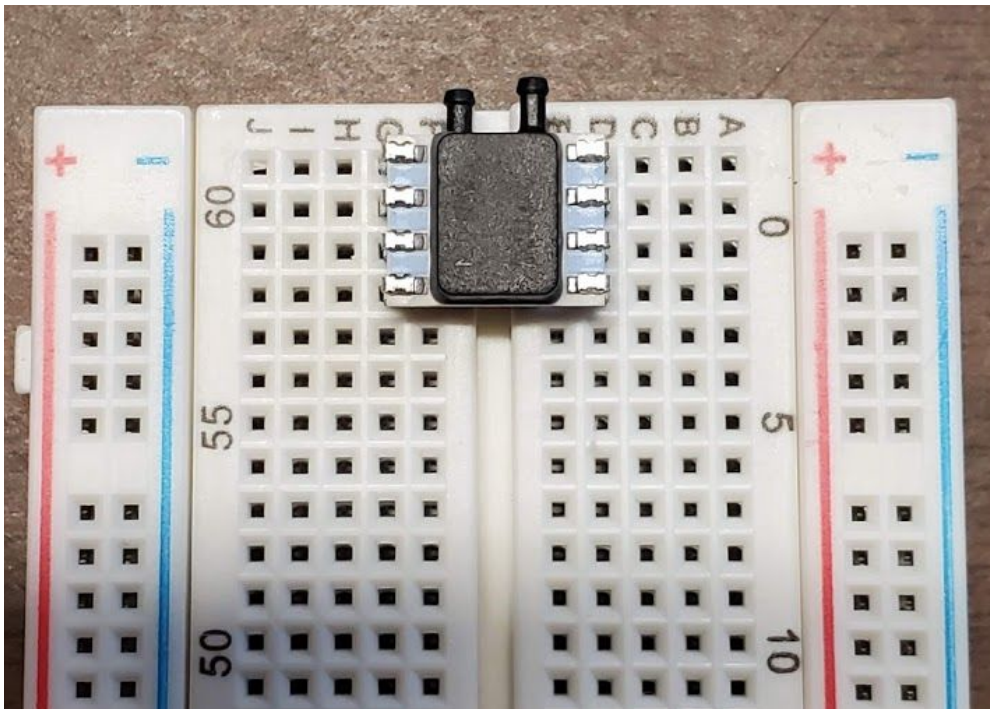
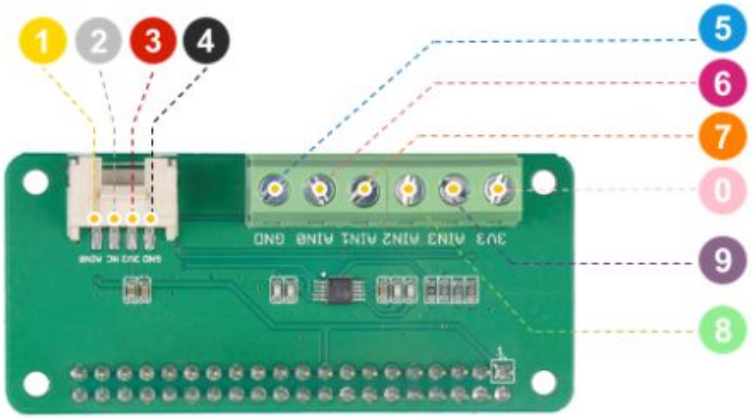


Figure 10.1 The pressure transducer in the breadboard.

If the ADC HAT is being used, part E-18
10.2a) With the ports on the pressure transducer facing upwards, the pins on the LEFT side should be connected to the screw terminals as follows, from top to bottom: port 5 (GND), port 6 (AIN0), port 0 (3V3), port 7 (AIN1). Refer to Figure 10.2 for how the ADC screw terminals are numbered.

If the soldered ADS1115 ADC is being used, part E-21
10.2a) With the ports on the pressure transducer facing upwards, the pins on the LEFT side should be connected to ADC pins as follows, from top to bottom: GND, AIN0, VDD, AIN1.

10.2b) Plug the ADC into a breadboard. Use a wire to connect the VDD pin to a 3.3V screw terminal on the Breakout HAT. Connect the GND pin to a GND screw terminal. Connect the SCL pin to GPIO 3. Connect the SDA pin to GPIO 2. Connect the ADDR pin to VDD.



4 **GND: Power pin, GND output**
3 **3V3: Power output, out put 3.3V**
2 **NC: I²C serial data**
1 **AIN0: Analog pin 0**

5 **GND: the same as pin 4.**
6 **AIN0: Analog pin 0**
7 **AIN1: Analog pin 1**
8 **AIN2: Analog pin 2**
9 **AIN3: Analog pin 3**
0 **3V3: Power output, out put 3.3V**

Figure 10.2 Pinout Diagram for the ADC Screw Terminal HAT.

10.3) Mount the breadboard with the pressure transducer connected, ports down, to the back of the ventilator using double-sided tape.

10.4) Connect one end of the alarm to a GND terminal, and the other to GPIO 25.

10.5) Connect one end of the second alarm to a GND terminal, and the other to GPIO 8.

10.6) Use double sided tape to mount the alarms to the back of the screen housing.

10.7) Slide a T-slot nut into the top side of the front bottom piece of extrusion. Secure the bottom of the power switch mounting bracket (with two long holes) with the button-head screw. Secure the power switch to the other side of the mounting bracket, with its lever pointing outwards. See Figure 10.3 for how the power switch should be mounted.

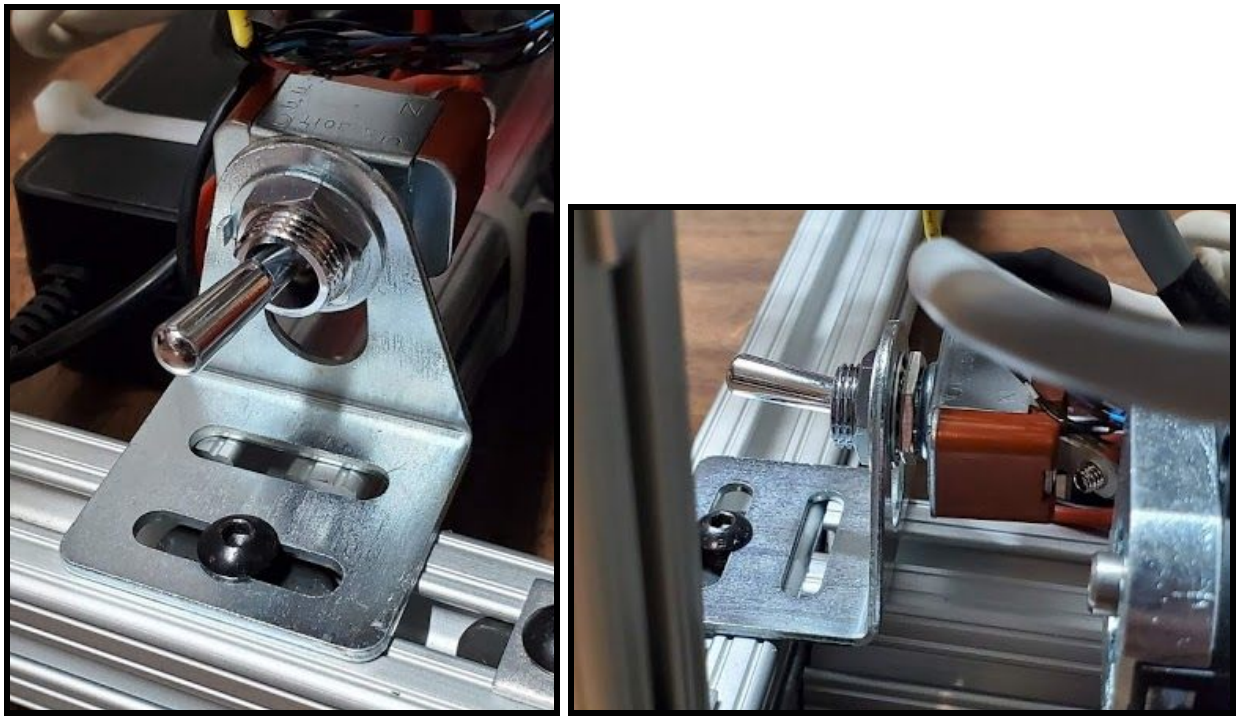


Figure 10.3 The power switch mounting from the front and side.

10.8) Solder wires to the two ports of the power switch. One end should go to GPIO 17 and the other end should go to GND on the Screw Terminal HAT. See Figure 9.2 for the pinout diagram of the Screw Terminal HAT.

10.9) Orient the long side of the limit switch parallel to the long side of the plastic mounting piece and use the two small screws to secure the limit switch to the corresponding holes at one end of the mounting piece, with the lever hinge on the opposite side of the big hole in the mounting. Slide the t-slot nut into the top end of the upwards-pointing extrusion at the back of the machine, and secure the entire bracket to the extrusion. See Figure 10.4 for how this limit switch should be mounted.

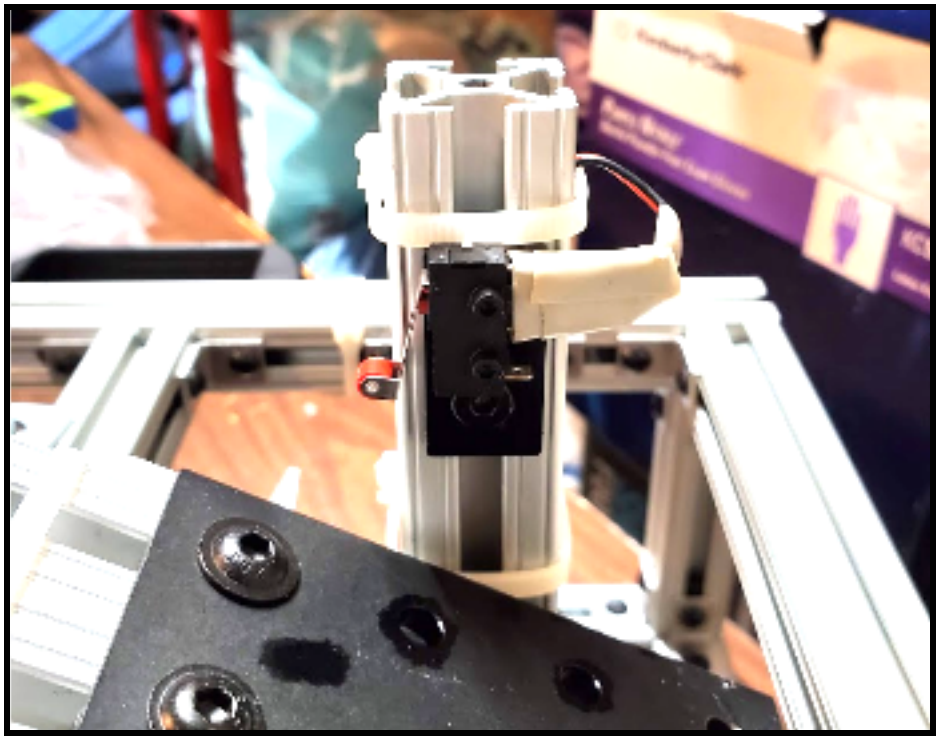


Figure 10.4 Example of how the absolute limit switch should be set up at the back of the machine.

10.10) Take the first (absolute) limit switch and use a wire to connect its NO terminal to a ground terminal on the Breakout Hat, and connect its C terminal to GPIO 23.

10.11) Orient the long side of the limit switch parallel to the SHORT side of the plastic mounting piece and use the two small screws to secure the limit switch to the corresponding holes at one end of the mounting piece.

10.12) Take an L-bracket assembly from Step 0. Slide in a t-slot nut into the left piece of extrusion on the arm and secure the L-bracket to the extrusion with the bolt. Make sure the other side of the L-bracket is between the door handles.

10.13) With the other side of the L-bracket, bolt the mounting bracket to the L-bracket using the large bolt and nut included with the limit switch mounting bracket. Ensure the limit switch and the L-bracket aren't on the same side, and the hinge is towards the base of the arm. See Figure 10.5 for how this should be set up.

Figure 10.5 Images that show how the contact limit switch should be set up from the front, right, and left.

10.14) Take the second (contact) limit switch and use a wire to connect its NO terminal to a ground terminal on the Breakout Hat, and connect its C terminal to a 24.

Step 11: Touchscreen Case Attachment

Part Code	Part Name	Quantity	Reference
E-4	7” Touchscreen (and included add-ons)	1	

Part Code	Part Name	Quantity	Reference
E-9	Raspberry Pi 3B+	1	

For more information, see: http://www.farnell.com/datasheets/1960197.pdf

11.1) On the driver board, pull out the black clamp from the display ribbon cable header and slide the ribbon cable into the ribbon cable port with the blue side facing DOWN (exposed pins facing up). Push the black clamp back in to lock the cable in place. See Figure 11.1 on how this looks.

Figure 11.1 The ribbon cable attached to the display driver board.

11.2) On the Raspberry Pi, pull out the black clamp from the other side of the ribbon cable header and slide it into the ribbon cable port with the blue side facing OUT, then push the clamp back down to lock it. See Figure 11.2 for how this looks.

Figure 11.2 The ribbon cable attached to the Raspberry Pi.

11.3) Affix the driver board to the central holes in the screen with the spacers. Line up the holes in the board with the holes in the screen and place the spacer in the gap between them and use screws to secure the board. See Figure 11.3 for how the entire board setup looks, minus the ADC HAT.

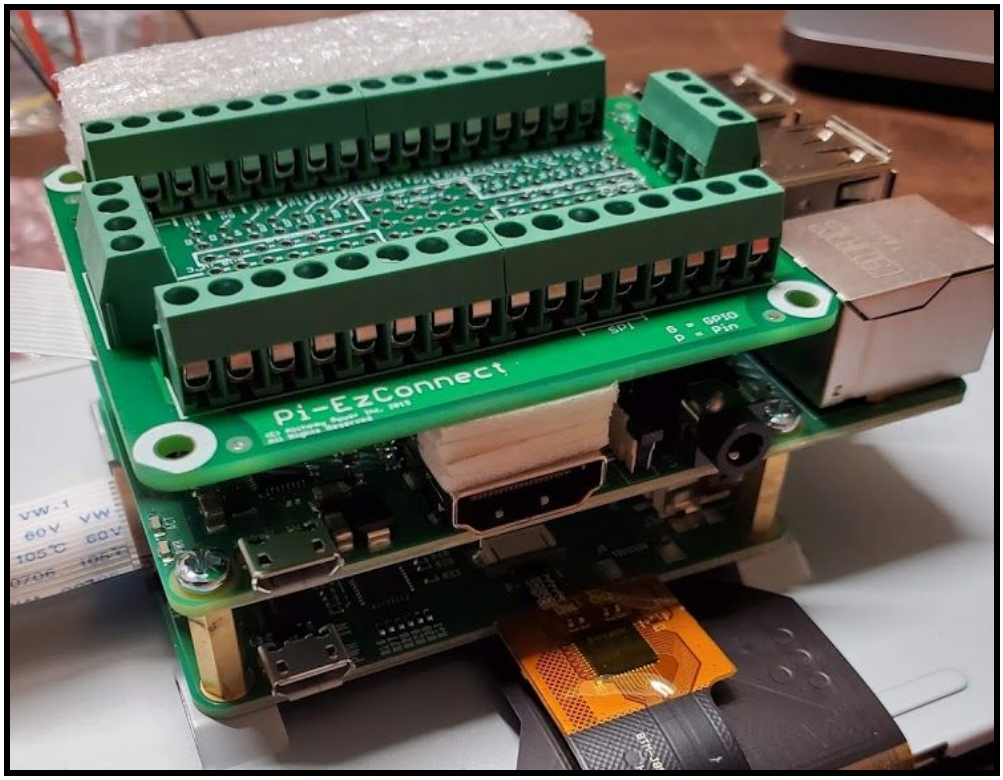


Figure 11.3 The display driver board, Raspberry Pi, and Screw Terminal HAT. Note that the tape (white) supports the Screw Terminal HAT.

11.4) Use the included wires to connect GND on the driver board to GND on the Raspberry Pi, and 5V on the driver board to 5V on the Raspberry Pi.

11.5) Remove the back cover from the display and cut out the left corner mounting bracket from the case.

11.6) Slide the entire Raspberry Pi setup into the case - it should slide right in and snap on, with all the ports lining up with the holes in the case.

11.7) Use the four small screws included with the display to attach the display and the case.

Step 12: Mounting the Pi

Part Code	Part Name	Quantity	Reference
E-2	Power Switch	1	
E-7	Stepper Motor with Encoder	1	
E-9	Raspberry Pi 3B+	1	
E-17	12V to Micro USB Power Source	1	

Part Code	Part Name	Quantity	Reference
E-6	Micro-USB to USB-A	2	
E-8	Encoder Cable	1	
E-14	Power Splitter	1	
E-19	USB-A Male to Female	1	

12.1) Place pieces of double-sided tape on the 80-20 extrusion along the front right side of the machine, as well as the upwards-facing surface of the bottom piece, and the downwards-facing surface of the top piece.

12.2) Mount the complete Raspberry Pi, in the screen enclosure and with its associated HATs, into the space created by the front right side of the machine. The Raspberry Pi section of the case should snuggle in comfortably between the top and bottom extrusion, and the back of the screen should stick onto the front face of the right piece of extrusion.

12.3) If the screen enclosure feels loose, run a piece of tape on the top edge of the screen to the top left corner, securing it to the extrusion behind it.

12.4) Use the male-female USB connector, plug it into the Raspberry Pi, and use the USB-microUSB cable to connect to the controller.

12.5) Connect the other end of the encoder cable to the corresponding port at the top of the encoder, which is attached to the motor.

12.6) Connect one end of the power switch to a GND terminal, and the other to GPIO 17.

12.7) When you're ready to operate the Raspberry Pi, use the 12V to Micro USB Power Source to connect the Raspberry Pi to the Power Splitter and plug the power splitter into the wall. Be sure the power switch is flipped in the "on" position, which is when the lever faces away from the notch.

Software Details

The following are package installation and configuration instructions for the VentCU control system. You will need the following items:

- Corresponding microUSB or USB-C power supply (2.5A or 3A)
- Raspberry Pi (3B or 4B)
- microSD card with appropriate reader/adaptor (8GB minimum)
- A screen (7” LED screen provided for you)
- A computer with stable internet connection

1) VentCU runs on the latest version of Raspberry Pi OS (Raspbian). See https://www.raspberrypi.org/downloads/ for the correct download version and further instructions.

2) Recommended: Raspberry Pi OS (32-bit) with desktop and recommended software (torrent, alternatively as a ZIP file)

3) Download the correct version of Raspberry Pi Imager for the OS you are running on: Windows, MacOS, Ubuntu

4) Image the latest version of Raspbian to your inserted SD card.

5) Select the correct timezone and location, as well as preferred login information.

6) If your touchscreen is rotated 180° the wrong way, do the following in terminal:

```
$ sudo nano /boot/config.txt
# in the file enter the following: “lcd_rotate=2”
# enter “CTRL+X”
# then “Y” and Return
$ sudo reboot
```

7) Enable I2C, Serial, VNC configurations:

- ONLY enable VNC if you wish to remotely access the Raspberry Pi over a cloud connection.
- If accessing only from a local network, consider enabling just SSH or Remote Desktop control.

From terminal:

```
$ sudo raspi-config
# select Interfacing Options
# one at a time, select and enable VNC, I2C, and Serial
# select <Finish> and reboot if requested
```

An alternative method is to install from desktop environment: *Preferences* > *Raspberry Pi Configuration* > *Interfaces* > Check *'Enable'* for VNC, I2C, Serial Port, Serial Console

8) Setup VNC (only for remote access). Make sure VNC interfacing is enabled.

```
$ sudo apt update
$ sudo apt install realvnc-vnc-server realvnc-vnc-viewer
# if establishing just a local direct connection
# run the following to find local pi address
# the following would be needed for SSH/RDP access
$ hostname -I
```

Sign up for a free RealVNC account here. VNC is a proprietary, private software requiring either a commercial license or as a free non-commercial license for the Raspberry Pi.

Then, run:

```
$ sudo vnclicensewiz
```

Enter your RealVNC credentials, and from the same account using RealVNC Viewer, you can now access the Raspberry Pi over a cloud connection.

9) VentCU runs on Python >3.6. Raspberry Pi OS is installed with version 3.7.3. VentCU's control system relies further on certain packages. The following can be installed via the command line Python package installer, pip:

```
$ sudo apt-get update
$ sudo pip3 install --upgrade pip
$ sudo pip3 install <package>
# the following is a list of packages you must install
Package                         Version
------------------------------- -----------
Adafruit-Blinka                 4.9.0
adafruit-circuitpython-ads1x15  2.2.1
adafruit-circuitpython-busdevice 4.3.1
adafruit-circuitpython-mcp3xxx  1.4.1
Adafruit-PlatformDetect         2.11.1
Adafruit-PureIO                 1.1.5
envirophat                      1.0.0
ExplorerHAT                     0.4.2
gpiozero                        1.5.1
numpy                           1.16.2
pigpio                          1.44
```

```
PyQt5
pyqtgraph                       0.10.0
pyserial                        3.4
RPi.GPIO                        0.7.0
smbus2                          0.3.0
```

10) Install Tic Stepper Motor Controller software for Raspberry Pi. Refer to this website for in-depth instructions. Otherwise, enter the following instructions:

```
$ cd /path/of/downloaded/tic/software
$ tar -xvf pololu-tic-*.tar.xz
$ sudo pololu-tic-*/install.sh
# after installation, plug Tic controller into the Pi via usb
# if already plugged in, unplug and plug back in for new udev rules
$ ticcmd --list
# check to see that Tic 36v4 is listed
# run ticgui to start the control center
$ ticgui
```

11) VentCU source code is accessible here. In a desired directory, enter the following in your terminal:

```
$ git clone https://github.com/VentCU/bbwtb.git
```

Congratulations. You are done configuring VentCU's software.

See external documentation links as well:

- Configuring your Raspberry Pi 3/4 (steps 1 through 3):
  - https://projects.raspberrypi.org/en/projects/raspberry-pi-setting-up/2
- Setting up and establishing a cloud connection:
  - https://www.raspberrypi.org/documentation/remote-access/vnc/
- Configuring Arduino ads1115 ADC:
  - https://learn.adafruit.com/adafruit-4-channel-adc-breakouts/python-circuitpython

Device Operation

Note: Do not place any body part inside the frame of the device while the device is in use. The only part of the device that the operator should interface with is the touchscreen provided.

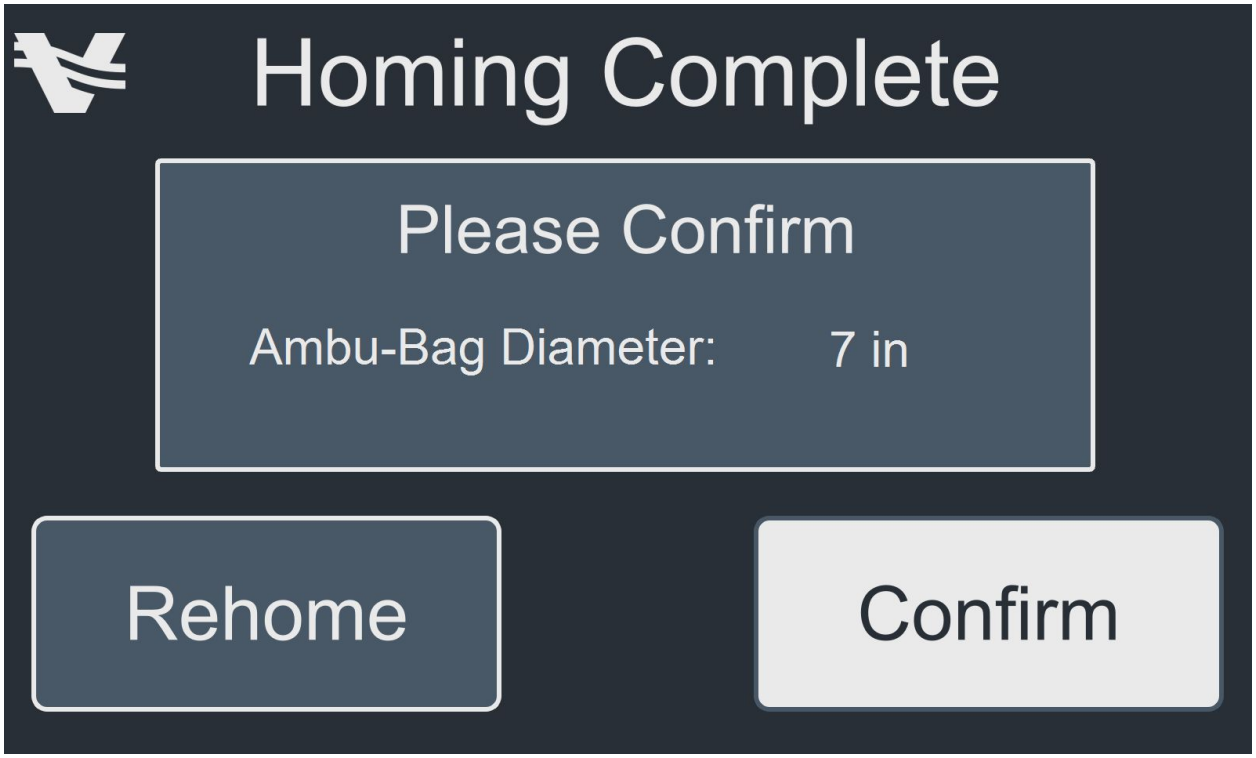
This device is only meant for indoor use. Exposing the device to moisture or extreme temperatures can cause the device to malfunction or become damaged.

1) Turning on the Device: Ensure the device is prepared for use by going through the preliminary checklist found below. If needed, insert a new Ambu-bag.

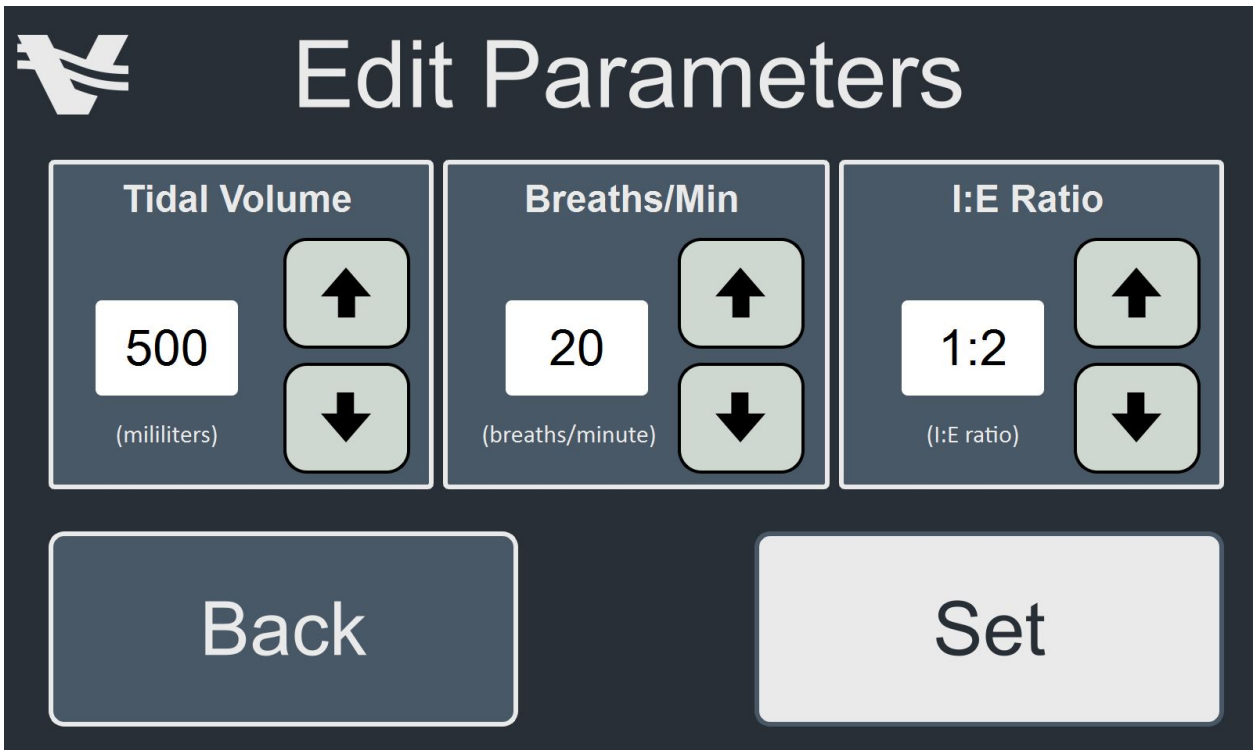
Description	Checkbox
Ensure that the entire device, including the frame, electronics, and plumbing, have all been disinfected before use	
Make sure that all structural connections are tightened, especially near moving parts	
Check that all electrical wiring is securely connected	
Check that all plumbing is securely connected	
Check that the operating area (specifically the moving arm) is clear of any obstructions	

Then connect the device to power and turn on the power switch. After the touch screen turns on, click ‘Start’.

2) Home the Device: Click ‘Start Homing’ on the touchscreen to start the homing procedure. The arm will rise to a fully upright position where it will hit the hardstop and trigger the upper limit switch. The arm will then move downwards until it contacts the Ambu-bag, triggering the contact limit switch. Upon successful completion of the homing procedure, the Ambu-bag diameter will be displayed on the touchscreen. If correct, click ‘Confirm’.



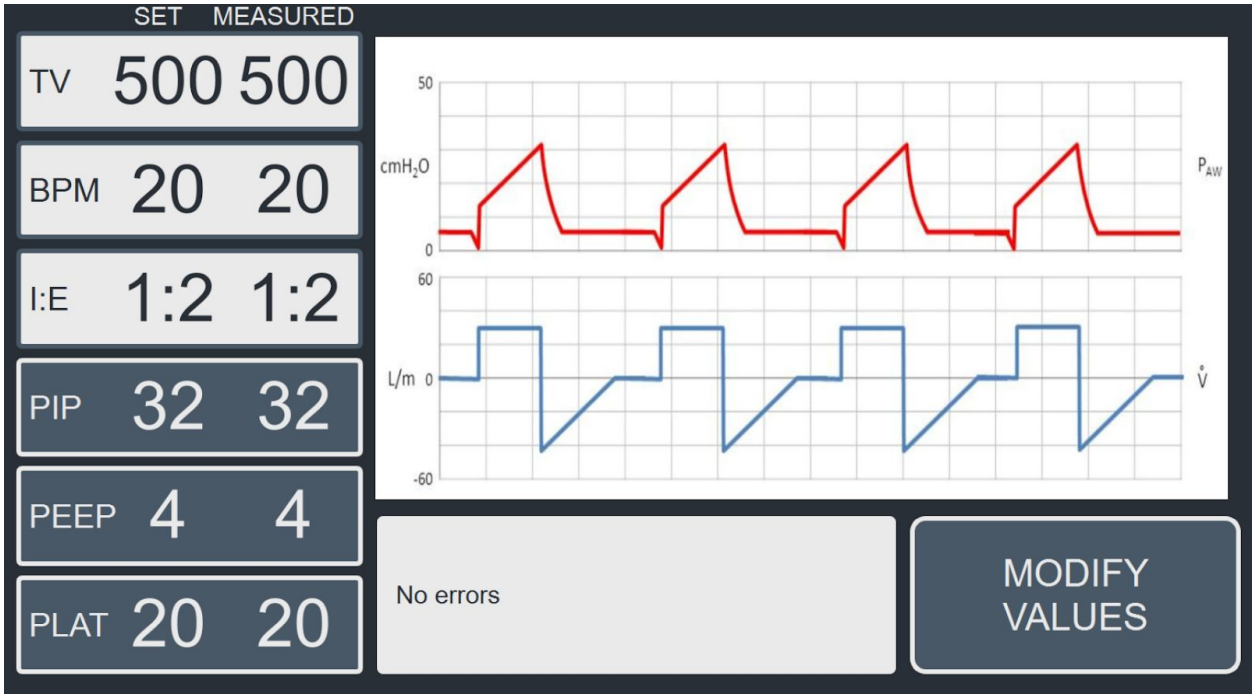
3) Set Parameters: Next, select the appropriate parameters for device operation, specifying the tidal volume, breaths per minute and I:E ratio. After clicking ‘Set’ the user will be asked to confirm the specified parameters. Upon doing so the device will begin normal operation.



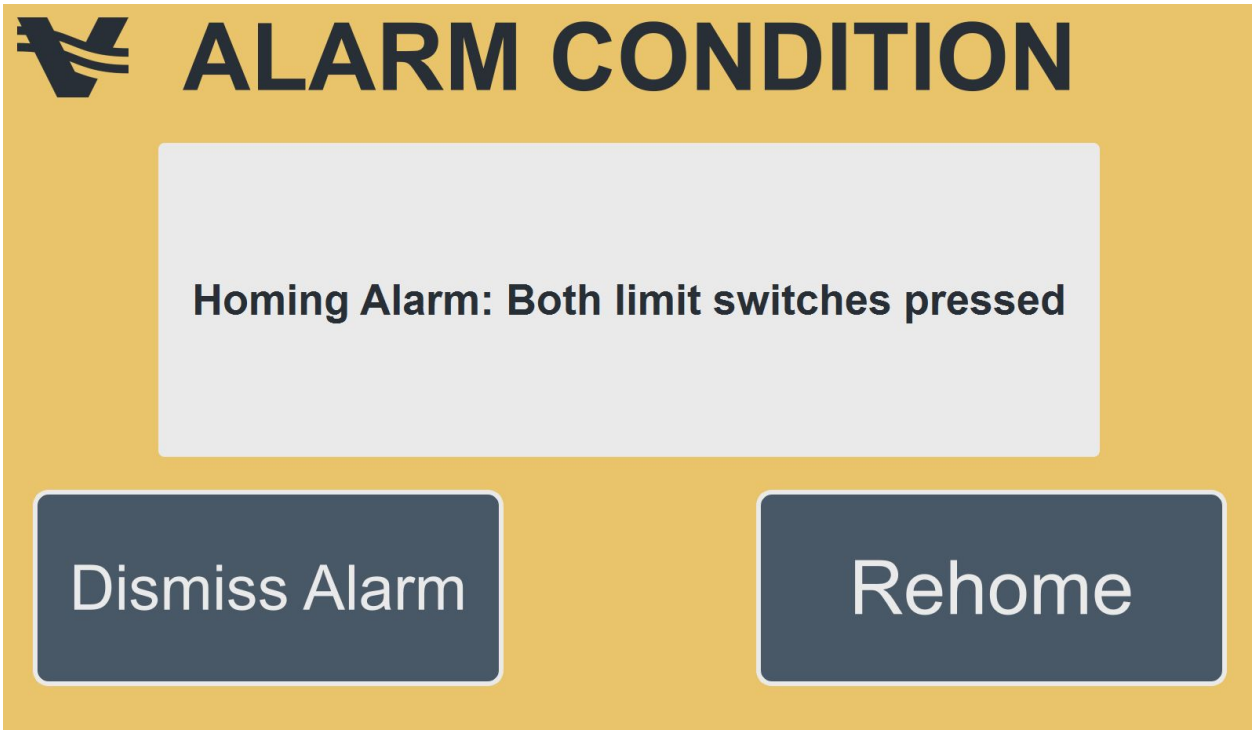
4) Normal Operation: The screen below is shown during normal operation and displays the specified parameters set previously, in addition to peak inspiratory pressure (PIP), Positive End-Expiratory Pressure (PEEP), and plateau pressure (PLAT). Measured values for tidal volume, breaths per minute and I:E ratio display the measured values during operation and thus may vary from the set values slightly.

Graphs displaying pressure and flow rate throughout the breathing cycle are also displayed. Relevant status or error messages may be displayed in the log.

Tidal volume, breaths per minute, and I:E ratio should be checked frequently. Values can be updated by clicking the ‘Modify Values’ button, which will then open the ‘Edit Parameters’ page.



5) Alarm States: In the case of an alarm the following screen will be displayed, alongside information specific to the alarm. Alarms should be dismissed and fixed. If the cause of the alarm is not fixed, the alarm will sound again. In some cases, it may be useful to rehome the device, in which case the ‘Rehome’ button should be pressed.



Maintenance and Repair

Mechanical Safety

The main mechanical components of the device that are in motion are the motor, the hinge of the arm, and the rope connected to the pulley. Over time, the rope is likely to wear down, and should be replaced at the user's discretion if they detect any damage. The hinge should be lubricated at least once every month to ensure a minimal amount of resistance between the arm and the hinge. General maintenance of all the screws, adhesives, and wires used on the device should be done each month as well, as the natural vibrations from the device may gradually affect these connections.

Health Concerns

Components of the device that can come directly in contact with patient expired gases are the endotracheal tube and the HEPA filter, where expired gases and saliva contaminate these areas. The rest of the plumbing should be protected from most bodily fluids and gases by the HEPA filter, but it is certainly still at risk should the device fail, and this risk extends to the Ambu-bag itself. To prepare the ventilator for a new patient, the HEPA filter should either be replaced or disinfected (if it is a washable HEPA filter), and the endotracheal tube should be replaced.

The pressure sensor within the plumbing should be protected by the HEPA filter, and thus, should be reusable without disinfection. The entire plumbing and frame of the device should be disinfected between each use.