# 1 PT-019 Elevator Redesign

| Artifact ID | Artifact Title | |
|---|---|---|
| PT-019 | Elevator Redesign | |
| **Team** | **Revision** | **Artifact Date** |
| BYU Mars Rover | 1.0 | 24 January 2022 |
| **Prepared by:** | | **Checked by:** |
| Dallin Cordon | | Chris Sypherd |

## 1.1 Revision History

| Revision | Date | Made by | Checked by | Description |
|---|---|---|---|---|
| 1.0 | 10 Jan 2021 | D. Cordon | | Elevator Redesign |
| 1.1 | 13 Apr 2021 | D. Cordon | C. Sypherd | Added further details on System Overview, Drawings, and Future Recommendations section |

## 1.2 Purpose

The purpose of this artifact is to describe the redesign of the elevator.

## 1.3 System Overview

The elevator is designed to provide the maximum possible vertical motion of the SCARA arm and science module while staying under the 1.2m URC height restriction. It consists of 7 main components:

- **Linear Rail**: 1.15m long C-Beam Rail from OpenBuilds. Provides vertical structure along which the gantry plate can move.
- **Lead Screw**: Transfers vertical motion to the gantry plate.
- **Gantry Plate**: Point of attachment for arm or science module.
- **Bottom Plate**: Attaches linear rail to bottom of electrical box. Supports the weight of the lead screw as well as anything attached to it (gantry plate, arm, and science module). Provides alignment for the lead screw.
- **Top Plate**: Provides alignment for the lead screw. 180 degree mounting attachment for the motor.
- **Motor**: Provides necessary torque to drive the system.

- **Belt and Pulley System**: Allows the motor torque to be transmitted to the lead screw in a 180 degree configuration as opposed to a direct connection. This allows for additional vertical height.

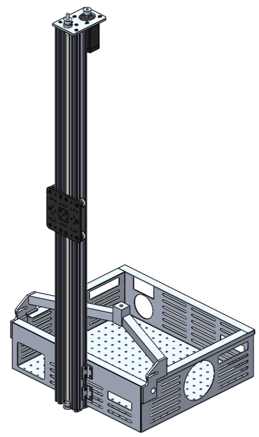


Figure 1: Model view of elevator design.

### Linear Rail

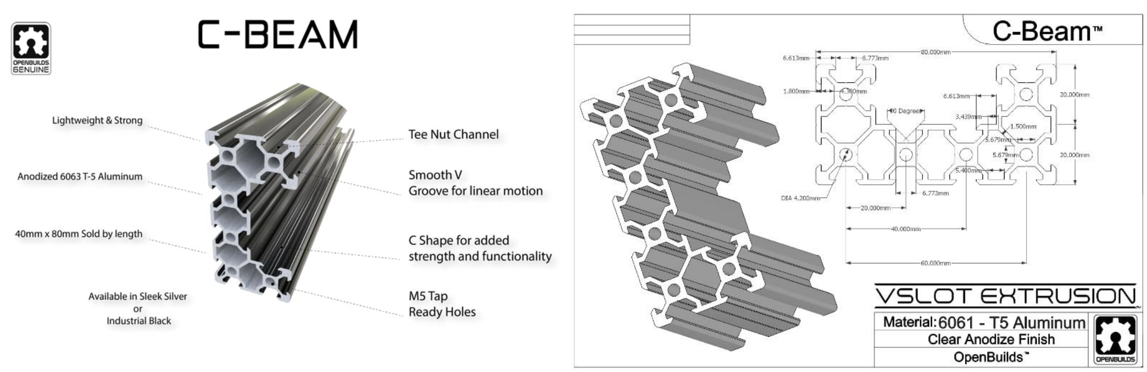



Figure 2: Promotional material for OpenBuilds C-Beam Rail.

The linear rail forms the bulk of the elevator and consists of a 1.15m long section of C-Beam Rail from OpenBuilds. The built in t-nut channels allows for attaching the elevator directly to the front of the electrical box via L-brackets. Be sure that the elevator is always connected to the electrical box by both the bottom plate and the L-brackets.

## Lead Screw

A precision trapezoidal 8mm metric ACME lead screw. According to the product specifications, the sizing is defined as "Tr8*8-2p (4 starts)" with a 2mm pitch and a diameter of 7.8 (mm). Additionally, they specify that this lead screw has been customized to work directly with the OpenBuilds system. A 1.540m section was purchased and cut to 1.185m. The lead screw's primary function is to drive the gantry plate (and–in conjunction–the arm and science module) up and down. The bottom of the lead screw features two threaded lock nuts which are tightened relative to one another to create a jam nut. This jam nut sits upon a precision shim which, in turn, presses on a flanged bearing which transmits loading to the bottom plate. Therefore, the weight of the gantry plate along with any attachment is transferred into the lead screw and is supported by the bottom plate using the jam nut and bearing combination. This can be seen in Fig. 3.

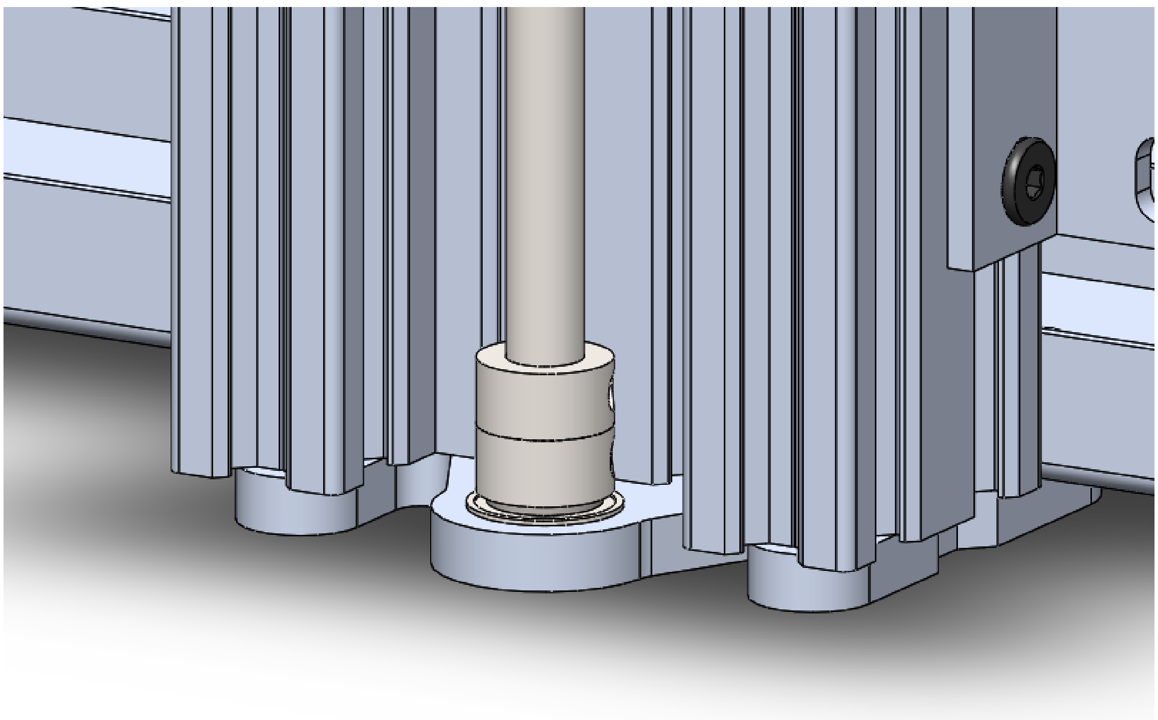


Figure 3: Lower extremity of the lead screw. Jam nut, precision shim, flanged bearing, and bottom plate can be seen in descending order.

## Gantry Plate

The gantry plate provides the interface whereby the arm and science module can be mounted to the elevator. Rotary motion of the lead screw is translated to longitudinal translation of the gantry plate via two nut blocks attached to the back of the plate. A 6mm spacer and a precision shim is used to verify the relative distance between the gantry plate and the lead screw such that lateral forces are not introduced due to improper alignment thus removing any bowing from the lead screw. The gantry plate has four wheels that can be tightened onto the linear rail. These wheels help the gantry plate traverse the rail smoothly and prevents twisting moments. In addition to these wheels, acetal (or Delrin) runners provide a clamping force between the gantry plate and the linear rail. These runners prevent the gantry plate and lead screw from flexing forward due to the weight of the arm. These moments and their associated mechanisms for counteraction can be seen in Fig. 4. Furthermore, the presence of the runners prevents the moments caused by the arm to deflect gantry plate and, in association the wheels and lead screw.

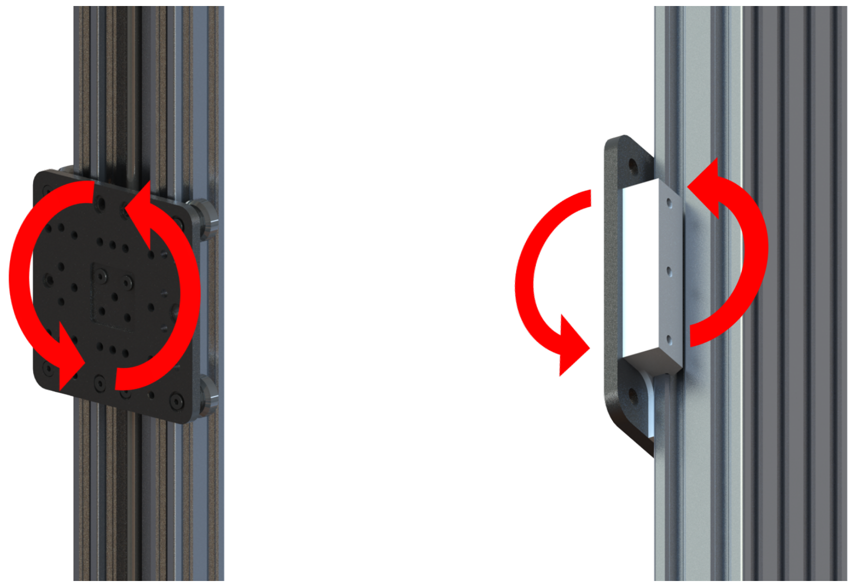


Figure 4: Moments counteracted by various components associated with the gantry plate. Left: The four wheels counteract torsional moments caused by arm configurations where the center of mass is off centered. Right: The runners counteract moments caused by the weight of the arm. Notice the small flange extending from the bottom of the runner. This provides the appropriate spacing between the gantry plate and the linear rail to ensure further rigidity, thus keeping the plate parallel to the rail.

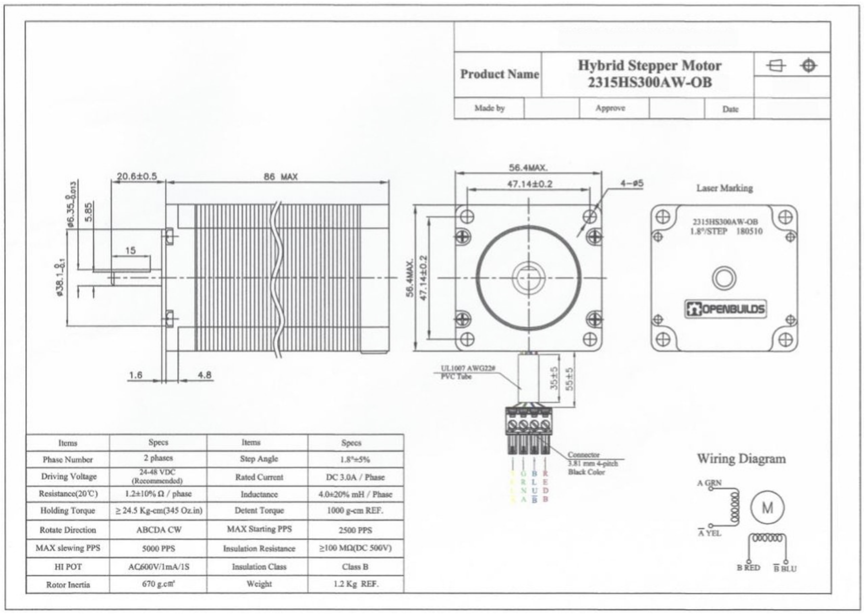
## Bottom Plate

The bottom plate attaches the linear rail to the electrical box. It supports the weight of the rail as well as the arm as transferred through the lead screw. The plate been machined in accordance with the OpenBuilds system so as to ensure proper lead screw alignment in reference to the mounting points for the rail. It has been optimized for minimum deflection and minimum weight as guided by Altair topology optimization software. The plate features slots at the connection between the plate and the electrical box so as to be adaptable to different electrical boxes and varying tolerances in the sheet metal bending process. As such, the exact distance between the holes in the box and the edge of the box becomes inconsequential. In addition, several areas are counter-sunk so as to allow the M5 low profile mounting fasteners to sit flush with the plate as well as to provide a housing for the flanged bearing. This bearing provides radial alignment for the lead screw and, as previously stated, is the load bearing component of the lead screw and associated components.

## Top Plate

The top plate provides a mounting surface whereby the belt and pulley system can function (see the following section for more information). As with the bottom plate, the relative dimensions between mounting holes is such as to provide precise lead screw alignment as it passes through the top, gantry plate assembly, and bottom. Keeping the lead screw as straight as possible is ideal for proper elevator functionality.

## Motor




| Items | Specs | Items | Specs |
|---|---|---|---|
| Phase Number | 2 phases | Step Angle | 1.8°±5% |
| Driving Voltage | 24-48 VDC (Recommended) | Rated Current | DC 3.0A / Phase |
| Resistance(20℃) | 1.2±10% Ω / phase | Inductance | 4.0±20% mH / Phase |
| Holding Torque | ≥ 24.5 Kg-cm(345 Oz.in) | Detent Torque | 1000 g-cm REF. |
| Rotate Direction | ABCDA CW | MAX Starting PPS | 2500 PPS |
| MAX slewing PPS | 5000 PPS | Insulation Resistance | ≥100 MΩ(DC 500V) |
| HI POT | AC600V/1mA/1S | Insulation Class | Class B |
| Rotor Inertia | 670 g.cm² | Weight | 1.2 Kg REF. |

Figure 5: Stepper motor data sheet.

The motor is a 2 phase 1/4" shaft NEMA 23 "High Torque Series" stepper motor. According to product specifications, the recommended range of operation is between 24-48 VDC. It's listed torque is 345 oz*in which translates to 2.436 N*m or 21.56 in lbf. The motor attaches to the underside of the top plate as seen in Fig. 6, 8, and 9.

## Belt and Pulley System

The belt and pulley system allows for the lead screw to be driven by the motor while maintaining a 180 degree mounting configuration. The draw to a belt and pulley system over a direct drive system is space saving. The lead screw connects to an OpenBuilds 3GT (GT2-3M) 20-tooth aluminum timing pulley with an 8mm clamping bore specifically made for OpenBuilds lead screws. The motor shaft connects with another OpenBuilds 3GT (GT2-3M) 20-tooth aluminum timing pulley with a 1/4" bore. The two pulleys are connected by a 3GT (GT2-3M) 9mm wide single-sided timing belt.

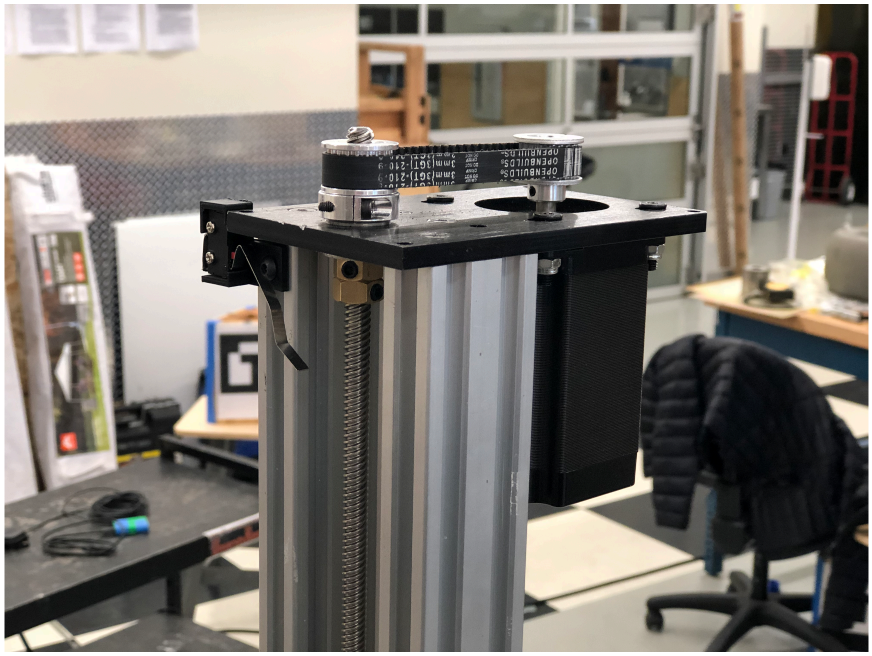


Figure 6: Belt and pulley system.

## 1.4 Development

### The Need for an Elevator

The use of the elevator is directly related to the choice of arm. Previous years used articulated robotic arms which could achieve vertical height through rotary joints as seen in Fig. 7. However, upon inspection of this arm's performance at competitions, it was observed that the majority of tasks required manipulability in a single horizontal plane (e.g., flipping a row of switches, pulling open a cache, and typing on a keyboard). As such, the 2020 team elected to redesign the arm in favor of a Selective Compliance Articulated Robot Arm (SCARA) arm with a spherical wrist. This redesign increased the arm manipulability in a single working plane and had the added benefit of supporting arm weight through the joints rather than directly by the motors, reducing likelihood of motor burnout.

However, this redesign eliminated the arm's capacity to attain vertical height. Thus, the elevator was designed and implemented to allow the SCARA arm to reach heights of up to 1.5m in accordance with competition rules which specified, "Equipment will be between 1.5m height and the ground" **(3.d.ii)**.

### Elevator Redesign

The URC rules were updated for the 2022 competition to add a 1.2m height restriction.

> (**2.a.ii**) "Rovers shall be weighed by the judges during the set-up time of each mission. For weighing the rover **must fit completely within a 1.2m x 1.2m x 1.2m box**.

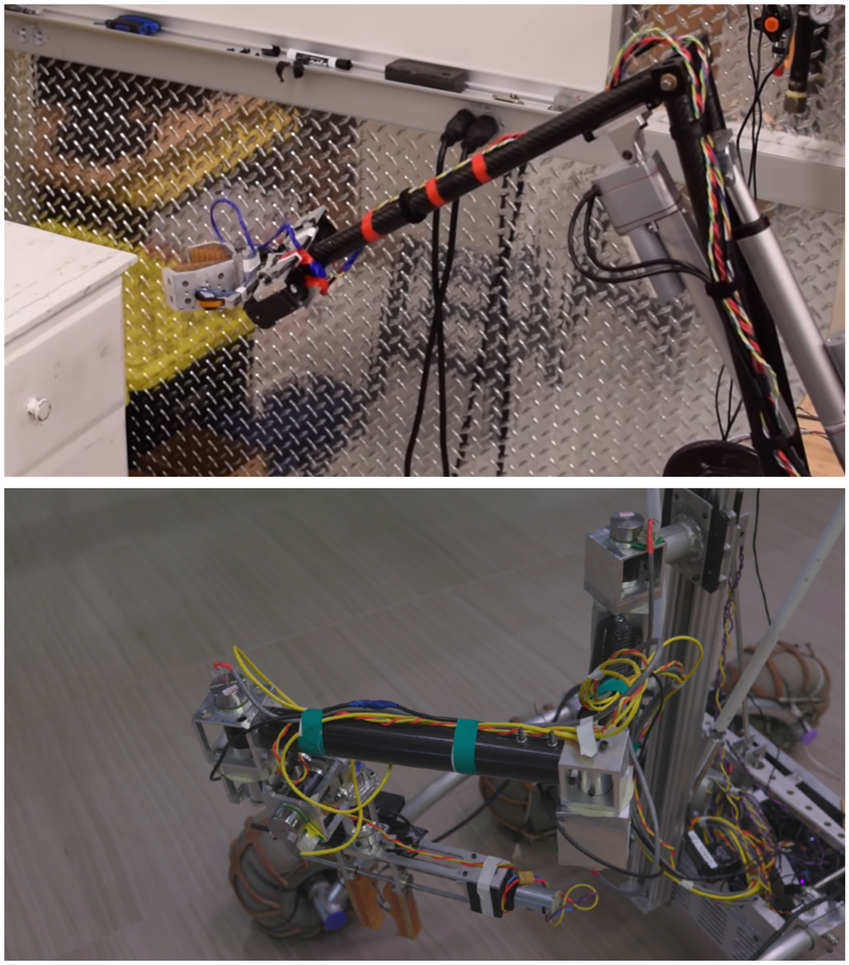


Figure 7: Screenshot comparisons of arm designs taken from the BYU Mars Rover 2019 SAR submission video (top) and 2021 SAR submission video (bottom). Notice the implementation of the SCARA arm configuration in 2021 and the use of the elevator for attaining vertical height.

> Rovers may be placed in any orientation, and articulate/fold/bend to fit within the transport crate, but may not be disassembled to do so. This includes wheels, antenna, and any other system protruding from the rover. **Failure to fit within the specified dimensions at weigh-in will result in a 40% penalty. After weighing, rovers may unfold/expand to any size**."

To accommodate these new size restrictions, the existing rover was redesigned such that the rocker-bogie system could fold up, allowing the rover to sit on its electrical box for weigh-in (for more details regarding this folding system, see PT-014). Theoretically, this would allow the elevator to be exactly 1.2m tall when the legs were folded for weigh in. As such, when the legs were deployed, the added height would allow the arm to reach its desired 1.5m maximum height.

### Issues With Existing Elevator

The existing elevator is 1.42m tall thus necessitating a redesign. As discussion turned to the elevator, a number of issues were brought up that the redesign would need to address.

- **Height**: The existing elevator is 1.42m tall. It needs to be a maximum of 1.2m tall.
- **Usable Space**: Approximately 0.156m of the elevator is taken up by the stepper motor and its coupling to the lead screw.
- **Binding**: According to faculty and other team members, there have been issues with mechanical binding in the elevator assembly. Dr. Killpack has theorized that this may be due to misalignment and poor tolerances. Dave Laws additionally pointed out the lack of bearings on the elevator assembly allowing the lead screw to wander.

A successful redesign of the elevator would address each issue effectively, however, height was determined to be the most critical concern.

### Height

To reduce the height of the elevator, two options were available: cut the existing elevator to size, or purchase new components to build a second elevator. It was decided we would build a new elevator so we could have a working elevator to fall back on in case something went wrong with the new one. Additionally, buying new components would allow us to address the other issues previously listed.

Under the assumption that nothing else about the design would change, we sought out to calculate the maximum height the gripper could reach if the elevator were shortened to be exactly 1.2m tall and the wrist were positioned vertically. With a goal of 1.5m, the following calculation was determined,

$$\text{Max Gripper Height} = [\text{Ground Clearance}] + [\text{Max Elevator Height}] - [\text{Top of Elevator to Tip of Gripper}]$$

The current electrical box gives 0.24m of clearance. However, a new electrical box is under development (see ) which would allow for 0.275m of clearance. It was also determined that the gripper extends 5.6cm above the top of the elevator when vertical at its highest point. Therefore,

$$\text{Max Gripper Height} = [0.275\text{m}] + [1.2\text{m}] - [0.056\text{m}]$$

$$\text{Max Gripper Height} = 1.531\text{m}$$

This calculation, though idealized, confirmed that shortening the elevator to exactly 1.2m with no other changes would be sufficient to fulfill the URC requirements albeit right on the edge. If only the very tip of the gripper can reach 1.5m, that leaves very little room for manipulability. Additionally, this calculation did not take into account sagging arm joints which result in lower attainable heights. As such, the team began research into additional ways to gain vertical height from the elevator.

**Usable Space**

With 0.156m of the elevator dedicated to the motor and the coupling, two space saving concepts were developed. Both would allow more of the 1.2m height to be allocated to rail, thus allowing the arm and gripper to travel higher.

The first design involved installing the stepper motor at a 90 degree angle to the elevator and connecting the stepper motor to the lead screw with a worm gearbox. The gearbox would be purchased rather than designed. However, difficulty arose in sourcing a compatible gearbox and what could be found was generally to large for our applications.

The second design involved installing the stepper motor at a 180 degree angle to the back of the elevator rail. The motor would connect to the lead screw via a belt and pulley system. The belt system takes up less vertical space on the elevator, giving the arm greater height, while also being more lightweight. However, there is debate that this belt and pulley system is less robust.

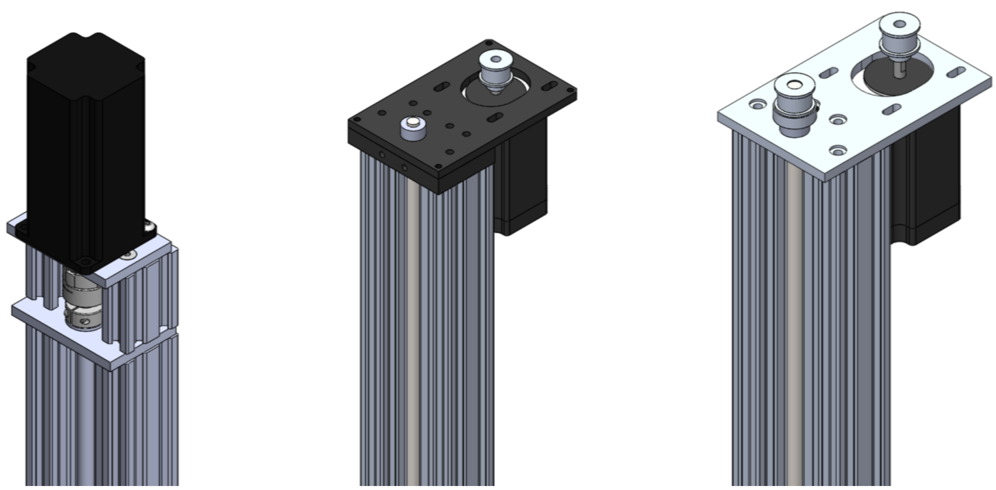


Figure 8: Comparison of initial motor mounting configuration (left), commercially available reduction stand-off motor mount plates (center) and student designed single plate motor mount configuration.

OpenBuilds Part Store has a belt and pulley motor mount system specifically designed for the C-Beam linear rail. These components were purchased and implemented. For greater detail regarding the assembly, see the attached CAD drawings. Dimensions for the top and bottom plates were taken from open source CAD drawings developed by OpenBuilds and altered to reduce weight and ensure proper mounting of the motor to the linear rail (see Fig. 8).

Next, the exact height of the linear rail for the elevator needed to be determined. By subtracting the height of the belt system (28.35mm) and bottom mounting plate (6mm) from the 1.2m size restriction, it was calculated that the rail could be no more than 1.16565m or 1165.65mm. To accommodate any unforeseen issues in mounting, the rail was cut to 1.15m, allowing a 15.65mm clearance between the top of the elevator and the 1.2m height restriction. The 8mm diameter lead screw, while in theory could be exactly 1.2m, was cut to be approximately 1.185m allowing a 15mm clearance from the height requirement.

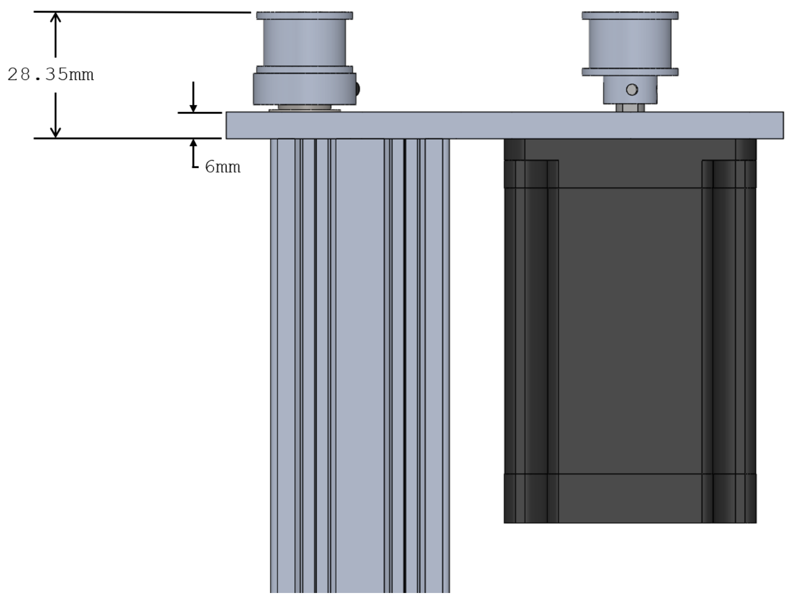



Figure 9: Height measurements of plates and drive system components atop the elevator's linear C-Beam rail.

**Binding**

The team settled on using nearly the exact same elevator system with some simple redesigned components. The original elevator consists of a C-Beam extruded aluminium linear rail manufactured by OpenBuilds Part Store. All other components were purchased from McMaster Carr or machined. Imperfections in these interactions between the linear rail and the various mounting plates and hardware resulted in a poorly aligned system subject to significant binding.

It was discovered that OpenBuilds Part Store sells an assortment of plates, lead screws, and hardware specifically built to accommodate their C-Beam linear rails. By utilizing these components, we save time given that the work of component tolerances and interfaces has already been accounted for. It is important to note that all of the OpenBuilds systems are metric and use M5 bolts for assembly. While the majority of the rover's fasteners will be use customary units, the elevator assembly will need metric M5 fasteners.

The previous design used very few bearings, thus contributing to the binding issue.

In order to ensure proper alignment, extra care was taken to square off the edges of the linear rail with an end mill. In order to save time, it was decided that the top plate would not be ordered from scratch but instead ordered directly from OpenBuilds (SKU: 872) and then altered to include the necessary counter bores for screw heads and, most important, the flanged bearing. However, when this was carried out, we discovered that the alignment between the stock and the position of the various holes in this plate was slightly askew. As a result, when we set up the CNC toolpathing and ran the mill, the conterbored holes were slightly off from the through hole location. Simply put, this created an ever so slight misalignment between the holes wherein the lead screw passes through the top and bottom plates. In order to eliminate this very slight misalignment, the top plate was machined from scratch and was not manufactured from a preexisting OpenBuilds part.

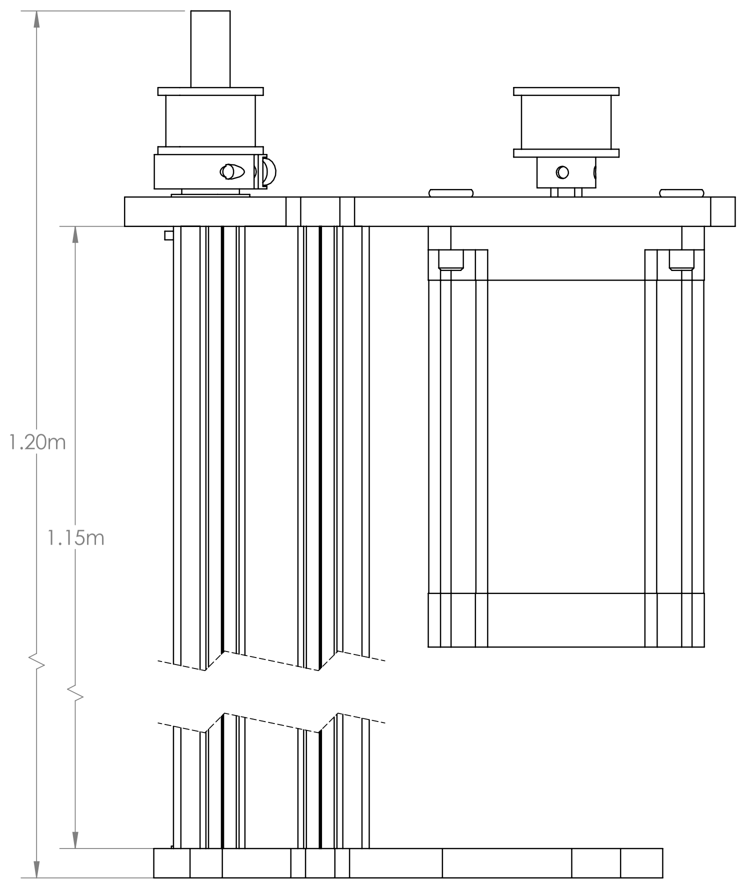
As previously mentioned, open source CAD drawings for the end mount and reduction/stand-off plates were used to develop a single plate solution that would reduce weight and ensure proper mounting of the motor to the linear rail (see Fig. 8). Another plate, based on the OpenBuilds C-Beam End Mount plate, was designed for the bottom whereupon the elevator rests and is connected to the electrical box.

## 1.5 Future Recommendations

- Use topology optimization software to implement weight reduction on the runner.
- The OpenBuilds system components are all custom designed to work together and therefore will be incompatible with other off-the-shelf available parts. If you would like to swap out any individual component for a component from, say, McMaster Carr, you will likely need to replace most of the remaining system. It could be worth looking into redeveloping the system using more generalized parts so as to remove the dependency on OpenBuilds.
- Spec out a motor that produces less noise while operating.
- Use dry lubricant for elevator components.
- Implement limit switches on the top and bottom to ensure the gantry plate does not exceed upper and lower travel limits.
- Add some functionality to ensure proper tension of the timing belt. This could be some mechanism to verify the motor stays at a given location without moving or could be a timing wheel to reduce slack in the belt.
- The pulley that attaches to the motor has a space for two set screws to tighten down on the motor shaft. The motor shaft only has one flat section where a set screw can attach. Consider grinding down another face at 90 degrees to the current face for the second set screw to clamp down on.

## 1.6 Drawings

See the following pages for drawings of the system. Currently, drawings have yet to be formulated for the runners.

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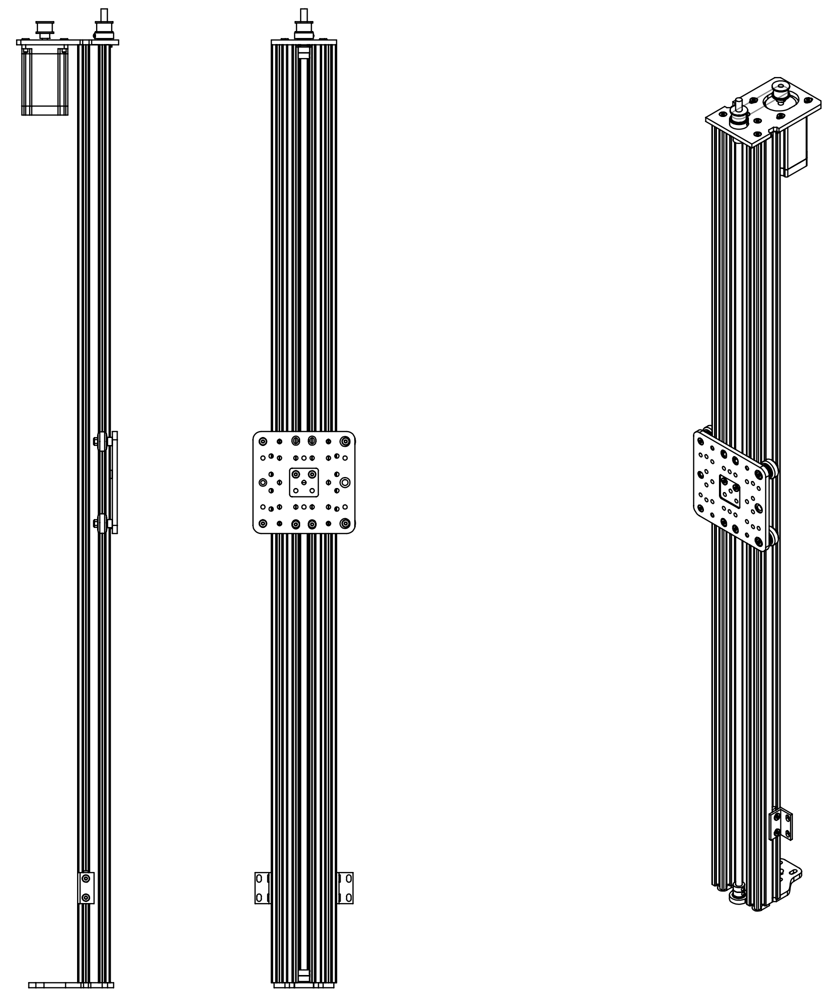

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COMMENTS:

TITLE:
# High Level System View

SIZE **B** DWG. NO. Elevator REV A

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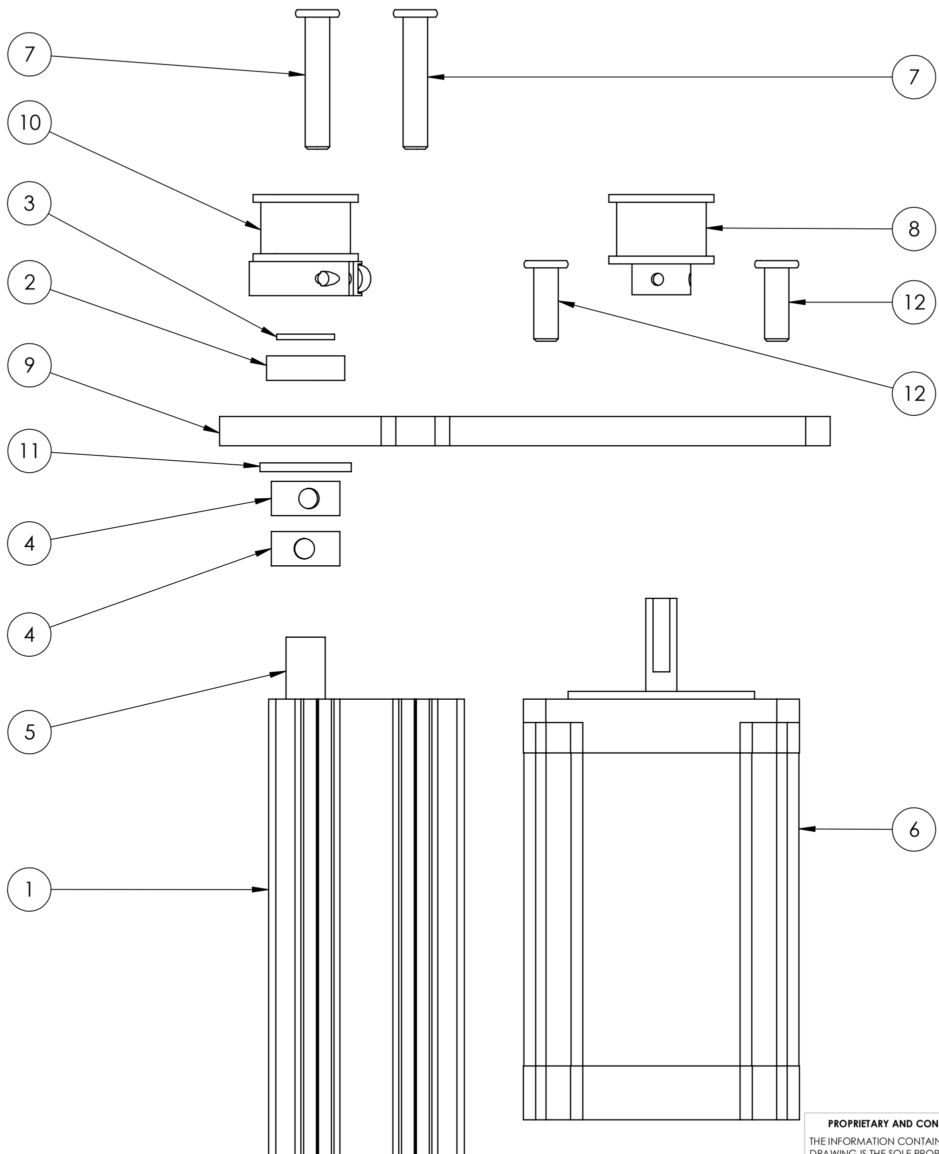


| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | OpenBuilds SKU: 50-LP | C-Beam 40 x 80 x 1200 Linear Rail cut to 1.15m | 1 |
| 2 | OpenBuilds SKU: 2215 | Flanged Ball Bearing 688ZZ 8 x 16 x 5 | 1 |
| 3 | OpenBuilds SKU: 835 | Shim Washer - 12 x 8 x 1mm | 1 |
| 4 | OpenBuilds SKU: 3025 | Tension Lock Nut 8mm. M5 set screw included. | 2 |
| 5 | OpenBuilds SKU: 100-LP | 8mm Metric Acme Lead Screw | 1 |
| 6 | OpenBuilds SKU: 596 | NEMA 23 Stepper Motor - High Torque Series | 1 |
| 7 | M5 x 27 | Low Profile Screw M5 x 27 | 4 |
| 8 | OpenBuilds SKU: 712 | 3GT (GT2-3M) Timing Pulley - 20 Tooth - .250" Bore - 9mm Belt. 2 M3 5mm x 1.5mm set screws included. | 1 |
| 9 | OpenBuilds SKU: 872 | Modified NEMA 23 Reduction/Stand Off Plate. Critical modification is ⌴ ⌀16.1mm ↧ 4.5mm at center lead screw hole. | 1 |
| 10 | OpenBuilds SKU: 2130 | 3GT (GT2-3M) Timing Pulley - 20 Tooth - 9mm Belt - 8mm Clamp Bore. 2 M3 5mm x 1.5mm set screws included. | 1 |
| 11 | Flat Washer 0.25in | Basic wide diameter >8mm bore washer | 1 |
| 12 | M5 x 15 | Low Profile Screw M5 x 15 | 4 |



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COMMENTS:

TITLE:
# Top Level Assembly

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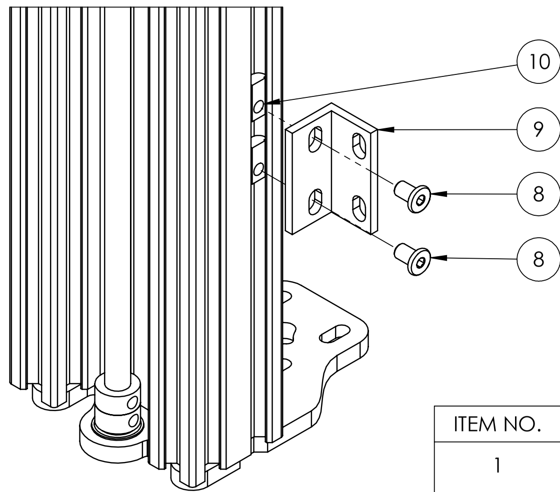
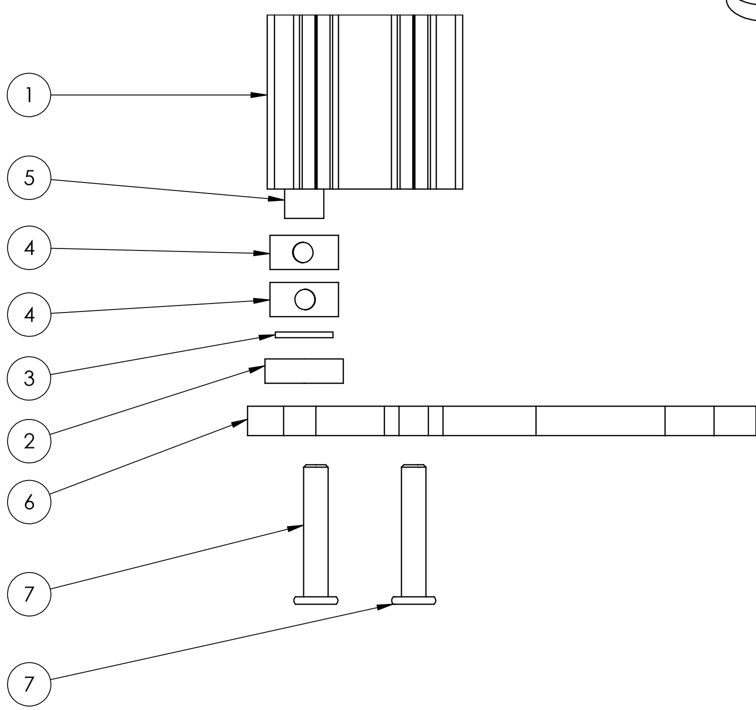



FOUR ADDITIONAL SCREWS (NOT SHOWN) ATTACH THE L BRACKET TO THE ELECTRICAL BOX (NOT SHOWN)

SCALE 2 : 3




| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | OpenBuilds SKU: 50-LP | C-Beam 40 x 80 x 1200 Linear Rail cut to 1.15m | 1 |
| 2 | OpenBuilds SKU: 2215 | Flanged Ball Bearing 688ZZ 8 x 16 x 5 | 1 |
| 3 | OpenBuilds SKU: 835 | Shim Washer - 12 x 8 x 1mm | 1 |
| 4 | OpenBuilds SKU: 3025 | Tension Lock Nut 8mm. M5 set screw included. | 2 |
| 5 | OpenBuilds SKU: 100-LP | 8mm Metric Acme Lead Screw | 1 |
| 6 | BottomPlate | Topology Optimized Bottom Plate based on dimensions of OpenBuilds parts (SKU: 2330) and (SKU: 872) | 1 |
| 7 | OpenBuilds SKU: 2260-pack | Low Profile Screw M5 x 27 | 4 |
| 8 | OpenBuilds SKU: 946-pack | Low Profile Screw M5 x 8 | 8 |
| 9 | OpenBuilds SKU: 485 | Double L Bracket | 2 |
| 10 | OpenBuilds SKU: 150 | Spring Loaded Tee Nuts | 4 |



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COMMENTS:

TITLE:
# Bottom Level Assembly

SIZE **B** | DWG. NO. Elevator | REV A

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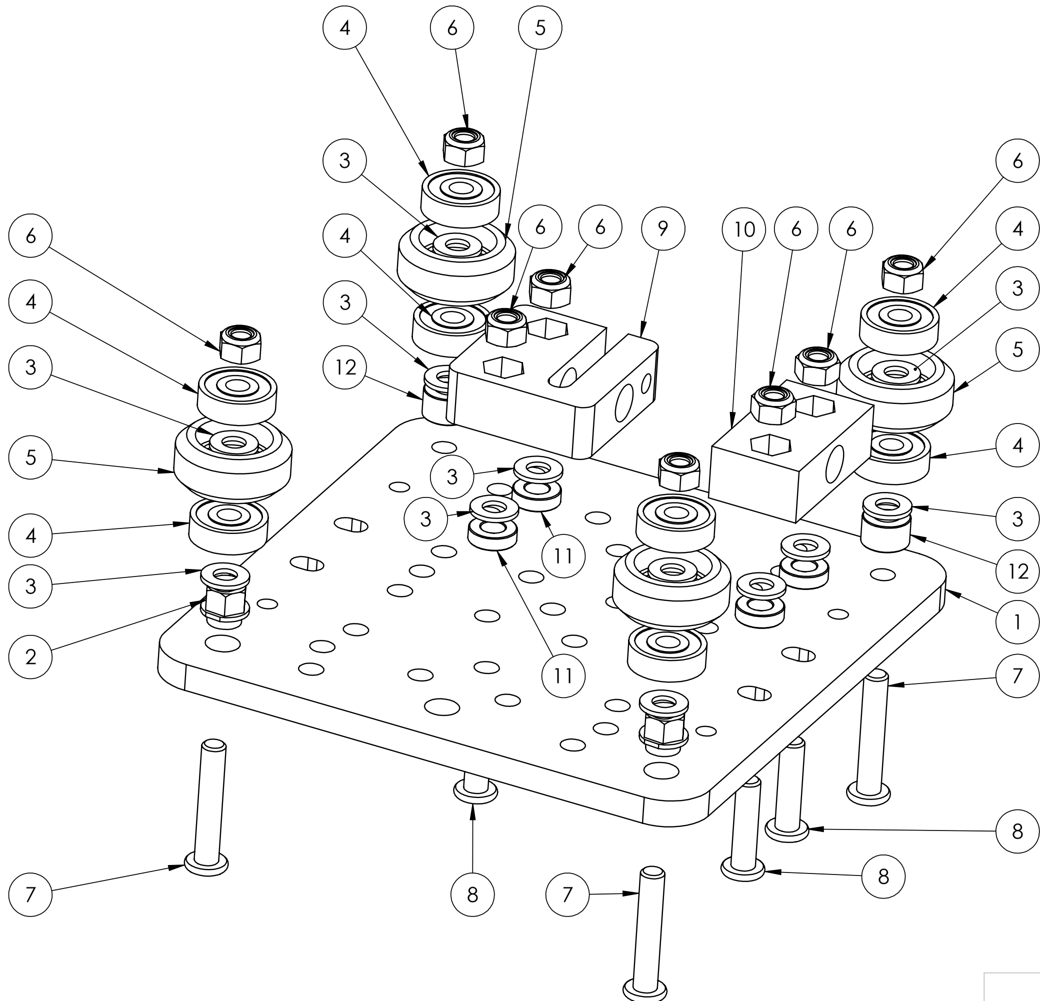


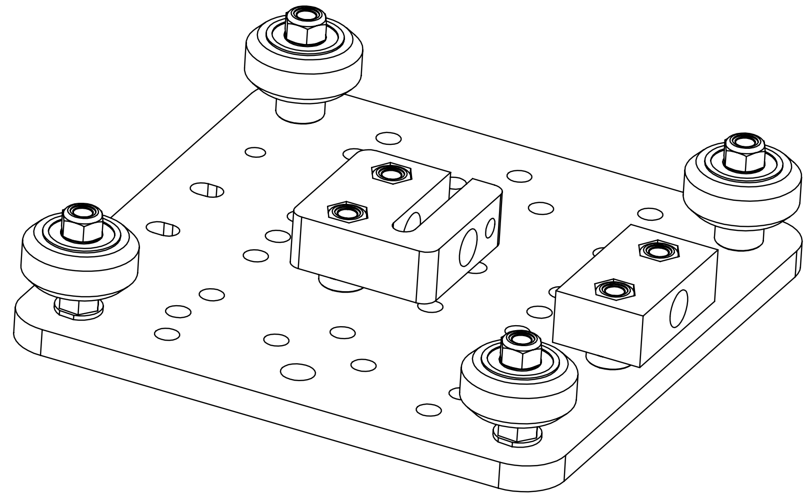

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | OpenBuilds SKU: 2030 | C-Beam Gantry Plate XLarge | 1 |
| 2 | OpenBuilds SKU: 226 | Mini Eccentric Spacer 6mm | 2 |
| 3 | OpenBuilds SKU: 5 | Precision Shim 10 x 5 x 1 | 12 |
| 4 | OpenBuilds SKU: 30 | 625 2RS Ball Bearing 5 x 16 x 5 | 8 |
| 5 | OpenBuilds SKU: 55 | Xtreme Solid V Wheel | 4 |
| 6 | OpenBuilds SKU: 10-pack | Nylon Insert Lock Nut M5 | 8 |
| 7 | OpenBuilds SKU: 2260-pack | Low Profile Screw M5 x 27mm x 0.8 thread. For attaching wheels. | 4 |
| 8 | OpenBuilds SKU: 750-pack | Low Profile Screw M5 x 20mm x 0.8 thread. For attaching nut blocks. | 4 |
| 9 | OpenBuilds SKU: 1055-set | 8mm Acme Anti Backlash Nut Block | 1 |
| 10 | OpenBuilds SKU: 740-set | 8mm Acme Nut Block | 1 |
| 11 | OpenBuilds SKU: 175-pack | Aluminum Spacer 3mm | 4 |
| 12 | OpenBuilds SKU: 90-pack | Aluminum Spacer 6mm | 2 |



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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | D.CORDON | FEB 02 22 |
| CHECKED | J.C.LIECHTY | FEB 22 2022 |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |

COMMENTS:

TITLE:

# Gantry Plate Exploded ASM

SIZE **B** | DWG. NO. GantryPlate | REV

SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1