Micron Actuator Version History Blog

Baird Bankovic

***Top of document is most current design.**

Project Goals

There are two primary goals from this project. First, a low cost general purpose micro-meter precise stepper motor actuator. Second, a low cost three axis micro-meter precise motion system.

Actuator

Since the motion system will need an actuator, the primary focus is to develop an actuator. Commercial actuators do exist, but due to the low volume and high reliability requirements, there are only two manufactures that make nice stages: ThorLabs and Standa. ThorLabs μm stages use DC brushed servo motors, starting at $1100 per motor (for 25mm travel); while Standa's start at $750 for 25mm travel bipolar stepper motor actuators. **I have full disassembly photos of the Standa motors, please leave a comment if you would like me to post those.**
My goal is to create an open-source bipolar stepper motor actuator that is precise down to single-digit μm, and provide this actuator design at a hobby-accessible price which factors in my assembly time, and bill of materials (BOM). I intend to sell these actuators to members of the community at such a cost.
The Standa motors which I plan to out perform are shown below.

Figure 1: $750 Under torqued μm actuator

Motion System

In order for single-digit μm to be useful, they need to be paired with a motion system. For this, I have tried numerous different economical (sub $500) linear 3-axis stages. I found the best **price-to-**

performance to be the `mpositioning.com` T60XYZ-25L10A for $330 at `https://www.amazon.com/gp/product/B00WMSJX9W/ref=ppx_yo_dt_b_asin_title_o00_s02?ie=UTF8&psc=1`, below.

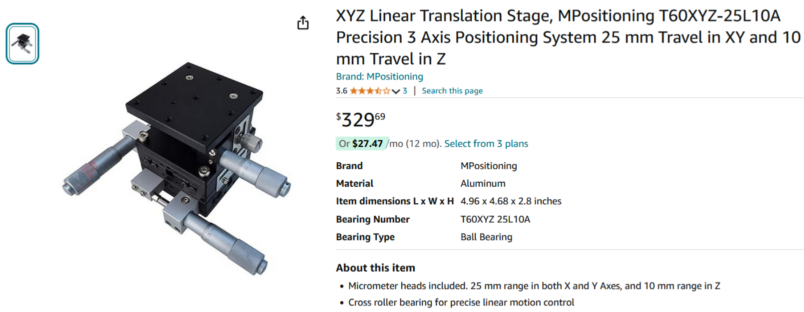


Figure 2: Low-cost 3-axis μm precise motion system.

This stage is cheap, yet still has nice enough bearings such at that the limitation will be on the motorized actuators and not the stage itself. However, the preloading from springs on the stage do mean that the actuators do need a considerable torque. If able, the actuators paired with this stage result in a relatively low-cost 3-axis single-digit μm modular motion system!

Version 3.0, Proposal — Nov-2024 — NEW

The previous versions were focused on creating a general-purpose actuator. For Version 3, I am focusing on getting a different project done which needs $1\mu m$ precise xyz stage. I am going to more closely integrate Version 3 to work specifically with the MPositioning stage linked above. Once that stage is working as a prototype, I will do a thorough characterization of the performance with a longevity test which will be summarized in a video. After I am confident in the results, I will post the motorized xyz complete stage for purchase on my website `bairdbankovic.com`.

This update shows the current designs for the XY stages (which use a coaxial drive design), and the Z stage (which uses a self-contained motorized micrometer, 10mm travel design).

XY Stages

After playing with a number of other undocumented designs, I have settled with a design that reduces the number of parts, while also keeping motor weight low and torque/speed/acceleration high. Nema 11 (in general) always has better torque/weight than Nema 8 due to the increase lever arm. The only Nema 11 I found with a 6mm ID with a hollow tube weighs 190 grams, and is way over-torqued. However, Kozak Micrometers is manufacturing a custom run of threaded rods/bushings at M3 size long enough for me to use in this project. That allows me to use a motor with a tube ID of 3mm. Now, I switched to Stepper Online's 28x28x32mm NEMA 11 with a weight of 110 grams. With this new motor, I will drill and ream the ID to 4.5mm, which will form a slip-fit with the 4.5mm (1 thou under) bushing. Loctite Red is rated to bridge this 1-5 thou gap, which I will use to mount the bushing in the motor. This is a VERY low part count, low run-out design. Only difficulty is having a lathe tram enough – which I now have. The mount will be SLM 3d printed for cheap, and critical features milled and drilled to dimension.

Here is the BOM for a total of two complete actuators, including 3-day shipping on everything:

- Stepper Motor: Qt2 from Stepper Online: $56.81 Shipped
- Threaded Rod & Bushing: Qt2 from Kozak Micro Adjusters: $37.39 Shipped
- Motor Mount: Qt2 from IN3DTEC: $44.55 Shipped
- 4.5mm Reamer: $35.50
- Loctite Red: $7.49 Shipped
- Fasteners (NOT INCLUDING IN TOTAL COST):
  - M2.5x5, Qt3 bought in bag of 100: $6.00
  - M2.5x20, Qt3, bought in bag of 50: $15.58
- **Total Cost Per XY Actuator at QT2: $90.85**

While this is still much lower than commercial solutions, the cost is higher than it initially seemed it would be. Additionally, I am not factoring in machining costs (time). At higher volumes the cost will come down, but not much I imagine. The goal was less than $100 per actuator, that has been met at least! I will follow-up with "Version 3.0, Realized" once I have all the parts and test it.

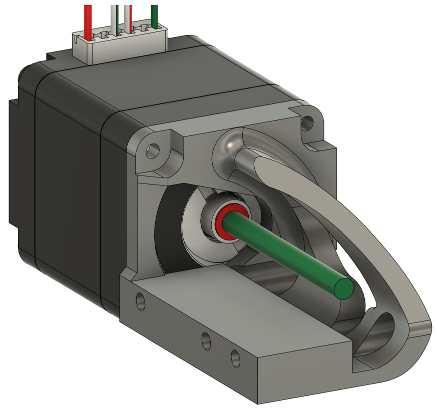


Figure 3: CAD of proposed design. Red: Threaded bushing, Loctite Red in place in reemed stepper's shaft. Green: M3-0.05 up to M3-0.25mm threaded rod (Provided by Kozak).

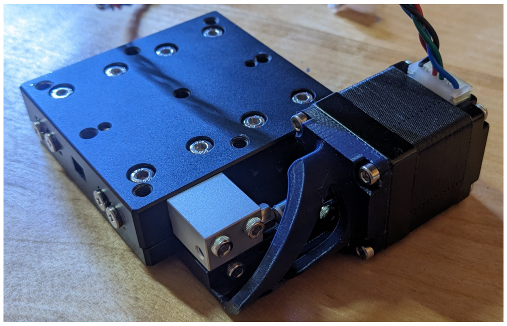


Figure 4: FDM prototype of Version 3. Motor size is roughly accurate.

Z Stage

The Z stage is more difficult because it uses a right-angle slip motion linkage (see figure 5). **If you read this, send me a message at bairdlabs@bairdbankovic.com with code "MAX9945 is cool 77K" and I will Venmo you $2.50, curious if people read this far.** Because the angle the linkage is at changes as it moves, using a hex head on the linkage as is done on the XY stages is a bad idea, and will bind up.

For the Z stage, I am using a refined design similar to Version 1.0.

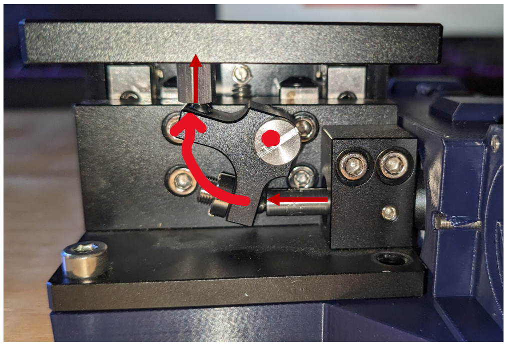


Figure 5: Showing Z axis uses a 90 degree motion transfer.

Since the XY stage will need machining, doing an operation to ream the motor mount from Version 1 to solve the problem of keeping the motor shaft and micrometer screw parallel will not be a big issue. Figure 6 shows a “cobbled” together motorized z. The final version will look very similar to Version 1, except it will be made for only a 10mm travel micrometer (as opposed to 25mm travel), and be designed for milling operations to get the critical tolerances correct (viz. reeming, threading). *Updates soon to come...*

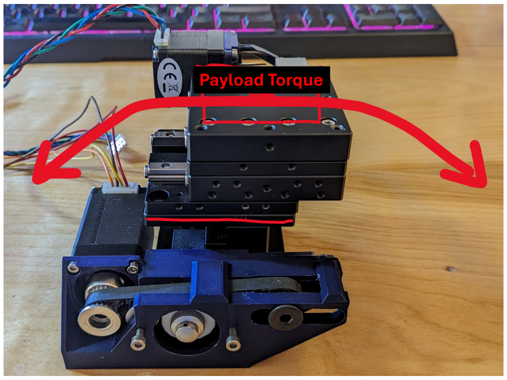


Figure 6: Z axis prone to flexing under large overhanging payloads. Because of this, I want to keep mass low and central!

Version 2.1 — Nov-2024

Version 2.1 attempts to combine the advantages from Version 1.0 with that of V2.0. This consist primarily of reducing the actuator weight so that the load on the motion system is not too great. Target weight is less than 150g while V2.0 is around 190g. Also, this version should see SLS-based metal 3d printed components, and a homing switch. A BOM is provided below. Due to weight constraints, this design uses a nema 8 stepper motor with a hollow shaft. This seems to provide enough torque at a quoted 15mNm; significantly less than that in V2.0, but since the thread pitch is so fine, torque requirement are low anyway.

- Nema 8 Stepper: `https://www.omc-stepperonline.com/dual-shaft-nema-8-hollow-shaft-stepper-mo` `search=Dual%20Shaft%20Nema%208%20Hollow%20Shaft%20Stepper%20Motor%20Bipolar%201.` `5Ncm%282.12oz.in%29%200.49A%2020x20x27mm` Stepper Online, Nema 8 Hollow Shaft $20.55.
- ThorLabs Scew: #F3SS25 25mm long M3x0.25 screw, $5.42
- ThorLabs Bushing: #FSSSN1P M3x0.25 nut, 5mm long, $4.31
- **Total Cost Excluding 3D Print: $30.28**

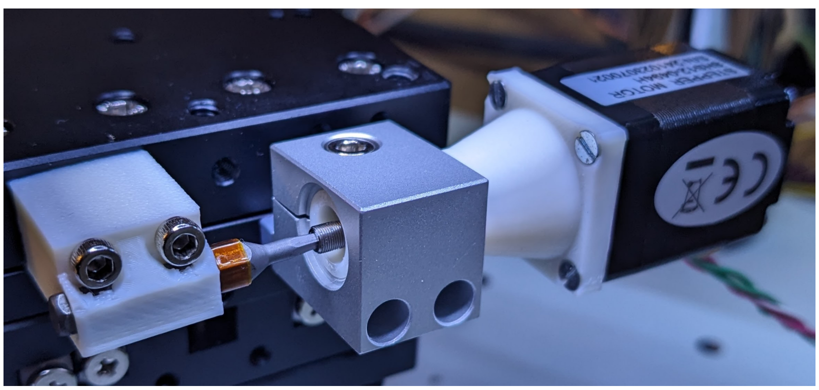


Figure 7: Version 2.1

The actuator works almost perfectly, which a motor weight of only 50g! There are three issues that came up with this design. **First**, the motor just barely has enough torque to drive the stage. (I measured the stage's preloading to be 7 Newtons.) The motor current was difficult to measure since I am using very bad stepper drivers at the moment. Version 2.2 will use a board that has TMC2209 in UART mode – which I will use a reference to set motor currents. **Second**, since is design has the screw stationary and the nut spinning, there needs to be a hex head on the movable section. This works fine for the xy stages, but the z axis cannot be driven co-linearly, and cannot have the hex head. I am working on an additional design for the actuators to fix this. **Third**, the hex head introduces some backlash into the system which can be seen in this video: `https://youtu.be/d6tqoY9BWb0?si=ZW9KK-UpSQC4lQeH`

Figure 8: Stage's xy axis are preloaded with a 7 Newton spring when centered in their travel.

Version 2.0 — Sept-2024

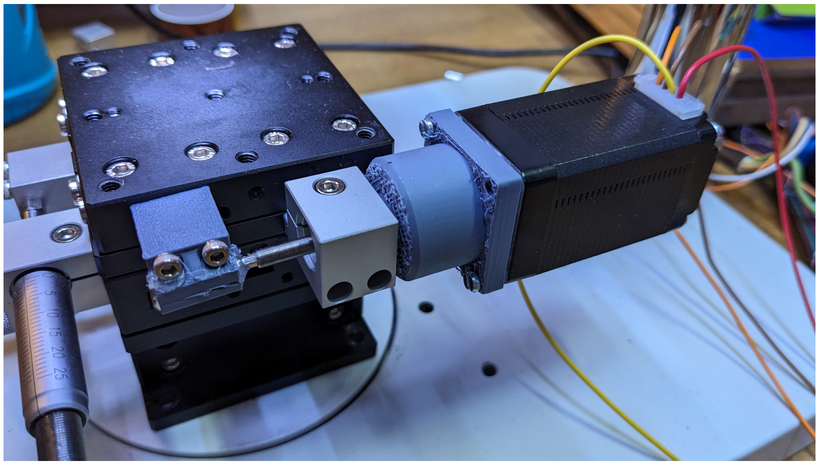


Figure 9: Version 2.0

Version 2.0 eliminates the need for the belt. The difficulty in the design is making $1\mu m$ precise motion, while keeping component tolerance as loose as possible, and minimizing the weight to reduce loading on the linear stage. Version 2.0 utilizes a neat design, whereby the nut rotates in a hollow-shaft nema 11 stepper motor, and an ultra-fine screw remains fixed relative to the motion stage. A jogging demonstration is available at `https://youtube.com/shorts/Wi0tIMpuJTY?si=6TsyFnaCuhp9Vi3V`.
I am using a 6-120 threaded rod and bushing by ThorLabs (see BOM V2.0) which makes this design possible.

- Stepper motor: `https://www.aliexpress.us/item/2251832431362887.html?spm=a2g0o.order_list.order_list_main.5.21ef1802Lm5pEN&gatewayAdapt=glo2usa`
  $40.00 per pair, Nema 11, hollow shaft, internal diameter = 6mm
  Claimed holding torque = 80mN*m
- Threaded micrometer screw: ThorLabs #F6USN2P, 6-120 0.375” long screw, $10.23
- Micrometer bushing: ThorLabs #F6US200, 6-120 2” long bushing (brass), $12.23
- **Total Cost Per Actuator: $42.46**

I HIGHLY recommend the ThorLabs screw and bushing! They are a fantastic price and the quality is perfect. The screw appears to be made of either stainless steel or steel, while the bushing I am certain is a brass alloy. This means the nut will wear faster than the threaded rod, so ideally, the design of the actuator would allow for replacement of the nut.
This version does not have a homing switch, that can be added later.
One disadvantage to this design is that since the motor rotates the nut, there needs to be something to keep the screw from rotating. The ThorLabs 6-120 screws have a hex socket on them, which means the fixed part on the stage can simply have an allen hex head on it to retain the micrometer screw.

I do not see this as a limitation, as all the micrometer stages I have worked with could easily comply with this hex-head constraint.

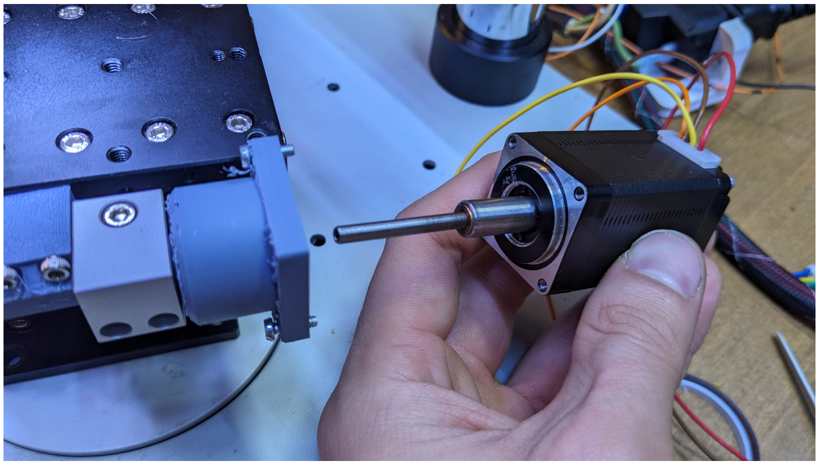


Figure 10: Version 2.0

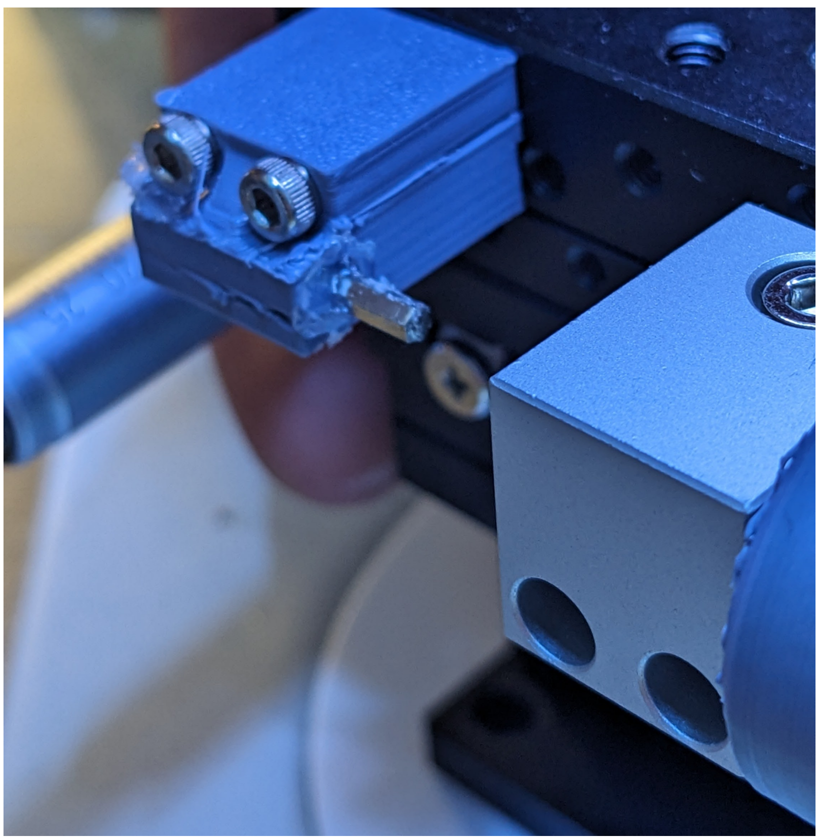


Figure 11: Version 2.0

Version 1.1 — Sept-2024

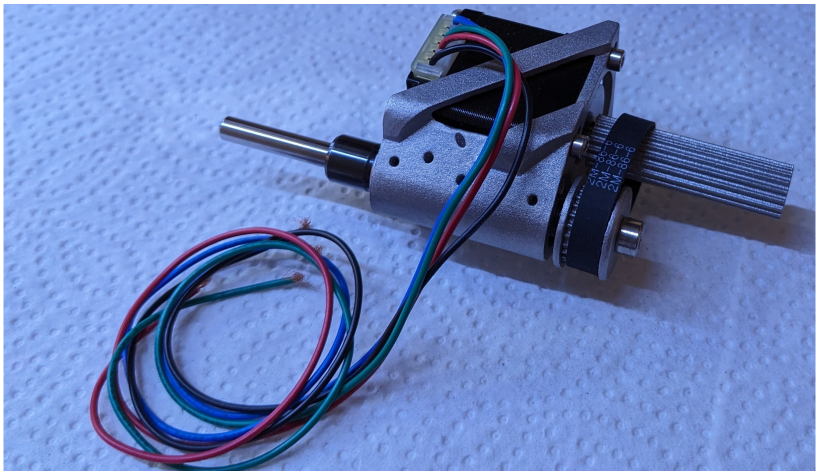
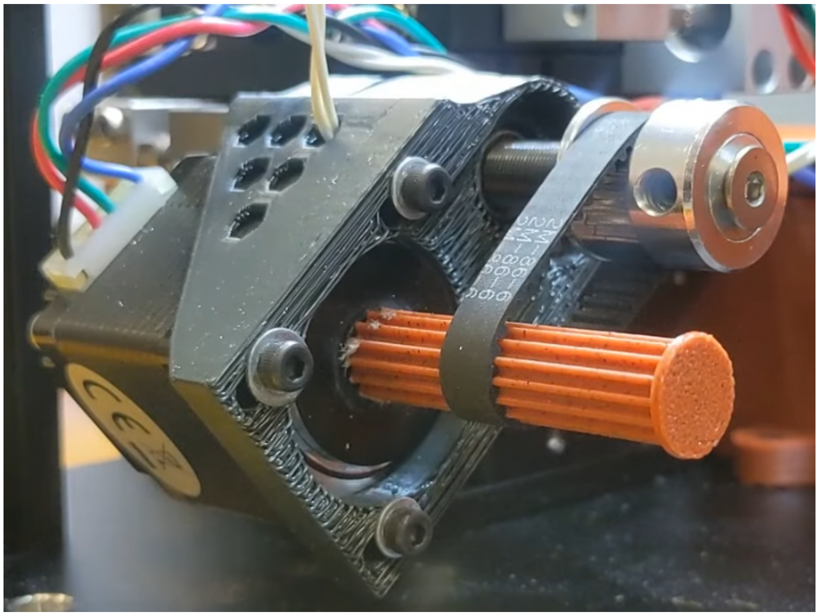


Figure 12: Version 1.1 – Metal Aluminum Body

Version 1.1 uses an SLS-based aluminum metal 3d printing process for the main body so that material creep which happens with [any?] thermo plastic is eliminated. Also, the hope was that a cheap SLS aluminum parts would have dimensional accuracy great enough that the parallel-ness (tram) would be precise enough that the long pulley on the stepper motor and the micrometer screw would be parallel enough such that the belt tension does not change along the travel of the actuator. However, tramming the motor's axis to the micrometer screw seems to be a big issue with this design. While there are many advantages with the belt-drive design, tramming will pose a large enough issue that precise manufacturing is necessary, which increases cost.

Version 1 — Sept-2023



Overview

Version 1 uses a nema 11 motor (so that torque is not an issue and manufacturing tolerances can be looser) to drive a roughly 1:1 ratio on micrometer thumbscrews which ships with Mpositioning.com's 3 axis micrometer stage ($329, `https://www.amazon.com/gp/product/B00WMSJX9W/ref=ppx_yo_dt_b_asin_title_o00_s02?ie=UTF8&psc=1`). The design uses an 11mm push button as a homing switch, which is set in the body of the actuator using a pause-place-print method on the FDM poly carbonate (PC) body. The micrometer screw has an M3 thread on the end, which I use to clamp a GT2 timing belt pulley onto. Then, a PLA 3D printed GT2 long pulley on the nema 11's shaft is used to drive the micrometer motor's GT2 pulley.
The belt tension is set by sliding the motor out on M2.5 screws which are included on the PC part. 25mm travel demonstration can be seen at `https://youtu.be/tTEV1oiOAYE`

Design Advantages

The bill of materials (BOM) consists of a homing push button, PC FDM 3d print, GT2 timing belt pulley, GT2 timing belt loop (87 tooth), and some screws; this makes it rather cheap. Also, the integrated homing switch reduces part count. Additionally, the center-of-mass (COM) is close to the mounting point on the micrometer stage, which means the actuator's weight does not impart a large force on the motion system – which increases the life time of the stage.

Design Disadvantages

Belt tension greatly effects the backlash performance. With the perfect belt tension, the actuator can do $1\mu m$ positional accuracy in a backlash test. However if the belt is too loose, accuracy can be as bad as $10\mu m$ in a backlash test. If the belt is too tight, the motor will skip steps, and positional accuracy is lost. The parallel-ness of the motor's shaft (and 3d printed long GT2 pulley)

and the micrometer screw is incredibly important so that the belt tension is constant along the $25mm$ travel. Because of this, version 1.1 was made.
Another big con of this design is that the micrometer screw provided with the stage is relatively course. Thus for μm positional precision, I am relying on proper micro-stepping with the TMC2209 drivers I am using.

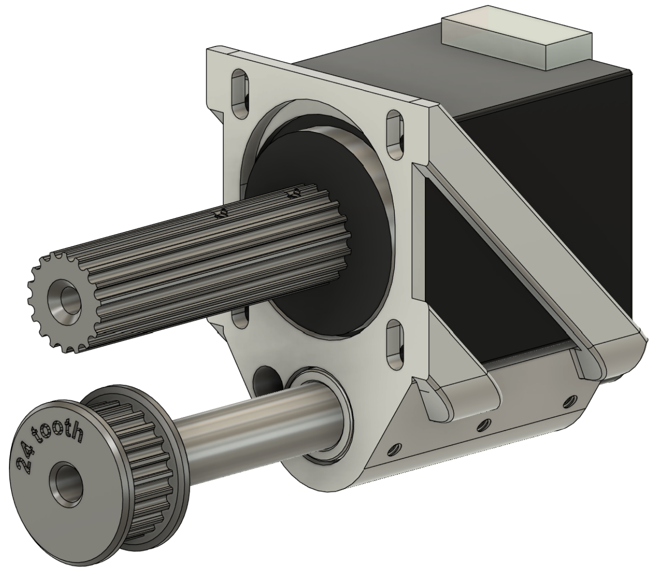


Figure 13: Version 1

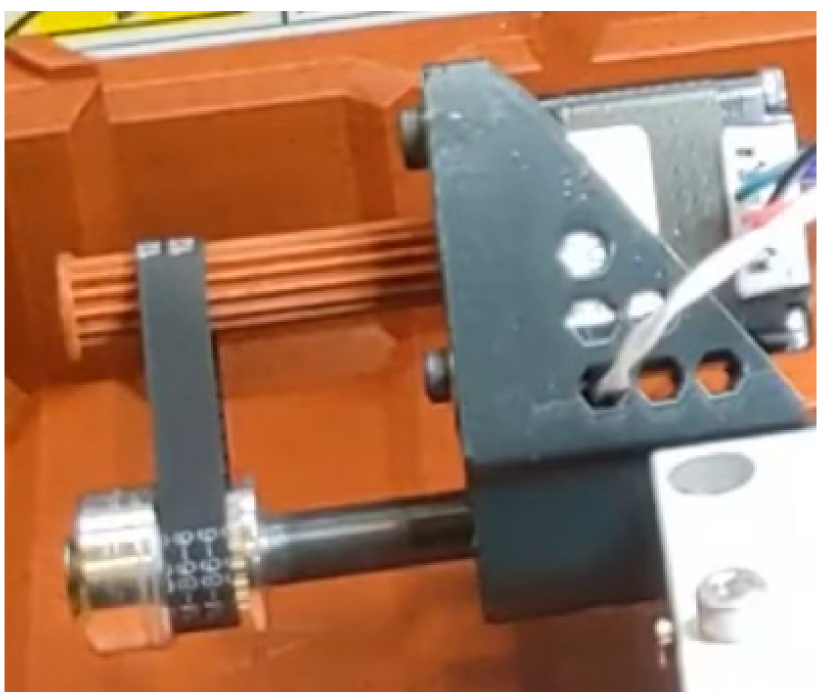


Figure 14: Version 1