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Accepted Manuscript

# Approaches to Open Source 3-D Printable Probe Positioners and Micromanipulators for Probe Stations

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**Title:** *Approaches to Open Source 3-D Printable Probe Positioners and Micromanipulators for Probe Stations*

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**Abstract:**
Three types of highly-customizable open source probe positioning systems are evaluated: (a) mostly 3-D printed, (b) partially printed using OpenBeam kinematic constraints, and (c) a 3-level stack of low-cost commercial single axis micropositioners and some printed parts. All systems use digital distributed manufacturing to enable bespoke features, which can be fabricated with RepRap-class 3-D printer and easily accessible components. They are all flexible in material choice for custom components. The micropositioners can be set up for left-right use and flat or recessed configurations using either mechanical or magnetic mounting. All systems use a manual probe holder that can be customized and enable a quick swap probe system. System (a) is purchased for $100 or fabricated for <$5, (b) fabricated for $25, and (c) fabricated for $145. Each full turn of a knob moves an axis 0.8 mm for (a) and 0.5 mm for (b,c) providing externally measured positional control of 10 microns for the latter. All three designs can utilize a customizable probe holder and tungsten carbide needle for $56. The designs are validated using microchips with known feature sizes and underwent mechanical stress tests. The maximal deflection of (a) was >200 microns, (b) 40 microns and (c) 10 microns. A tradeoff is observed for 3-D printed percent between cost and accuracy. All systems provided substantial cost savings over proprietary products with similar functionality.

**Keywords:** 3-D printing; manipulators; micromanipulator; open hardware; open source hardware; open source scientific equipment; probe; probe holder; probe positioner; probe station

**Specifications table**

| | |
|---|---|
| Hardware name | *Open Source 3-D Printable Probe Positioners* |
| Subject area | • Engineering and Material Science |
| Hardware type | • Measuring physical properties and in-lab sensors<br>• Electrical engineering and computer science |
| Open Source License | *(a) Cc-by-SA, (b) and (c) GNU General Public License (GPL) v3.0* |
| Cost of Hardware | *(a) $5-99, (b) $25, (c) $145 for manipulator, with $56 probes* |
| Source File Repository | *https://osf.io/r264u/* |

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## 1. Hardware in context

One of the primary benefits of the use of an open hardware approach to design is the ability to quickly and easily build upon the work of others [1,2]. An example of the success of this approach is the evolutionary development of the self-replicating rapid prototyper (RepRap) 3-D printer [3-5]. RepRaps and their various commercial variants have obtained 3-D printing qualities of interest to the scientific community and is now widely used to fabricate scientific hardware [6,7] including biological [8,9], biotechnological [10], chemical [11-15], nanotechnological [16], medical [17], materials [18], microfluidics [19-23] and even remote sensing [24]. In addition, to the use of open source hardware designs being shared for digital distributed manufacturing, there are also open hardware designs that are primarily distributed conventionally. For example, OpenBeam [25], is an extruded aluminum framing system meant for rapid prototyping and built using standard hardware (T-slots for DIN934 M3 nuts) instead of proprietary and expensive fasteners. OpenBeam has been adopted to improve several types of 3-D printers [26,27] as well as for robotics [28] and opto-mechanical equipment [29-30].

To contribute to this trend, this paper evaluates three types of highly-customizable open source probe positioning systems for micromanipulators in probe stations: a) a mostly 3-D printed positioner making using of only a few mass produced fasteners, b) partially 3-D printed system using OpenBeam kinematic constraints, and c) a 3-level stack of low-cost commercial single axis micropositioners and some key 3-D printed parts. A microscopic probe positioner is used to make electrical contacts to test microelectronics under a microscope and demands a level of precision of movement that cannot be achieved by the unaided human hand [31]. Manually adjustable probe positioners are utilized in thousands of microelectronics labs while prototyping or manufacturing in small volumes. In addition to fully automated production wafer probers, manual systems are still used in parallel for process monitoring and debugging purposes. In most cases, contact pads as small as 50 x 50 microns need to be reliably contacted. Sometimes it is beneficial if smaller structures all the way to a 10 micron level are accessible. These 3-D printable probe positioners combine the benefits from custom digital replication using a RepRap 3-D printer and the wide availability of non-printed parts including fasters for (a) and (b), extruded linear railing system of OpenBeam for (b), and mass produced single axis micropositioners for (c).

Micromanipulators are either precision machined [31] or purchased commercially for significant costs generally over $1,000 USD per probe positioner. This paper evaluates previous attempts to design 3-D printed manipulators for biological experiments, (a) which have been made mechanical [32] as well as automated [8] and presents two new open source micromanipulators (b) and (c). Here highly-customizable open source 3-D printable probe positioners are developed based on a digital distributed manufacturing design procedure [33]. Other previous automated probes, which were used as four-point probes [34,35], were not appropriate for either microelectronics single probe applications or for multiple probes testing various sample geometries of different types of electronic devices. All three systems evaluated use digital distributed manufacturing to enable five bespoke features: 1) fabrication with RepRap-class 3-D printer and easily accessible components; 2) flexibility in material choice for custom components; 3) left-right, flat and recessed configurations; 4) mechanical and magnetic mounting; and 5) a manual probe holder customization and quick swap probe system. The design are validated and tested and the cost saving of the probe positioning systems are compared against commercially available products with similar functionality.

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## 2. Hardware Description

### 2.1 Nearly Fully 3-D Printed Mechanical Manipulator

Backyard Brains (BYB) of Ann Arbor Michigan, a company attempting to democratize neuroscience research by making neuroscience equipment low cost, developed an open source 3-D printable mechanical manipulator [32]. It was later redesigned in OpenSCAD [36] and upgraded with optional servo mounts [8,37]. The commercial version was tested here, which cost $99. It is an elegant design, which is made almost completely out of a minimum number of simple 3-D printed parts and a minimum number and variety of fasteners as seen in Figure 1. The custom parts can be fabricated with any form of fused filament fabrication (FFF) – based 3-D printer such as a RepRap or any other 3-D printer with better than 100 micron positional accuracy. The components are small enough to fit individually on even the smallest FFF 3-D printer beds. The parts can also be fabricated from other 3-D printing processes such as stereo lithography or laser sintering. This makes the accessibility of manufacturing high as such devices are widely available now in fab labs, makerspaces, universities and now many libraries as well as 3-D printing services (both brick and mortar and online). As the primary components can be 3-D printed from any FFF-available thermopolymer they can be customized for specific testing environments. Here orange acrylonitrile butadiene styrene (ABS) is demonstrated for probing at room temperature. However, more exotic 3-D printing polymers can be used for more challenging testing environments. For example, uv-stable acrylonitrile styrene acrylate (ASA) can be used for probe positioners utilized in high intensity light applications to test optoelectronics. Researchers printing one themselves and using hardware store fasteners can build one for under $5.

**Figure 1.** BYB 3-D printable manipulator. Inset: Bottom.

Each BYB manipulator is distributed fully assembled with four degrees of freedom: up/down (at an angle), left/right, forward/backward, and electrode angle of attack (135 degrees). The latter can be adjusted by changing the angle of the printed parts. It comes ready to mount with four small rare earth magnets on the bottom of the manipulator (inset Figure 1). The positioner has a total volume (without electrode attached) of 10.5 cm long by 7.9 cm wide by 9.5 cm high. Each full turn of a knob moves an axis 0.8 mm. The range of motion is 37 mm (x), 32 mm (y) and 18 mm (z). For assembly instructions as well as STLs see [32]. The primary challenge for this design for microelectronics applications is that the z stage moves at an angle rather than perpendicular to x and y. This makes it impractical for needle type microscopic contacts, however, it can be used for larger pads, which might for example use a balled end gold wire as a contact. An improved OpenSCAD [36] parametric version of this design [37] was demonstrated and automated [8]. This latter design overcomes the z-axis issue, while still enabling a custom angle of attack with the probe tip. Both designs can hold the open source probe holder described in section 2.4. All of the components can be printed in under 4 hours using about 60 grams of filament.

### 2.2. Partially 3-D Printed OpenBeam Kinematic Constrained Micromanipulator

The open source 3-D printable OpenBeam kinematic constrained probe positioners can be fabricated in less than 30 min. after the components are assembled for under $25 using widely available components

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and using easily accessible tools. Each full turn of a knob moves an axis 0.5 mm and the knobs as shown here have 60 scores, providing human externally measured positional control of 8.3 microns. It should be noted that this design specifications can be altered by changing the type of screw as the inclination of the screw defines how far the probe will move on a full turn. With the aid of a microscope this positional system is capable of reliably hitting 20 micron targets as designed and tested. This open source 3-D printable probe positioners has unprecedented customizability enabling it to be useful for a wide array of experiments both inside and outside of the microelectronic field.

The basic operation ensures linear motion in the x, y and z plane using OpenBeam aluminum extrusions [38] as kinematic constraints to allow the gliders to move only in one degree of freedom. OpenBeam has been tested on a Class A inspection grade granite table (flat within 10 microns over the 1 m surface length) with a dial test indicator and found to be 0.04 mm of deviation over 1 m (50% below 0.02 mm of deviation) [39]. The probe positioning system as designed has OpenBeam lengths of 65 mm and a range of motion of 30 mm in the x, y and 35 mm z axis, indicating at worst an expected 1.4 microns of deviation on the z axis. In addition, this probing envelope can be easily reduced (to make a smaller probe positioner) or expanded by lengthening the threaded rods and up to a max of 0.96 m for the standard 1 m OpenBeam extrusion. In the present configuration, the probe positioners occupy a total work plane surface area of (without the open source probe holder described in section 2.4 and electrode attached) of 4,225 $mm^2$ , making it smaller than the fully 3-D printable version (although that version can similarly also be reduced in size at the expense of range).

The open source OpenBeam based 3-D printable probe positioners been developed in OpenSCAD (full source available in [40]) similar to the revised nearly fully 3-D printable version to enable parametric customization for any type of microelectronic probing experiments. By changing clearly commented variables users can customize every aspect of the design. The OpenSCAD code was written to be compatible with an open source customizer [41] to allow even inexperienced users to generate the necessary parts for a custom probe or experiment. So, for example, the probe holder diameter can be adjusted to fit any standard or custom probe holder (in addition to the one shown in section 2.4), while remaining electrically isolated from the mechanical movement of the probe positioner. Similarly the scale of the knob was manufactured with 60 divisions, but can be increased or decreased as necessary.

The custom parts can be fabricated with any form of FFF 3-D printer, with the same advantages discussed for the nearly fully 3-D printed manipulator. Here black acrylonitrile butadiene styrene (ABS) (IC3D, Lulzbot) is demonstrated for dark probing (probing without light) at room temperature.

The assembly of the design allows for four total configurations. First, the y axis mounting allows the device to be made for right or left handed researchers. At the same time, the device can be customized for two z direction configurations, which make for level and sub-level platforms. For changing between configurations four bolts must be removed and replaced, which can be accomplished in a few minutes.

The x-axis of OpenBeam can be fastened directly to the stage of a probing system using M3 nuts and bolts. The tightening of the M3 nut can occur anywhere along the x-axis providing another degree of freedom in the design. Additionally, and as shown here, it can similarly be mounted magnetically along the x-axis OpenBeam rail, which makes for easy mm scale positioning of the entire positioning system before using the knobs for microscopic positioning of the probe.

### 2.3 3-level Stack of Low-cost Commercial Single Axis Micropositioners and Some Key 3-D Printed Parts

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Using a 3-level stack of low-cost commercial single axis micropositioners and some key 3-D printed parts, both minimizes assembly time and enables high precision. This design provides maximum precision and rigidity of the micropositioners tested by using commercial, but low-cost, metallic x-y-z stages. The higher precision for the 3-level stack design is achieved at a higher component cost of $145, although it is still roughly an order of magnitude below the cost of proprietary micropositioners. The system can be assembled in less than 1 hour after the 3-D printed parts have been fabricated. The x-y-z stage is based on aluminum frame parts and standard micrometer heads providing a linear range of motion 13 mm (x), 13 mm (y) and 10 mm (z). A full turn of each micrometer head moves an axis 0.5 mm and as the micrometer heads have 50 scores resulting in nominal positional control of 10 microns. Smaller, but more accurate motion ranges mostly benefit the microelectronics applications where small test objects need to be accessed. Although it should be noted here that smaller areas can be targeted by turning the micrometer head less than a full marking. Using RepRap-class 3-D printing for some of the parts of system (c) still provides a technical benefit in addition to reduction in machining costs. 3-D printing provides customization capability and the high electrical isolation required for low current signal measurements. In this design the probe holder and the coaxial cable are mechanically secured together and into a spring mounted arm holder by casting with a highly isolating two-component epoxy. Efficient coaxial cable strain relief is provided by guiding the cable though a cover part towards the cast mechanical connection to the brass arm of the probe holder. The spring mounting of the probe arm holder prevents excessive probe (tungsten needle) pressure on the test object, by allowing the whole arm to bend upwards in case the user tries to lower the probe needle beyond test object's top surface. This spring-mounted tip thus protects the surface being studied from probe positioning and is well suited for delicate materials and devices.

**2.4 Open Source Probe Holder**

Finally, for all manipulator designs there is unit that holds the probe tip (normally a needle that contacts the electronic device being tested), which is moved by the micromanipulator. The probe holding design can be adjusted by drilling different hole diameters to enable any form of probe tip to be used. Likewise, multiple holes can be pre-drilled to enable rapid switching of probes using the innovative spring locking system. Similarly, as the probe holder is made from thin brass it can be custom bent by hand to fit any type of probing station. Commercial probe holders are not nearly as customizable and suffer from significant costs. The highly isolated signal path provided by the probe holder is based on guiding the measurement signal from 1) the tungsten carbide test needle to 2) a brass probe holder and further through the highly isolating 3-D printed polymer parts all the way to a 3) high-quality coaxial cable and finally a 4) standard BNC coaxial connector.

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## 3. Design Files

### 3.1 Design Files Summary

Design files for the nearly fully 3-D printed mechanical manipulator (a) is available from [32]. The seven files are for the first new design (b) and the last four for new design (c) are in 3.1.1 and 3.1.2, respectively. The openbeam-final.scad is the core OpenSCAD file. The design is a derivative of several other designs. It is built around 1) the OpenBeam rail designed by T. Tam [38] (whose design files are also included in the OSF repository for this project [40] as the Thingiverse repository's status as a safe open source design space is in question [42]), 2) an open source micromanipulator designed by J. Anzalone [43] and 3) Thumbwheel M3 with scale 0.01 mm with grip [44], which was derived from Thumbwheel M3 with scale 0.01 mm [45]. Design (c) has STL files for 3-D printing based on the JSX396347 linear stage. All STL files for the latter two designs are shown rendered in the Tables below for identification.

#### 3.1.1. Partially 3-D Printed OpenBeam Kinematic Constrained Micromanipulator

| Design file name | File type | Open source license | Location of the file |
|---|---|---|---|
| *openbeam-final.scad* | *CAD* | *GNU General Public License (GPL) v3.0* | https://osf.io/r264u/ |
| *endramp2.stl* | STL | *GNU General Public License (GPL) v3.0* | https://osf.io/r264u/ |
| endrampx.stl | STL | *GNU General Public License (GPL) v3.0* | https://osf.io/r264u/ |
| glider-rod.stl | STL | *GNU General Public License (GPL) v3.0* | https://osf.io/r264u/ |
| gliderx.stl | STL | *GNU General Public License (GPL) v3.0* | https://osf.io/r264u/ |
| gliderxy.stl | STL | *GNU General Public License (GPL) v3.0* | https://osf.io/r264u/ |
| knob.stl | STL | *GNU General Public License (GPL) v3.0* | https://osf.io/r264u/ |

#### 3.1.2 3-level Stack of Low-cost Commercial Single Axis Micropositioners and Some Key 3-D Printed Parts

| | | | |
|---|---|---|---|
| Arm holder.stl | STL | *GNU General Public License (GPL) v3.0* | https://osf.io/r264u/ |
| Leaf Spring holder.stl | STL | *GNU General Public License (GPL) v3.0* | https://osf.io/r264u/ |
| Top cover coax cable support.stl | STL | *GNU General Public License (GPL) v3.0* | https://osf.io/r264u/ |
| Coax color tag.stl | STL | *GNU General Public License (GPL) v3.0* | https://osf.io/r264u/ |

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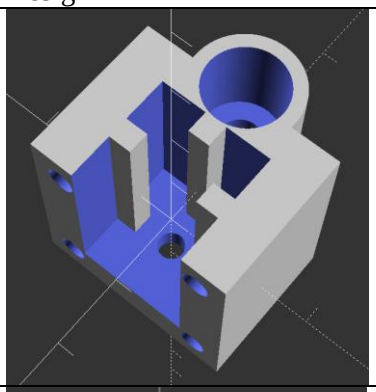
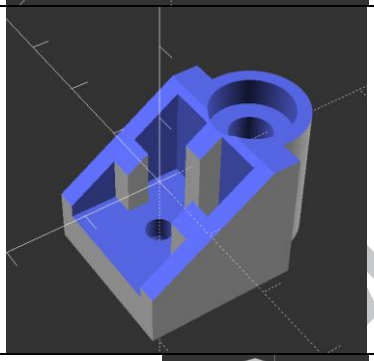
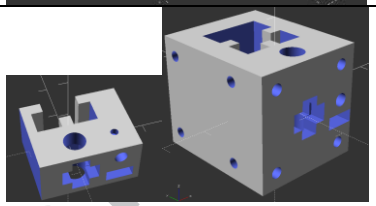
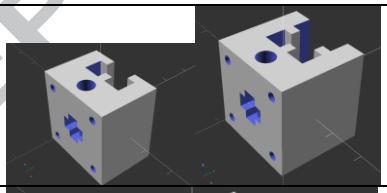
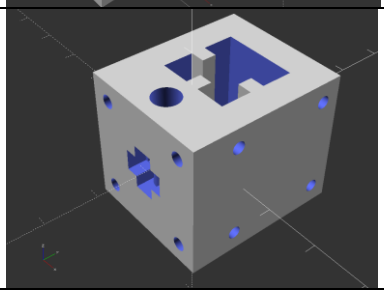
### 3.2 Design File Rendered Images of 3-D Printable Parts

#### 3.2.1. Partially 3-D Printed OpenBeam Kinematic Constrained Micromanipulator

| Design file name | Design | Description |
|---|---|---|
| *endramp2.stl* |  | Two endramp2.stl files need to be printed. They are attached to the OpenBeam rails and house bearings and a locking nut to hold the threaded rods. They are used on both the y and z axis. |
| endrampx.stl |  | The endrampx part is used on the x axis and is smaller because it does not connect to any parts other than the threaded rod and the x-plane OpenBeam. |
| glider-rod.stl |  | The glider rod moves along the z axis and has two nut traps, one for the nut that rides the threaded rod and the second for a bolt that holds the probe rod. Alternative versions of this can be made larger and based off of the standard gliderxy. |
| gliderx.stl |  | The gliderx part moves along the x axis and has a nut trap nut that rides the threaded rod. It is connected to the gliderxy. A more rigid version extends polymer down the side. |
| gliderxy.stl |  | The gliderxy is connected to the glider x and then rides the y OpenBeam rail. It has a nut trap that rides the y threaded rod. |

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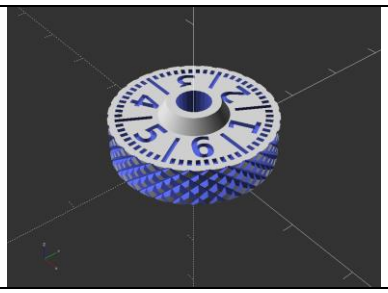
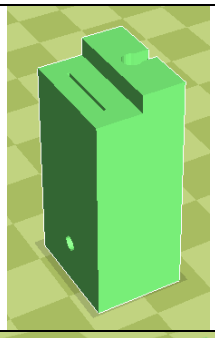
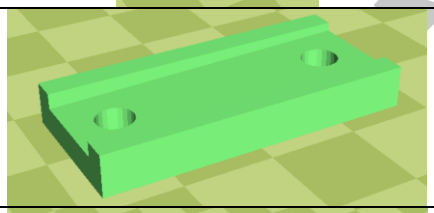
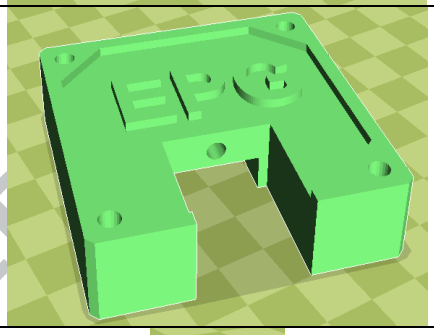
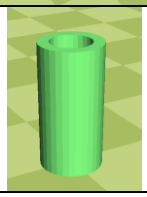
| | | |
|---|---|---|
| knob.stl |  | Three knobs are needed one for each axis. |

### 3.2.2 3-level Stack of Low-cost Commercial Single Axis Micropositioners and Some Key 3-D Printed Parts

| | | |
|---|---|---|
| Arm_holder v10.stl |  | Brass arm holder with spring mount |
| Center_spring_holder v3.stl |  | Center spring holder |
| Topcover_v13.stl |  | Placed on top of 3-level stack |
| Coax_color_tag_v3.stl |  | Allows for easy identification of probe in multiprobe station. |

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## 4. Bill of Materials

The BOM and material costs for each system is shown here, although the full cost analysis for all three systems and the probes is shown in Section 7.

### 4.1 Bill of Materials for Fully 3-D Printed Mechanical Manipulator (a)

The BOM for the commercial open source nearly fully 3-D printable design are available [32] and can be purchased for less than $5 or purchased assembled for $99 from BYB. The 3-D printable parts are shown in Figure 2 and completed assembly are shown in Figure 1.

### 4.2 Bill of Materials for OpenBeam Positioner (b)

The complete bill of materials (BOM) for the open source 3-D printable OpenBeam probe positioner (b) including source urls can be found in ODS format on the OSF here [40].

| Designator | Component | Number, (total mass) | Cost per unit – USD $ / | Total cost – USD $ | Source of materials | Material type |
|---|---|---|---|---|---|---|
| Endramp2 | endramp2.stl | 2 (6.4 g) | $0.043/g | 0.54 | [40], Lulzbot | ABS 3-D printed |
| Endrampx | endrampx.stl | 1 (4.1 g) | $0.043/g | 0.17 | | |
| Glider-rod | glider-rod.stl | 1 (3.2 g) | $0.043/g | 0.14 | | |
| Glider | gliderx.stl | 1 (6.9 g) | $0.043/g | 0.29 | | |
| Gliderxy | gliderxy.stl | 1 (10.9 g) | $0.043/g | 0.46 | | |
| Knob | knob.stl | 3 (1.9 g) | $0.043/g | 0.24 | | |
| OpenBeam | OpenBeam rails | 3 x 65 mm (195 mm) | $10/m | 1.95 | OpenBeam | Extruded aluminum rail |
| Bearings | MR105zz roller bearings | 6 | $7.99/10 pack | 0.48 | Amazon | Steel |
| M5 threaded rod | uxcell M5 x 170mm 304 Stainless Steel Fully Threaded Rod Bar Studs Fasteners | 3 x 85 mm (255 mm) | $9.13/5 x 170mm pack | 2.74 | Amazon | 304 Stainless Steel |
| M5 Nuts | Metric M5x0.8 mm Stainless Steel Finished Hex Nut Silver Tone | 3 | $7.19/ 50 pack | 0.43 | Amazon | 304 Stainless Steel |
| M5 Locking Nuts | M5 x0.8 mm zinc plated nylock nylon hex nuts | 6 | $9.50 / 100 pack | 0.58 | Amazon | Zinc plated steel |
| M3 Screws long | M3 x 27 mm socket head cap screws | 8 | $16.35/ 50 pack | 2.62 | Amazon | Steel |
| M3 Screws short | M3 x 10 mm socket head cap screws | 2 | $10.57/100 pack | 0.21 | Amazon | Steel |

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| | | | | | | |
|---|---|---|---|---|---|---|
| M3 screws flat | uxcell M3 x 10 mm hex socket countersunk flat head screw bolts | 3 | $8.95/100 pack | 0.27 | Amazon | Stainless steel |
| M3 nuts | M3 3 mm female thread hex metal nut fastener | 2 | $4.99/ 100 pack | 0.10 | Amazon | Steel |
| Magnet | Neodymium magnet | 2 | $5.49 | 10.98 | Clasohlson | Neodymium Magnet – zinc plated |
| | | | **Total** | **$22.20** | | |

The cost of the 3-D printed parts was approximated as the material costs of ABS (Lulzbot), and was the weighted fraction of $42.95/kg [46]. The 3-D printed parts cost $1.84 in total (or up to $2.79 for the more rigid options). The remainder of the parts were sourced at Amazon for $9.38 except for the magnets ($10.98), which were the most expensive components. Less expensive alternatives may be available on the web or locally, but the total system can be built for under $25.

### 4.3 Bill of Materials for 3-level stack design (c)

The complete bill of materials (BOM) for the open source 3-level stack design of the probe positioner (c) including source urls can be found in ODS format on the OSF here [40].

| **Designator** | **Component** | **Number, (total mass)** | **Cost per unit – USD $ /** | **Total cost – USD $** | **Source of materials** | **Material type** |
|---|---|---|---|---|---|---|
| Arm holder | Arm_holder v10.stl | 1 (6 g) | $0.043/g | 0.258 | [40] | ABS-3D printed |
| Leaf spring holder | Center_spring_holder v3.stl | 1 (2g) | $0.043/g | 0.086 | | |
| Top cover | Topcover_v13.stl | 1 (25g) | $0.043/g | 1.075 | | |
| Coax cable colour tag | Coax_color_tag_v3.stl | 1 (1 g) | $0.043/g | 0.043 | | |
| XYZ 3-axis linear stage | JSX396347 | 1 | 117.89 | 117.89 | Ebay | Metal pre-manufactured |
| Pot magnet | CSN-16 | 4 | 1.76 | 7.05 | Supermagnet | magnet |
| Leaf spring | Leaf spring 0.3 mm | 1 | 4.34 | 4.34 | Biltema (Sweden) | spring steel |
| Coax cable | Small diameter coax cable, 1.1m RG178 30000-178-50 | 1 | 7.00 | 7.00 | Partco | wire |
| BNC connector | BNC connector RG178 112516 Amphenol | 1 | 4.26 | 4.26 | Farnell | connector |
| epoxy | 2-component, 5-minute epoxy | 1 | 1.24 | 1.24 | Bison | epoxy |

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|---|---|---|---|---|---|---|
| M3x10, countersunk screw | M3x10, countersunk screw Magnet mounting in 4 corners | 4 | 0.055 | 0.22 | Amazon | Carbon steel |
| M3 washer | M3 washer Magnet mounting in 4 corners | 8 | 0.062 | 0.49 | Amazon | Stainless steel |
| M3 nut | M3 regular nut Magnet mounting in 4 corners | 4 | 0.046 | 0.18 | Amazon | Steel |
| M4x25, pan head screw | M4x25, pan head screw Top cover/ coax cable guide mounting | 4 | 0.277 | 1.11 | Amazon | Steel |
| M3x8 pan head screw | M3x8 pan head screw Leaf spring to plastic arm holder | 1 | 0.055 | 0.05 | Amazon | Steel |
| M4x10 pan head screw | M4x10 pan head screwLeaf spring holder to XYZ stage | 2 | 0.060 | 0.12 | Amazon | Steel |
| M4 washer | M4 washer Leaf spring holder to XYZ stage | 2 | 0.067 | 0.13 | Amazon | Steel |
| | | | **Total** | **145.54** | | |

For parts purchased in the European market prices were converted to USD using a conversion of 0.805854 from xe.com on 3.26.2018. It should be noted that for those purchasing components outside of the European market there may be less expensive alternatives for individual components.

**4.4 Bill of Materials for Probe used in (a), (b), and (c) designs.**

The complete bill of materials (BOM) for the probe in (a), (b), and (c) including source urls can be found in ODS format on the OSF here [40].

| **Designator** | **Component** | **Number, (total mass)** | **Cost per unit – USD $ /** | **Total cost – USD $** | **Source of materials** | **Material type** |
|---|---|---|---|---|---|---|
| Needle holder arm | 3 mm diameter brass pipe, pre machined | 1 | $49.64 | 49.64 | Ilmailutekniikka | Brass |
| Probe tip | Micro Punch / Probe Needle D=.020 A=11 R=.00025 L=1.25 (Lot #116) | 1 | $4.34 | 4.34 | Semprex | Grade 883, which consists of approximately WC=89.5% + Co=10.0% + Others=0.5% |

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| | | | | | | |
|---|---|---|---|---|---|---|
| Needle Holder Spring | Spring, length 30 mm, OD 4.0 mm,ID 3.5 mm | 1 | $1.24 | $1.24 | From standard ball point pen | Stainless steel |
| | | | **Total** | **$55.22** | | |

All parts for this assembly were sourced in Finland. The brass pipe was purchased machined from a small micomechanics firm located in Helsinki, Finland. For those working outside of Finland a local machining service may be more convenient. Costs could also be reduced if the machining could be accomplished in house. Micropunch needles from Semprex, although the second most costly line item for the probe system at $4.34 per needle, are significantly less costly than commercial probe tips and do not involve requesting a quote. Any spring from a standard ball point pen will work in this application or specialty springs can be utilized.

**5. Build Instructions**

**5.1 Build Instructions for Nearly Fully 3-D Printed Mechanical Manipulator (Design a)**

Detailed build instructions for the commercial open source nearly fully 3-D printable design are available in [32]. The 3-D printable parts are shown in Figure 2 and the final assembly is shown in Figure 1.

**Figure 2.** Cura Lulzbot v21.04 screen shot showing the plating of the 3-D printed components for design (a).

**5.2 Build Instructions Partially 3-D Printed OpenBeam Kinematic Constrained Micromanipulator (Design b)**

1. Obtain parts shown in the BOM and the tools shown in Figure 3 including 3-D printer (shown Lulzbot Taz 6), metric mm scale ruler, multi-tool with needle nose pliers and knife, M5 wrench, Allen wrenches size 2 and 2.5, sand paper and hacksaw.

**Figure 3.** Tools necessary to fabricate open source 3-D printable probe positioners.

2. Print out 3-D printed components (shown in the design file description above, nine parts in all) in an appropriate polymer for the application after making any additional custom changes to the OpenSCAD code on a FFF 3-D printer. Here a Lulzbot Taz 6 (Aleph Objects) was using the IC3D ABS high quality single extruder 0.5 mm nozzle Cura.ini file [47]. The layer height was 0.18 mm, shell thickness 1 mm, and fill density was 20%. A brim was used to ensure bed adhesion. The parts can all easily fit on the print bed as shown in Figure 4 and prints out in about 5 hours (6 hours with more rigid components). Cura [48] estimated 55 – 65 g of filament use depending on version. The actual components massed less after cleaning.

**Figure 4.** Cura Lulzbot v21.04 screen shot showing the plating of the nine 3-D printed components for design (b) (inset: minor modifications of designs for a more rigid assembly increases print time by an hour and cost by about $1.00).

3. Clean out the 3-D printed parts with a knife being careful to avoid cuts and slide the three glider components up and down a length of OpenBeam. The gliders should tightly fit on the OpenBeam, but

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should slide with moderate manual pressure. If the 3-D printed components are too tight or too loose adjust the parameters for the OpenBeam cross section and OpenBeam slot width in the OpenSCAD and print again or if close, gently shave with knife. The settings will depend on the 3-D printing polymer and supplier. These settings will determine the accuracy of the final device.

4. Use a hacksaw to cut OpenBeam and threaded rod to length. Here the OpenBeam is cut to 65 mm and the threaded rods (170 mm) are cut in half. Remove burrs from both with sand paper. Alternatively use power tools to do the same. Then gather all of the components in the BOM shown in Figure 5.

**Figure 5.** BOM for the open source 3-D printable probe positioner.

5. Assemble the rod ends by pushing the OpenBeam into the end ramp components and then securing each with one of the three M3x10 flat head screws. These screws can be directly screwed into the OpenBeam without tapping. Place two M5 nuts on the end of each threaded rod. Jam them together by tightening them together using the multi tool and wrench simultaneously. The procedure is shown in Figure 6 along with an inset of the finished jammed nuts.

**Figure 6.** Jamming M5 nuts on the threaded rod. Inset: Two jammed M5 nuts.

6. Place an MR105zz bearing on both sides of an end ramp in the recessed areas. Then while holding the jammed nut, thread an M5 locking nut down the length of the rod until there is just enough room to put another M5 locking nut flush against the back (see Figure 7). Then screw on the remaining M5 locking nut making a sandwich that still rotates easily. Remove the jammed M5 nuts. Repeat for the 2 normal end ramps and the smaller end ramp for the x axis. The result is shown in Figure 8.

**Figure 7.** Loading shafts onto the end ramps and mounting on the OpenBeam with end ramp on the x axis in place preloaded with bearing.

**Figure 8.** Threaded rods secured with locking nuts on both sides of the end ramp printed components for x axis (left) and on the y and z axes (identical to this point).

7. Place an M5 nut (being careful to line up the flat edges against the nut trap) in each of the gliders. Push down until there is a clear path for the threaded rod. Place the gliders onto OpenBeam. Then turn the end locking nut (thereby rotating the threaded shaft) with either a knob or the wrench while pushing on the gliders until the threaded rod engages on the trapped M5 nut, which should result in a single axis. Repeat for all x, y and z axes (Figure 9).

**Figure 9.** Completed three single axis setups.

8. Decide if the open source 3-D printable probe positioner is going to be left or right handed and then use four M3 x 27 mm socket head cap screws to anchor the y axis to the x axis. Tighten the screws step-wise, rotating through each screw to avoid breaking the components. The difference between left and right configurations is shown in Figure 10.

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**Figure 10.** Right handed probe positioner setup (inset: left handed probe positioner setup).

9. Similarly decide if the open source 3-D printable probe positioner is going to use an up or down z-axis and use four M3 x 27 mm socket head cap screws to anchor the z axis to the y axis.

**Figure 11.** Down orientation for the right handed micromanipulator (inset: up orientation).

10. Secure the magnet to the base of the x-axis by sliding an M3 nut into the slot at the bottom of the x-axis OpenBeam. Move the magnet along the x-axis until in the desired position and then tighten in place with the M3x10 mm bolt. Push the knobs onto the jammed M5 nuts (these should be tight but can be augmented with superglue if too loose or to make permanent). The final assembly is shown in Figure 12.

**Figure 12.** Final Assembly of partially 3-D printed OpenBeam kinematic constrained micromanipulator.

**5.3 Build Instructions for 3-level stack (Design c)**

1. Print the four 3-D printed parts (Figure 13) and purchase the components shown in the BOM [40].

**Figure 13.** Cura Lulzbot v21.04 screen shot showing the plating of the four 3-D printed components for design (c). The cost to print the four components is less than $1.50 with commercial filament.

2. Assemble the XYZ stage utilizing attached screws (provided with the stage) as shown in Figure 14. Note that the uppermost Z stage may be turned 180 degrees in relation to XY stage to make left and right handed versions. Right hand version shown.

**Figure 14.** 3-level stack in right hand version.

3. Mount the 4 magnets on the bottom of XY stage
Use M3x10 countersunk screws and place one washer between magnet and stage, and another below the nut in the mounting recess on the base plate. There is no space for a proper tool to hold the nut while tightening, so use a flat head screwdriver or similar tool to prevent the nut from turning. Repeat four times by placing a magnet in each corner of the base.

**Figure 15**. Image showing base with one magnet before assembly. Inset - Magnets have been assembled.

4) Mount the leaf spring and using the 3-D printed holder on top of Z stage (components shown in Figure 16. Note again the assembly orientation for left and right handed versions. Right hand version shown (spring tip towards the object to be probed). Use two M4x10 pan head screws and flat washers.

**Figure 16.** Main components of the spring assembly - -Inset assembled with leaf sprin.

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5) Attach a colour tag sleeve to the coax cable and feed the coax cable open end through the manipulator cover support hole as shown in Figure 17. The tag sleeve is used for coding each manipulator unit and related cable with a separate colour code. This will ease testing while inside a probe station and can be used with any type of probe or manipulator. As an example, the shown manipulator has a gray cable tag and gray cover parts on the manipulator. Plastic filaments of different colors may be used to print these parts with varying colors. The sleeve is a tight fit over the connector ferrule. The sleeve can be glued around the ferrule and cable if needed.

**Figure 17.** Coax cable with sleve and in manipulator cover in the correct direction.

6) Please note in this design the probe holder is integrated into the positioner device, while in designs (a) and (b) the instructions are followed for section 5.4 and then simply attached afterwards with a screw. In this design (c), push the top end of brass probe arm (before attaching to the wire) through the long hole in the 3-D printed arm holder, as shown in Figure 18. The brass arm is very tight fit in the hole as designed. Remove plastic burrs afterwards.

**Figure 18**. Brass support arm installed in holder.

7) Place the probe arm in table vice and complete then follow the first two steps in the Probe build section (5.4). After soldering the center wire, pull the brass arm top end, together with the coax cable, back into the arm holder top groove, so that the arm top end is approximately 5.5 mm inwards from the edge of the arm holder. Using the table vice and support coax cable as shown in Figure 19. **Warning: carefully check that the brass arm is exactly vertical oriented in relation to the arm holder**. Now apply 5 min two-component epoxy into the arm support groove to bind the arm, coax cable and arm support together. The epoxy will prevent the arm from turning within the arm support and will provide strain relief for the coax cable. Allow the epoxy to cure properly.

**Figure 19.** Application of epoxy for the brass suport arm and holder after soldering. Red arrow notes the location of the end of the arm.

8) Attach probe arm components on the manipulator. Slide the leaf spring of the manipulator through the slit in the probe arm support. Push it far enough so that arm support rests on the top plate of Z manipulator, as shown in Figure 20. Please note that mounting the probe arm support to the leaf spring as shown in Figure 20, enables the arm to be bend the spring up when the probe comes in contact with a surface. This acts as a safety feature preventing damaging of the probe. Finally, it should also be noted that the probe holder may need to be altered to a non-conducting material for electrophysiology experiments to prevent it acting as an antenna.

**Figure 20.** Probe arm assembly on manipulator.

9) Now slide the top cover along the coax cable and mount it on the Z manipulator top plate with 4 M4x25 pan head screws (Figure 21). Adjust arm holder position along the leaf spring so that a 2-2.5 mm gap is left everywhere between arm support and top plate (Figure 21).

**Figure 21.** Installation of the cover on the manipulator assembly.

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10) Use an M3x8 pan head screw to lock the arm support position from underneath as shown in Figure 22. The screw will tighten against the leaf spring. Do not use too much torque since the screw has no actual thread in the arm support. See photo below.

**Figure 22.** Locking brass arm into location – bottom view of assembly.

11) Finally, attach the probe needle and holding spring (Step 3 in the probe assembly below) and the probe is ready for use as shown in Figure 23.

**Figure 23.** Final assembly for the 3-level stack design (c).

**5.4 Build Instructions for Probe Holder**

In addition to the tools shown in Figure 3 are tape, small table vice, a drill press and drill bits (0.51 mm and 1.0mm) and a 0.128" hex crimping tool (for the ferrule of the outer conductor) are needed to fabricate the probe needle holder.

1. Manufacture the coax cable to length appropriate for the application and test system dimensions. In a typical silicon wafer probe station, suitable coax length is around 105-110 cm.

2. Cut and bend the brass probe arm to the geometry needed for the probe station and drill the holes for the probe tip (red) and holder (blue) as shown in Figure 24. There is a hole for coax cable soldering on the back end, and the front end has a 0.6 mm through-hole drilled in 45 degree angle, for holding the 0.51 mm (0.02") probe needle. The needle is held in its position by a spring, which is further supported by a metal pin pressed through a tight horizontal hole in the arm.

Note that the angle of the probe and the probe holder can be adjusted by changing this hole angle (red cylinder shown in Figure 24). On the other end of the probe arm drill a 1 mm diameter, 5 mm deep hole parallel to the probe arm in the center for soldering the coax cable center conductor. See details of cable in Figure 25.

**Figure 24.** Close up of the holes needed in the brass probe arm on the probe side. Inset left shows the holes for the probe needle and the pin. Inset right shows the hole for the conductor.

**Figure 25.** Details for stripping coax cable.

2. Attach the color sleeve if color coding as described above. Then if needed feed the wire through any plastic supporting parts (as with design c). Then set up to solder the center conductor to the center pin of connector. See connector datasheet for recommended cable stripping dimensions. A 0.128" hex crimping tool is needed for the ferrule of the outer conductor. Carefully solder the center conductor to the hole in the arm while constantly supporting the coax cable. Use tape or equivalent to support as necessary.

3. Attach probe needle and holding spring (as shown in Figure 26). Warning: Do not lead with the sharp probe tip for this step. While holding the lock spring tensioned with one hand, push the top end (not the actual bottom probing end) of the needle through the 45 degree hole in the lower end of probe arm.

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**Figure 26.** Final probe needle assembly.

The probe holder with needle assembly can then be fully mounted in any of the three designs using the integrated approach shown in Figure 23 for design (c) or using a screw to hold the brass tube in place of the empty clamp as shown in the top of Figure 1 for design (a) or the hole in the moving z-axis glider shown in the bottom left of Figure 12 for design (b).

**6. Operation Instructions**

After assembly of all three of the systems mount the open source 3-D printable probe positioning system on the metal stage of the probe station. Connect the probe cable to the measurement unit. Move the system in the x-y plane into macroscale position sliding it along the magnetic base/stage interface. When within a few mm, turn the x and y knobs, while looking through the microscope until the probe tip is above the targeted contact. Finally, carefully turn the z knob until the probe tip makes contact with the sample.

**7. Cost Analysis**

All three of the open source micromanipulators are significantly less expensive than commercial alternatives. It should be noted that the open source micromanipulators were compared to high-quality micropositioners needed for microelectronics work. There are lower cost probe positioners on the market, which are not acceptable for the majority of these applications. However, there are some exceptions. For example, a low cost commercial probe is adequate for contacting a 2 mm diameter experimental solar cell. Likewise the least costly open source design here would be more than adequate. However, both devices would have more difficulty with contacting a 20 micron pad reliably. High-quality probes are generally over $1000. For example probe manipulators with magnetic bases run between $1,320 and $2,085 from Micromanipulator [49], which provides a savings of 99% for constructing (a) to 92-95% for purchasing (a) assembled, building (b) provides about 98% savings and building (c) provides 89% to 93% savings.

Even the cost savings for only the probe holder (section 5.4) can justify the full cost of the micromanipulator-probe open source system. For example, the simple probe holders cost between $450-580 for a device that can hold a probe and has a connector [50], without a connector and including the wire they cost $280 [51] to $305 [52], while those with coaxial or tri-axial connectors cost from $490 to 860 [53]. Thus savings for the $55 open source probe shown here range from 80% to 90%, even when a professional machinist is used to fabricate the parts. As the open source TAZ 3-D printers used to fabricate the polymer components of the manipulators cost $2,500, a 3-D printer can be cost justified with the fabrication of a single micromanipulator if the technical specifications can meet the user's needs. However, it should be pointed out that typically probe stations and microelectronic applications need more than 1 manipulator (e.g. many probe stations need 4 to 6). Six micromanipulators for a probe station at a cost savings of $2,500 each is a total $15,000 of savings. This multiplier effect is particularly instructive for the use of distributed manufacturing with open source 3-D printers. Although, the first micromanipulator including the cost of the capital equipment can be fabricated for about the cost to purchase a proprietary one, every additional micromanipulator systems has a relatively incredibly small marginal cost as compared to purchasing proprietary equipment with similar functionality.

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**8. Validation and Characterization**

All three micropositioners were tested in a dark cabinet shown in Figure 27 with a commercial silicon wafer probe station (Figure 28). The wafer probe station floats on air cushions and is enclosed in a dark cabinet with a hinged access door. First, all three micropositioners were tested for the maximal deflection that the probe head would experience given the worst case scenario of a clumsy operating pushing on the z-axis holder. The results showed the maximum deflection for micropostioner design (a) was more than 200 microns, for (b) design 40 microns and for (c) design 10 microns. These limitations were primarily caused by the designs not inherent limitations of print quality or resolution. It should be stressed that these are the worst deflections possible and that under normal operation the values are significantly less. So for example, the 3-level stack design (c) micropositioners with careful operation result in a needle deviation less than 5 microns. The ability to hit targets was first determined with a 12 micron end tip probe contacting metal letters with 8.75 micron line width shown in Figure 29.

**Figure 27.** Dark cabinet for testing micropositioners

**Figure 28.** Commercial silicon wafer probe station used for testing mircropositioners (shown with two 3-level stack design (c) micropositioners with probes and tips). Note color coding with left (yellow) and right (grey) for easy identification regardless of probe count.

For design (a) the nearly fully 3-D printed micropositioner, each full turn of a knob moves an axis 0.8 mm and targets of 20 microns can be targeted with care with the aid of a microscope. It should be noted as tested care is necessary because of the movement along the test surface when moving down the z axis because of the geometry of (a).

For design (b) each full turn of a knob moves an axis 0.5 mm and provides positional control of 8.3 microns. With the aid of a microscope this positional system is cable of reliably hitting 20 micron targets with less user effort than design (a). Under normal silicon wafer prober operating conditions, needles do not move on the object surface with both this design (b) and with design (c).

For the 3-level stack design (c) each full turn of a knob moves an axis 0.5 mm providing externally measured positional control of 10 microns on the knob axis. This last design is the most accurate and stable and is capable of targeting contact areas below 10 microns. Design (c) is primarily limited by the 12 micron tip radius of the tungsten needle rather than the x-y-z positioning accuracy as shown in Figure 29. Using design (c) targeting of standard size test objects (50 x 50 microns or larger) is trivial, however requires high stability of the other test system components (in this case a commercial wafer probing station), and a good microscope.

**Figure 29.** 12 micron end tip probes contacting metal letters with 8.75 micron line width used for testing.

Not only is the maximum deflection and the positional stability important for micropositioners in these applications but also is the way in which they move in the x, y and z directions. For example, manipulator designs (a) and (b) travel along a screw, which not only involve translationally forces in the

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direction of travel, but also sideways forces perpendicular to that travel. In design c, the screw motion pushes a lever that eliminates this second force. Although designs (a) and (b) are constrained this causes motion out of the plane of the direction of travel. This is substantial as seen in the videos of design (a) in ref. [37]. To check this for design (b) a video is recorded with a 25X magnification with an optical microscope of the motion of (b) over a scale bar where each division is 0.1 mm [40]. This video shows another printed version of (b) in PLA and as can be seen the motion out of the axis of travel is minimized.

To gain a further understanding of the new designs (b) and (c) micropositioner performance videos were recorded using the camera of a Huawei P10 Lite smartphone, which was mounted into the ocular of the probe station microscope using a 3-D printed adapter as shown in Figure 30. The adapter was printed out of Polymaker Polylite PLA using a Lulzbot Taz 6 3-D printer (Aleph Objects, Loveland, CO). The micromanipulator needles were moved over a metallized wafer with 100μm x 100μm square regions shown in Figure 31. Videos of the motion for designs (b) and (c) are available in [40]. The travel path of design (b) does not have the same deviations seen for design (a) from the screw but has progressively greater degrees of deflection (increasing from x to y to z) due to the users hands is seen in the videos can be 50 microns. These deflections are highly dependent on the tightness of the printed components and thus can vary from probe to probe. These out of direction of travel deflections are all but eliminated for design (c). A summary of the three designs of the open source micromanipulators are compared in Table 1.

**Figure 30.** 3-D printed smartphone to optics adapter used for monitoring micropositioner travel paths.

**Figure 31.** Screen capture of microscopic image of probe tip moving over metallized wafer with 100μm x 100μm square regions.

Table 1. Summary comparison of three open source micromanipulators.

| **Design** | **Nearly Fully 3-D Printed Mechanical Manipulator** | **Partially 3-D Printed OpenBeam Kinematic Constrained Micromanipulator** | **3-level Stack of Low-cost Commercial Single Axis Micropositioners and Some Key 3-D Printed Parts** |
|---|---|---|---|
| **Cost** | *$5-99* | *$22.20* | *$145.54* |
| **Full turn of a knob moves an axis** | 0.8 mm | 0.5 mm | 0.5 mm |
| **Maximum deflection** | 200 microns | 40 microns | 10 microns |
| **x-y footprint excluding knobs** | 8295 $mm^2$ | 4225 $mm^2$ | 3600 $mm^2$ |
| **Range of motion** | 37 mm (x), 32 mm (y) and 18 mm (z) | 30 mm (x), 30 mm (y) and 35 mm z axis | 13 mm (x), 13 mm (y) and 10 mm (z) |
| **External measured** | 800 microns * | 8.3 microns | 10 microns |

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| | | | |
|---|---|---|---|
| **positional control** | | | |
| **Can reliably hit contact area** | 20 microns | <20 microns | <10 microns |

* This is for the as purchased version. It could be reduced with knobs used for design (b)

## 9. Limitations and Potential Modifications

There are several ways all three of these micromanipulator systems can be improved in the future. All three probes can take advantage of recent work on the chemical compatibility of 3-D printed polymers [55] to enable the probes to operate in challenging chemical environments. In addition, preliminary work indicates they could be used inside clean rooms as well [56].

System (a) can be fabricated with higher performance polymers and redesigned to offer greater rigidity and smaller volume.

For system (b), a lighter smaller version can be made by: i) shortening the probe volume envelope, ii) using M3 or M2 based threaded rods (and associated nuts) instead of M5s, iii) clamping the end ramps to the OpenBeam with M3 nut traps from the top in order to eliminate the need for the end screw and thus allowing the OpenBeam to be cut in half length wise as well as the reduction in height of the end ramps and gliders, iv) eliminate the need for a jammed nut and the use of the locking nut using superglue, v) sink the top of the end ramps to allow for the shortening of the M3 x 27mm socket head cap screws, and vi) eliminate all structurally unnecessary material from the 3-D printing designs that are there for FFF direct printing and print with a soluble support material such as polyvinyl alcohol (PVA).

For system (c) the 3-D printable parts can be redesigned to reduce mass, print time, cost and improve aesthetic appearance. In addition, as low-cost metal 3-D printing becomes more widely available additional purchased parts could be replaced by metal printed parts.

All three of the micromanipulator designs can be improved with the addition of a tilting base and automated following the work of Baden et al. [8] by mounting stepper motors on the ends of appropriately augmented end ramps to eliminate the manual knobs. The stepper motors could be controlled with a combination of stepper motor drivers and an Arduino or similar. Improved versions could be either controlled digitally from a screen of computer, tablet or smartphone or the system could be controlled by a dedicated 3-D printed controller such as a joystick. Automated manipulators with controllers are available from Sutter [57] and Thor Labs [58] from about $4,500 to over $16,000 so making the conversion is easily economically justified.

## 10. Acknowledgements

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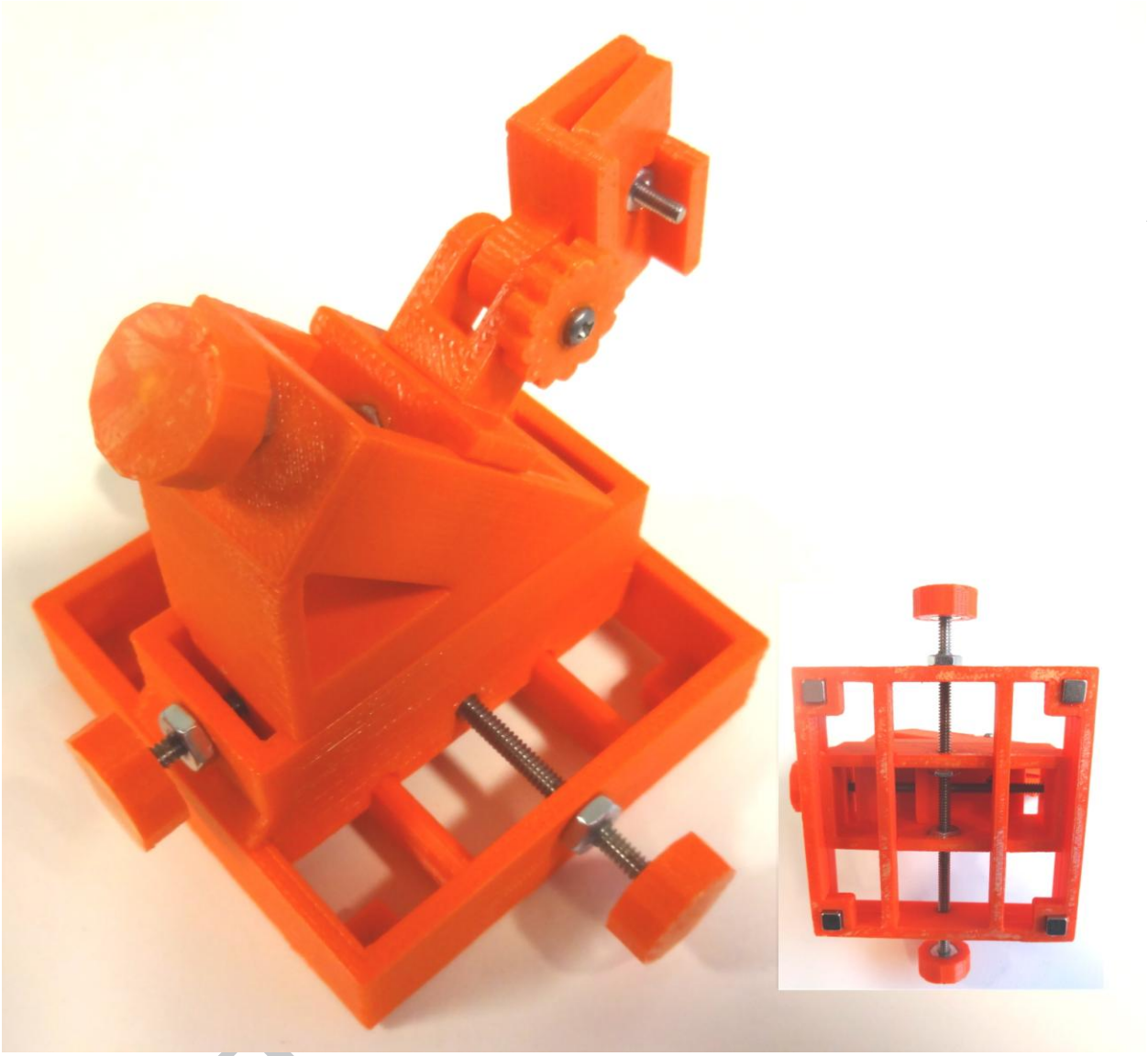

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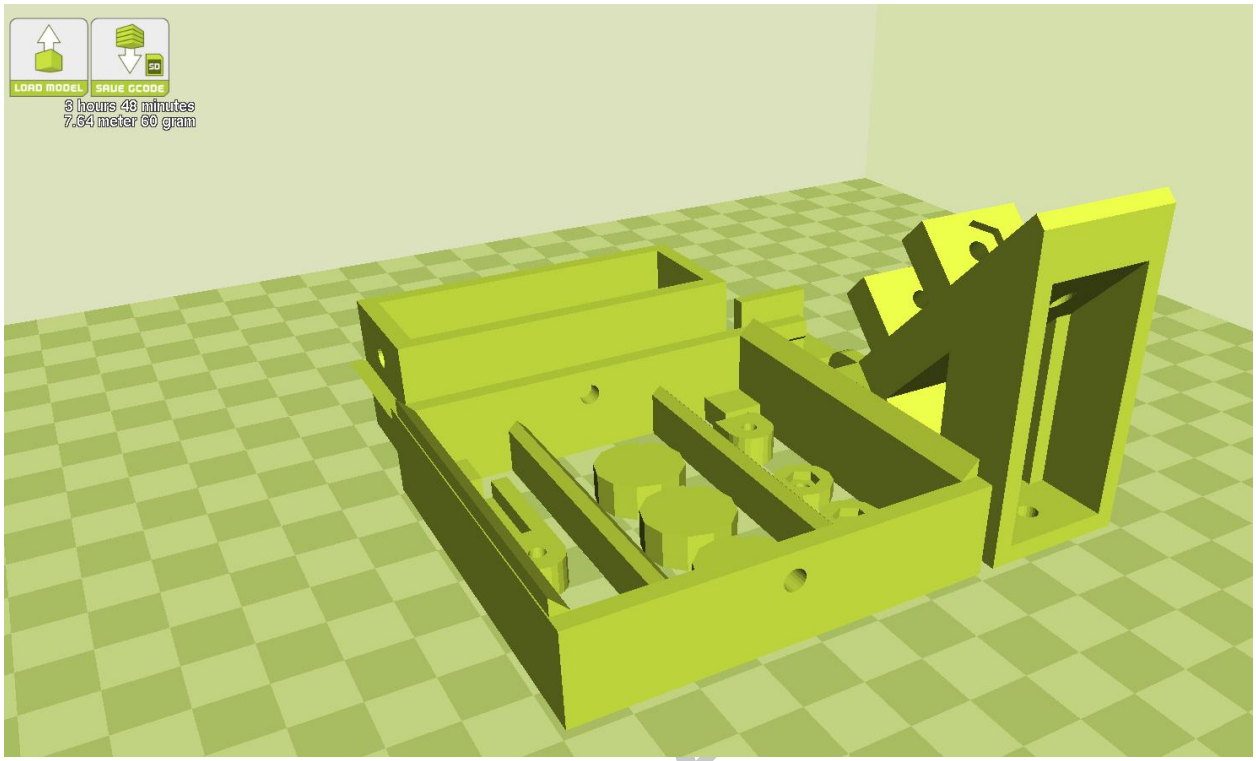


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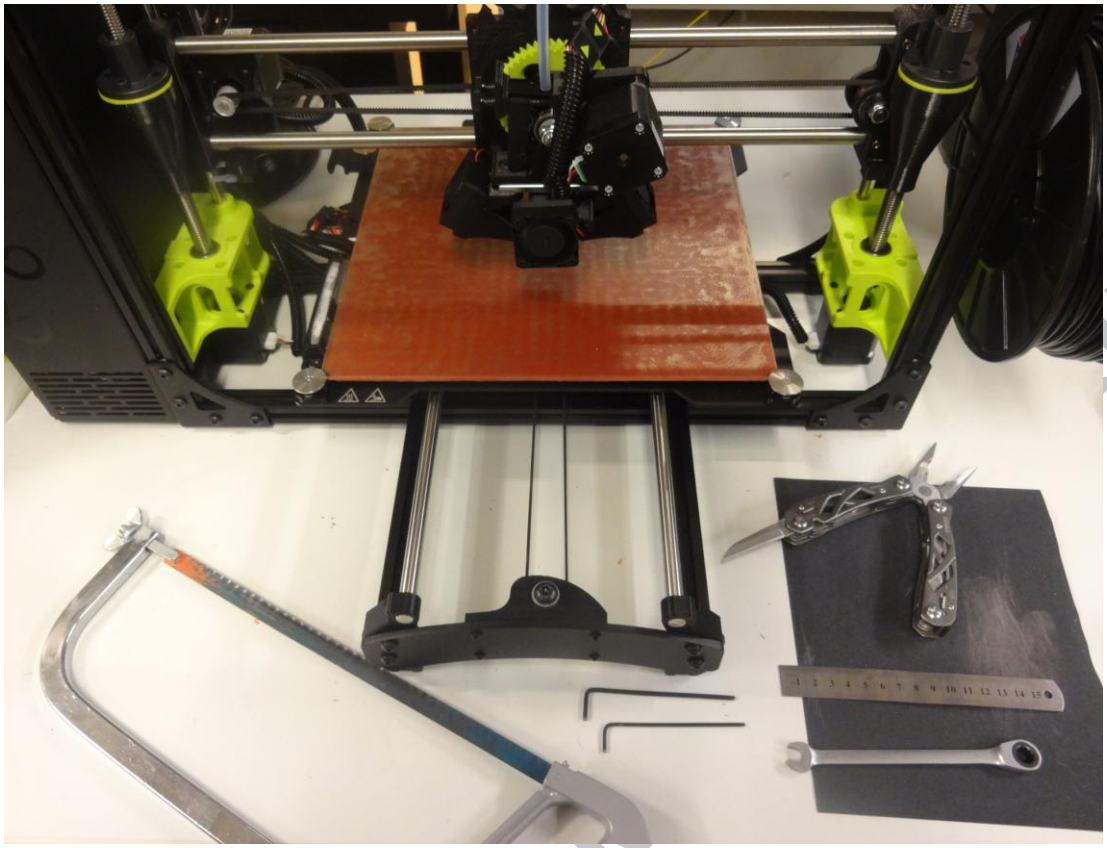

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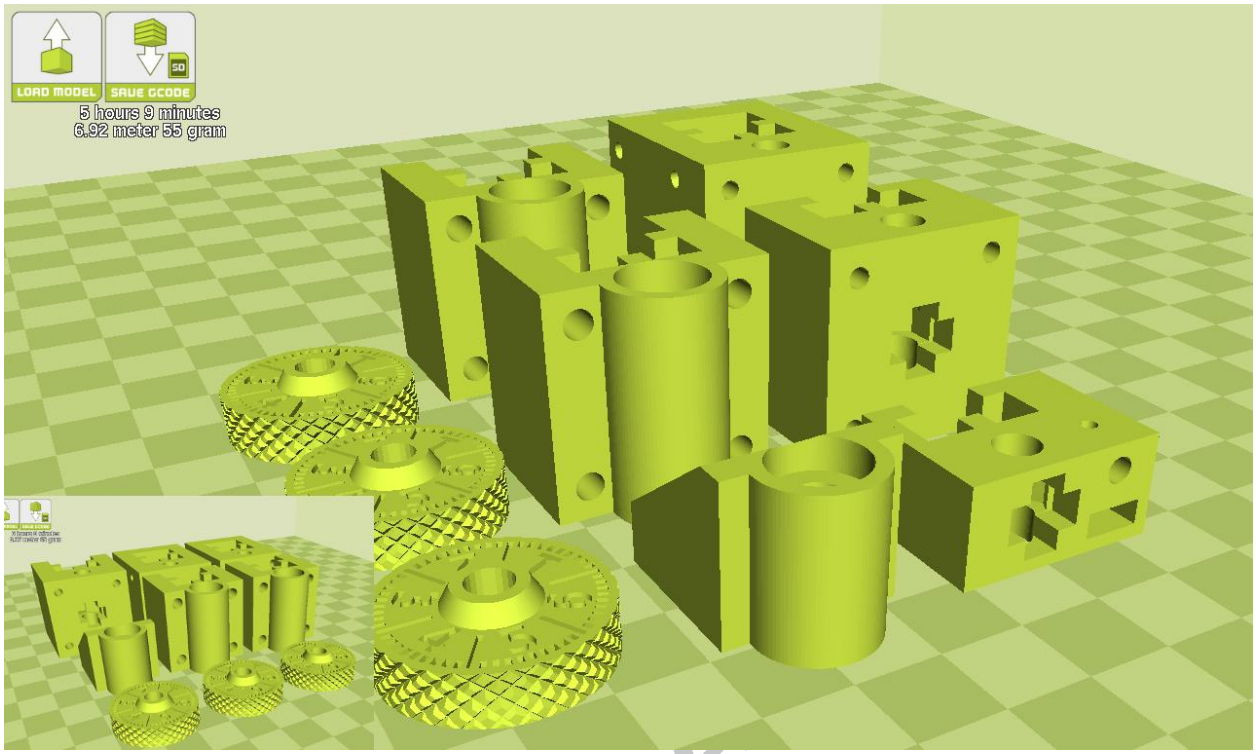


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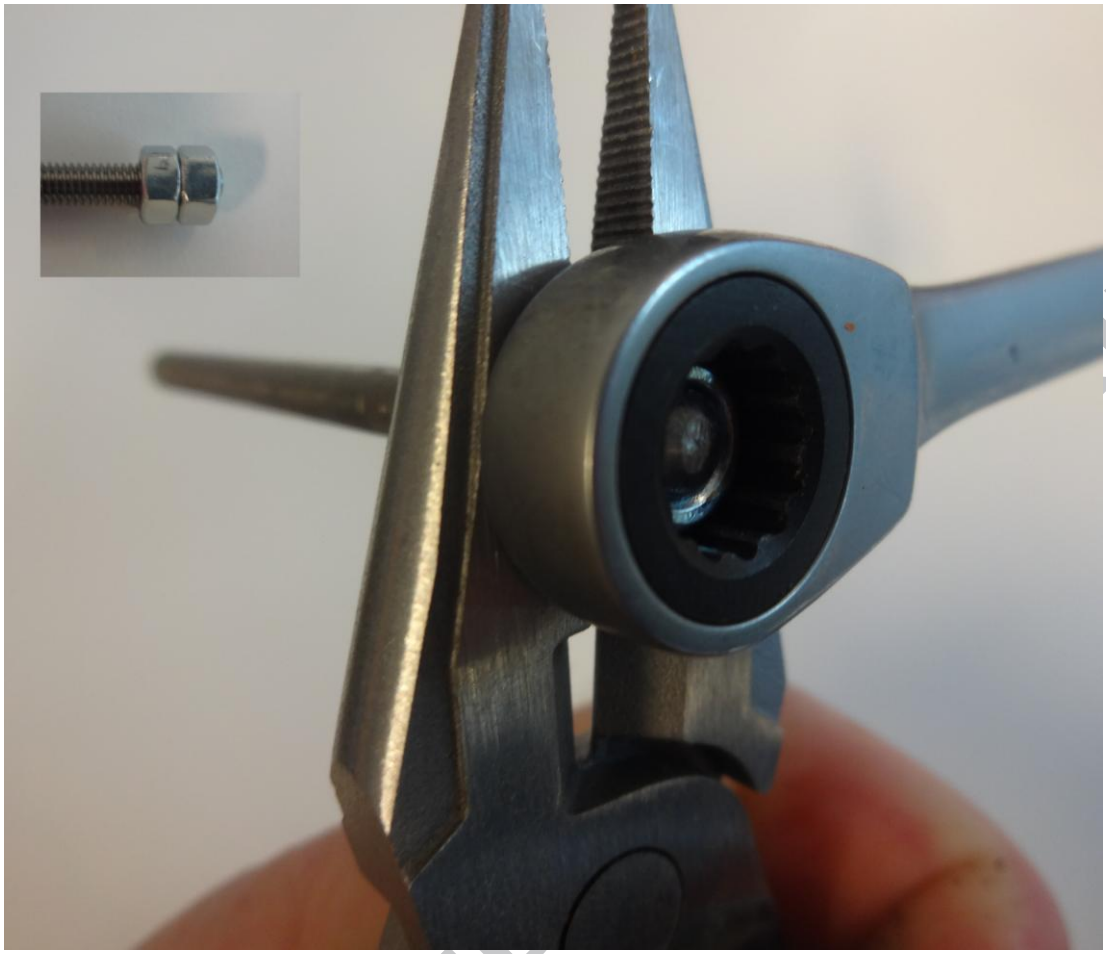

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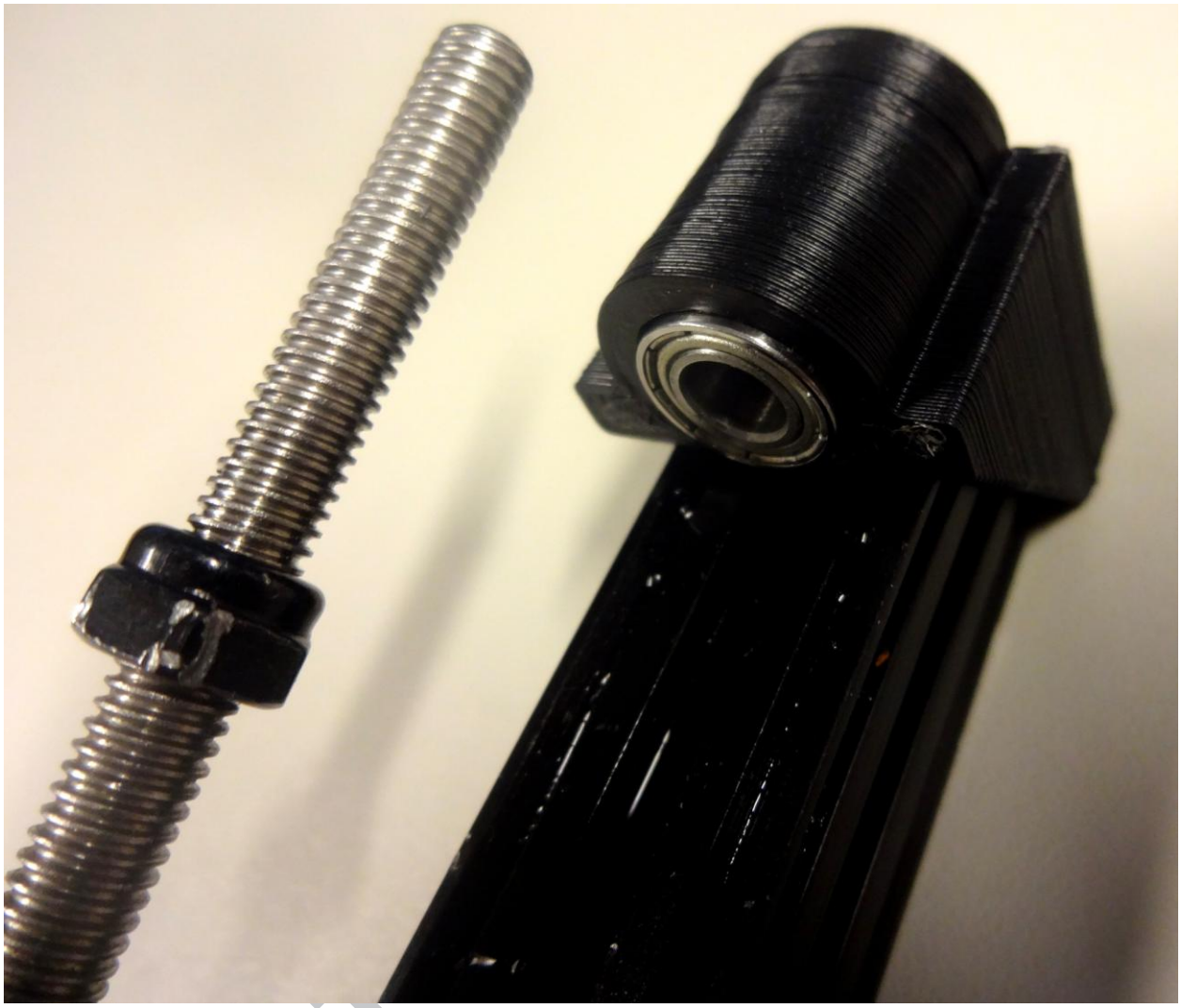

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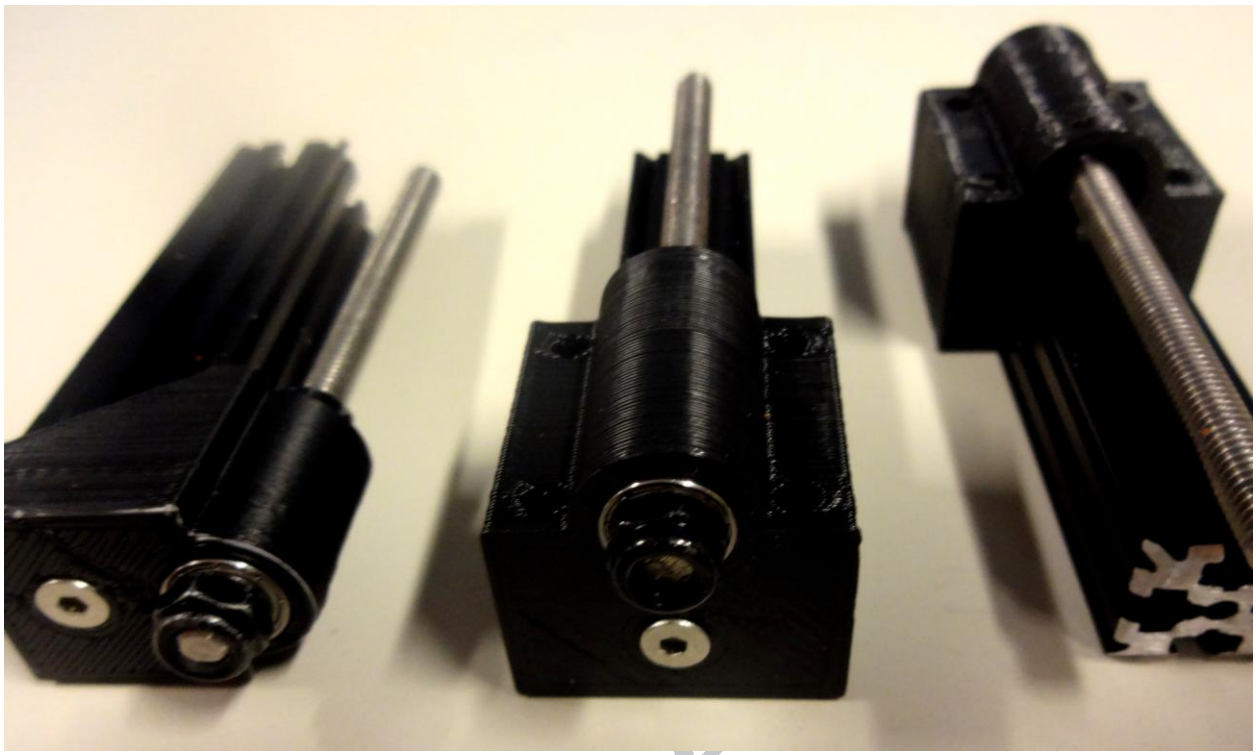

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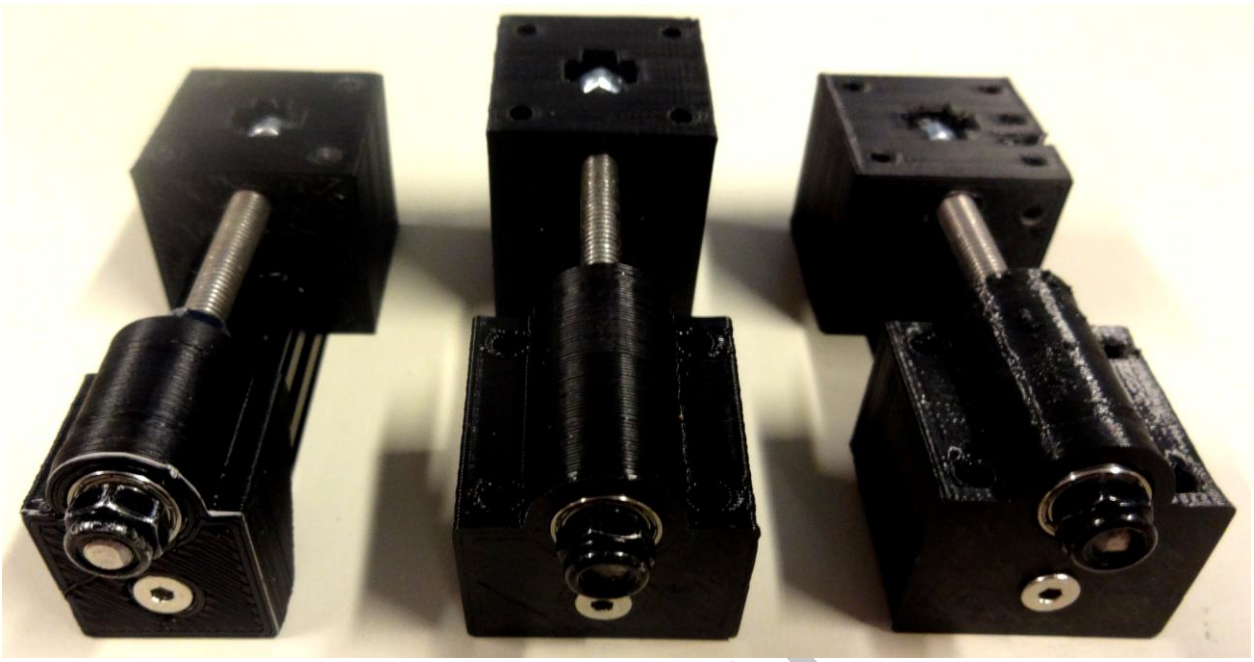

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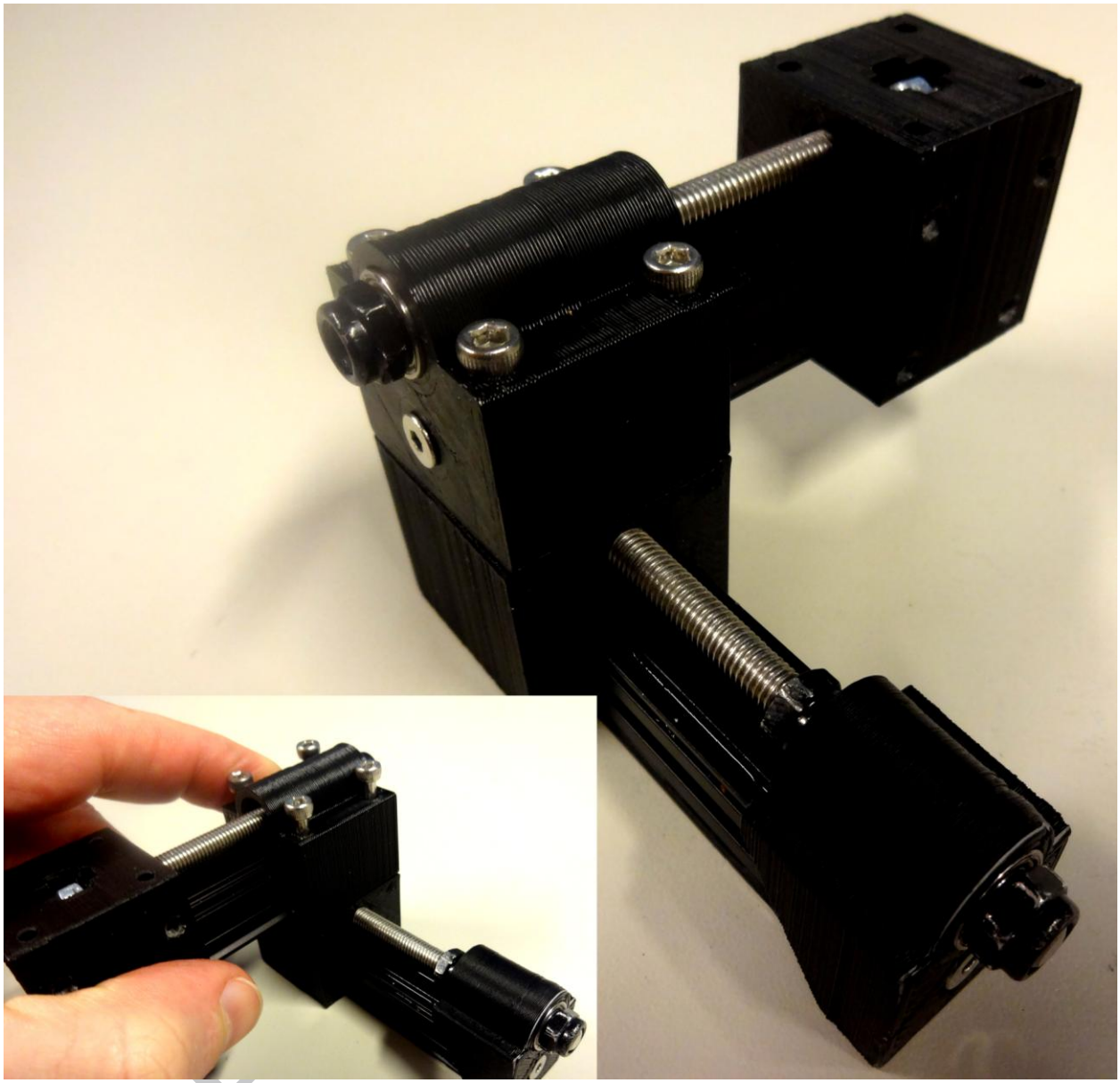

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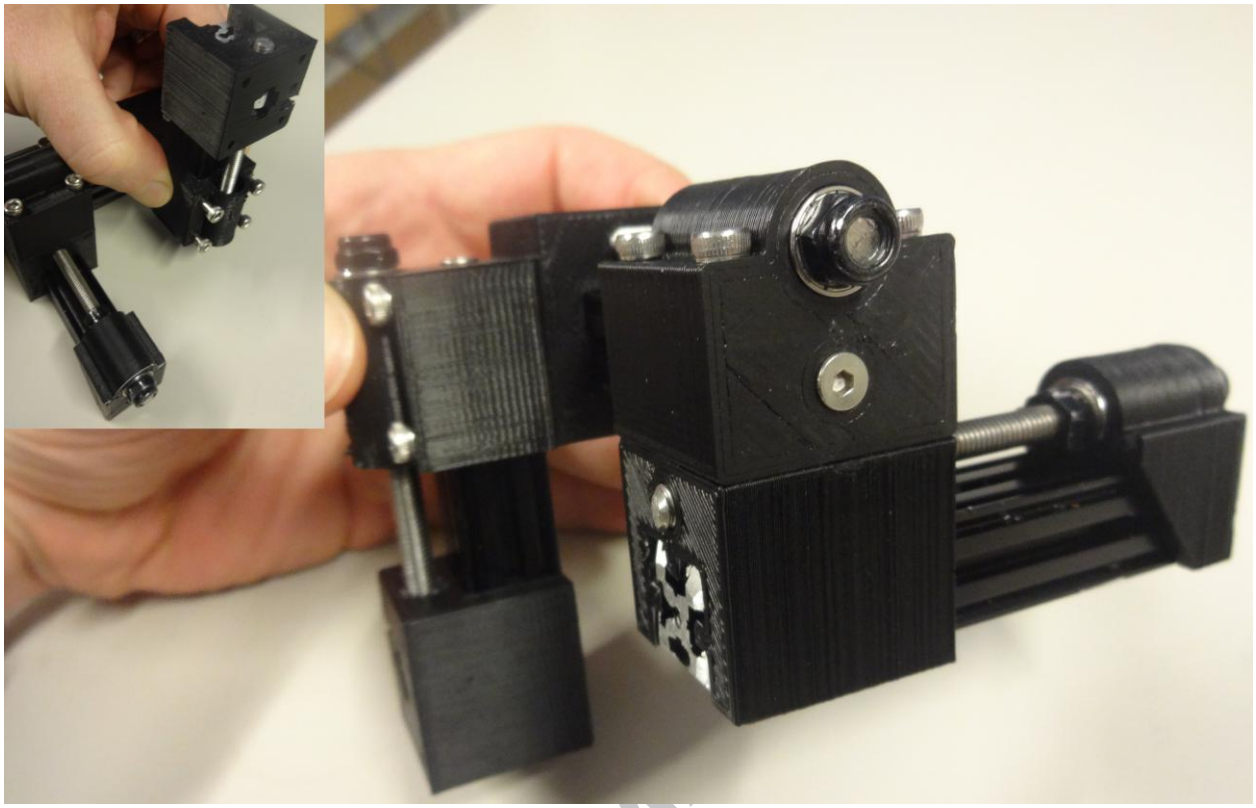

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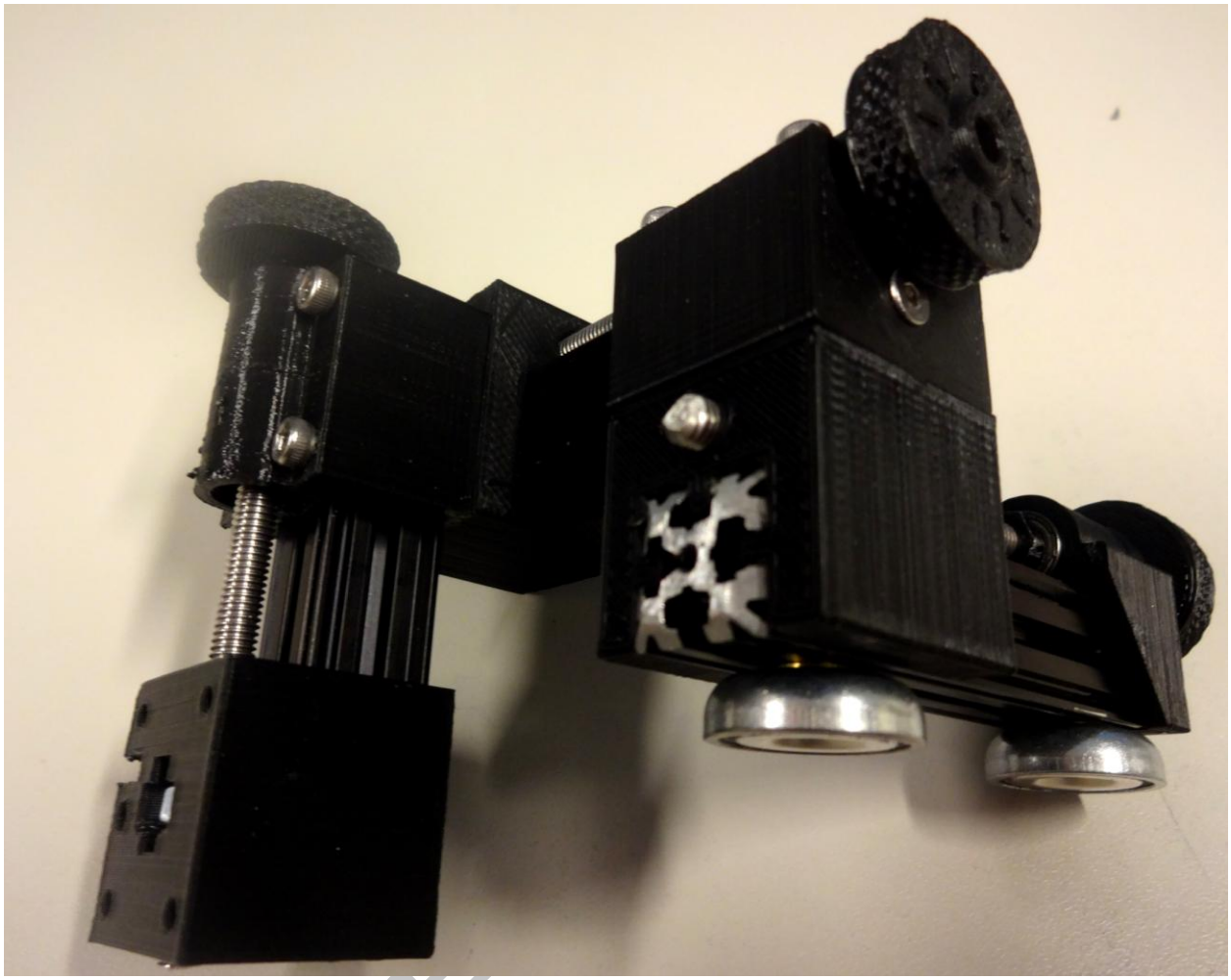

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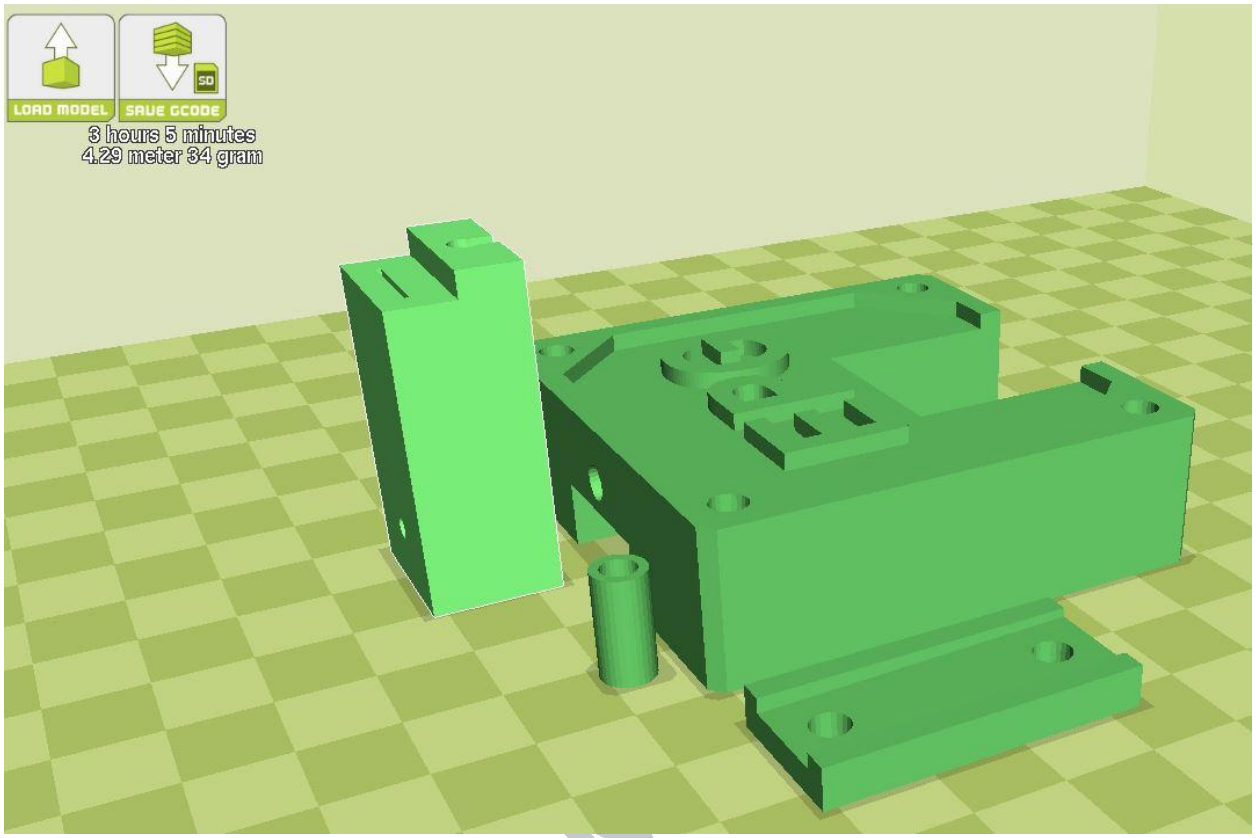


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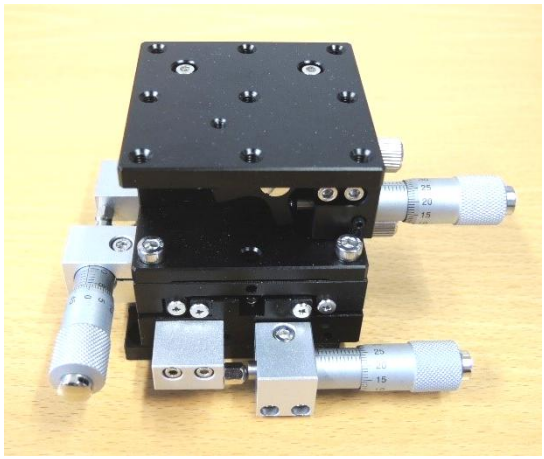

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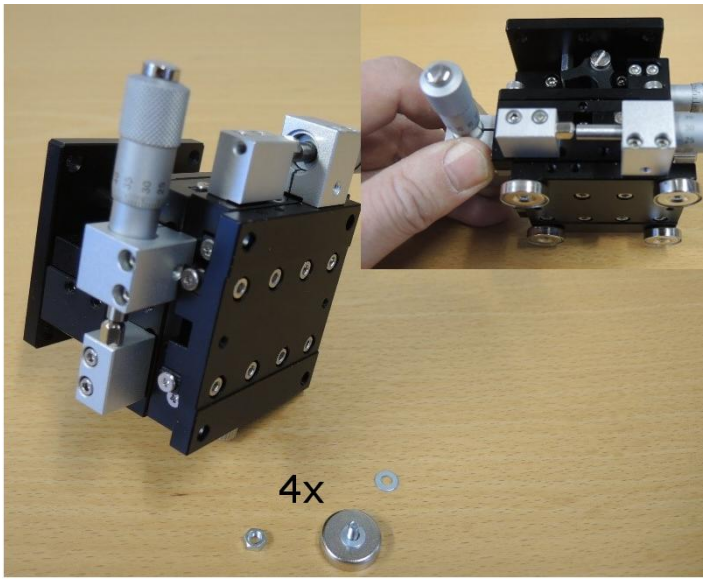


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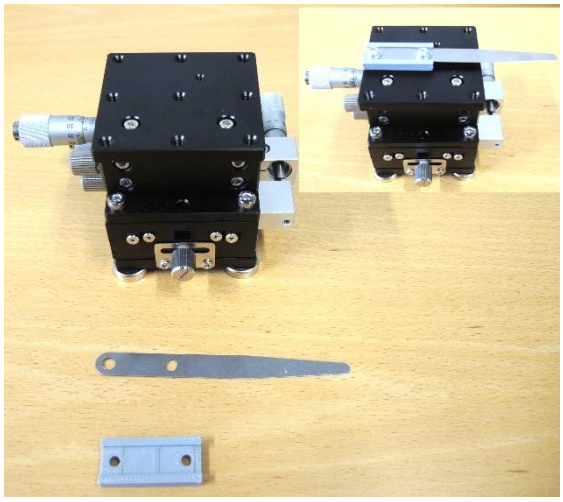

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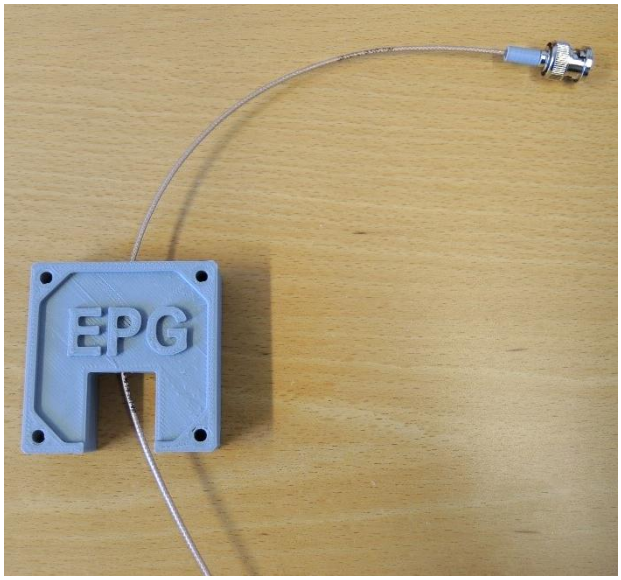


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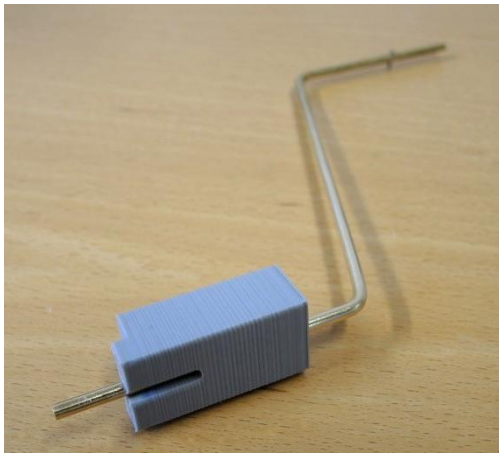

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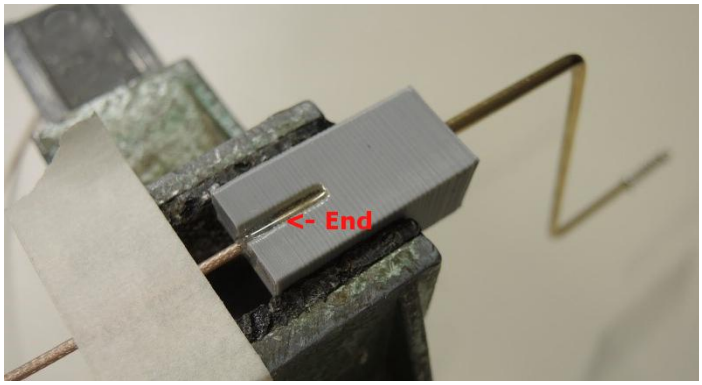


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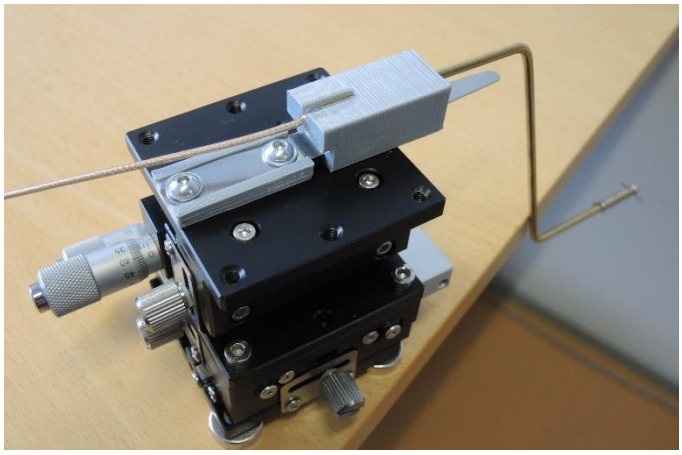

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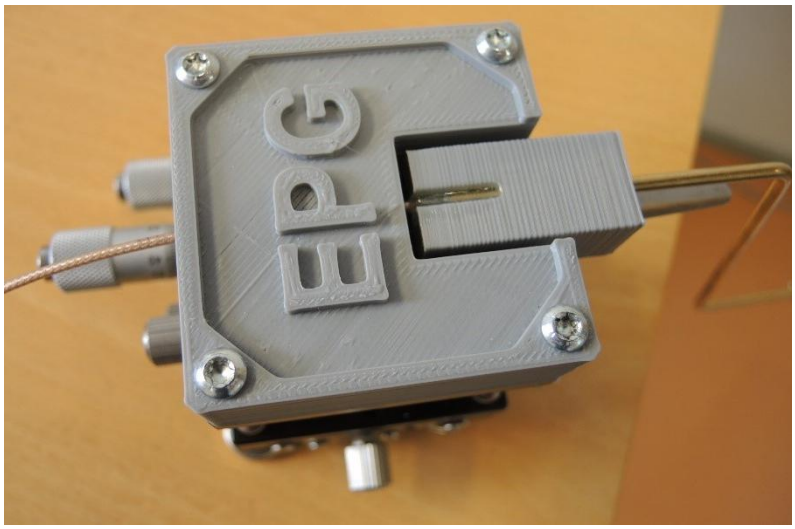


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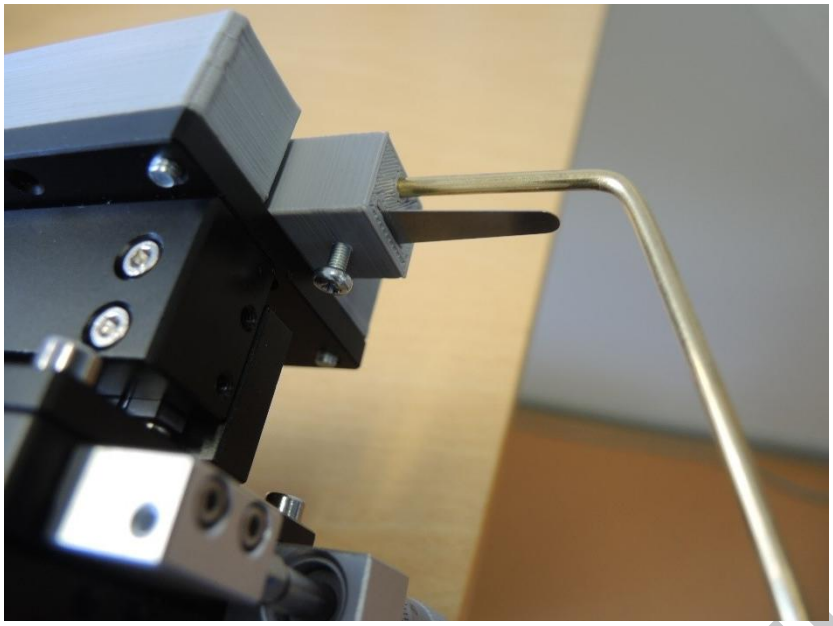

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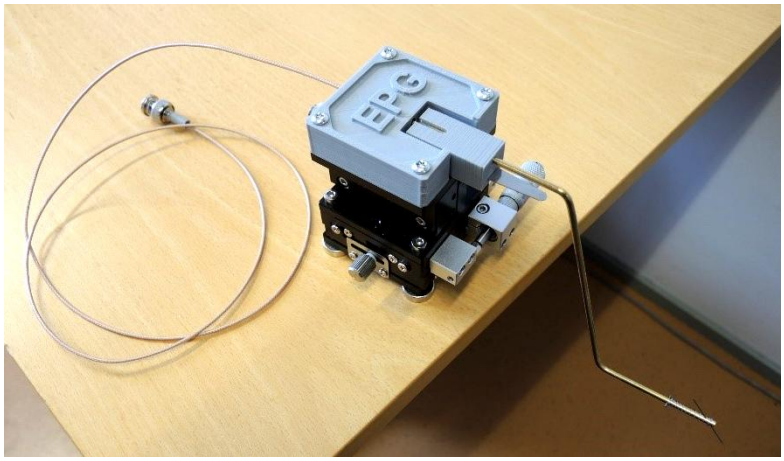


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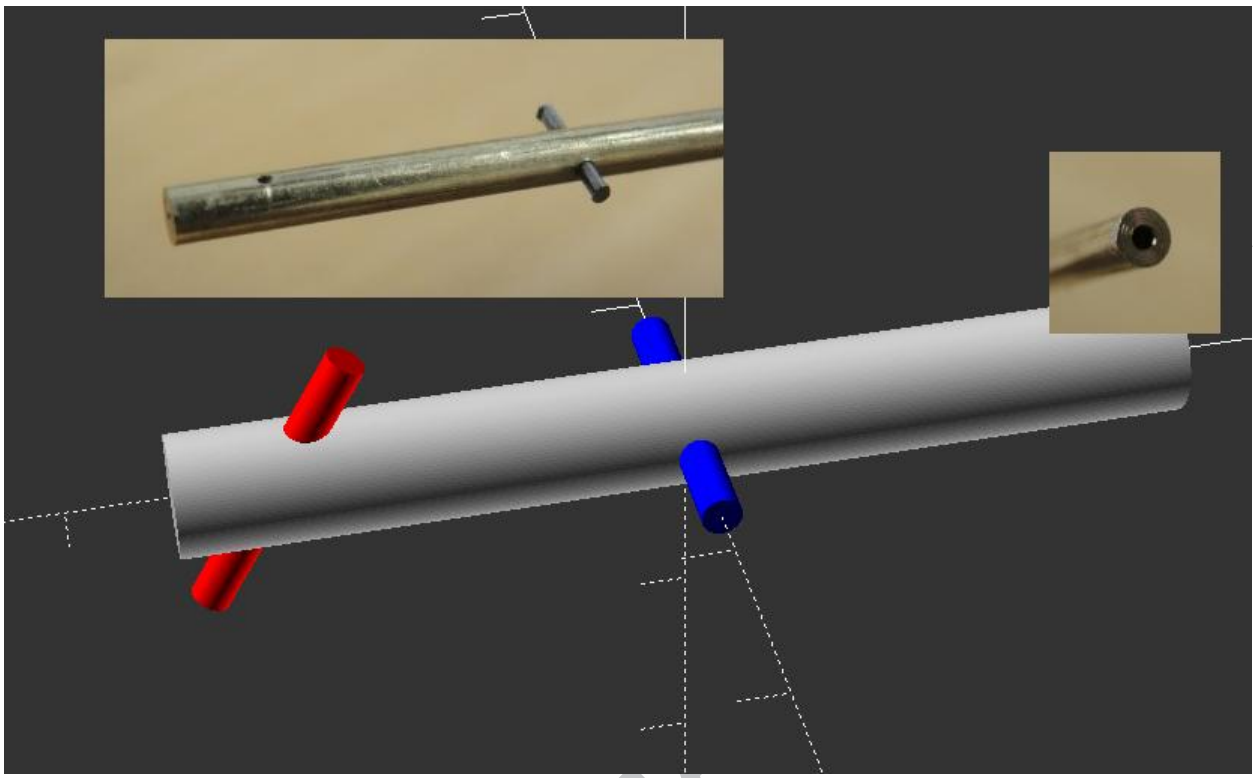

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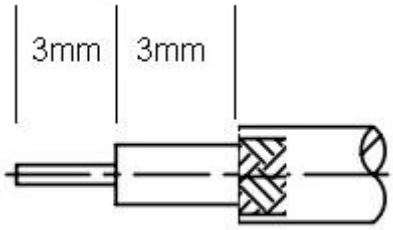


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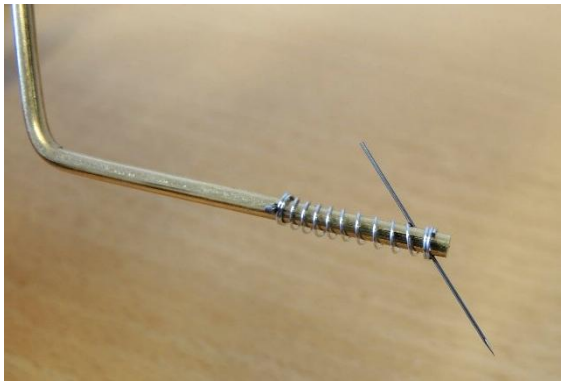

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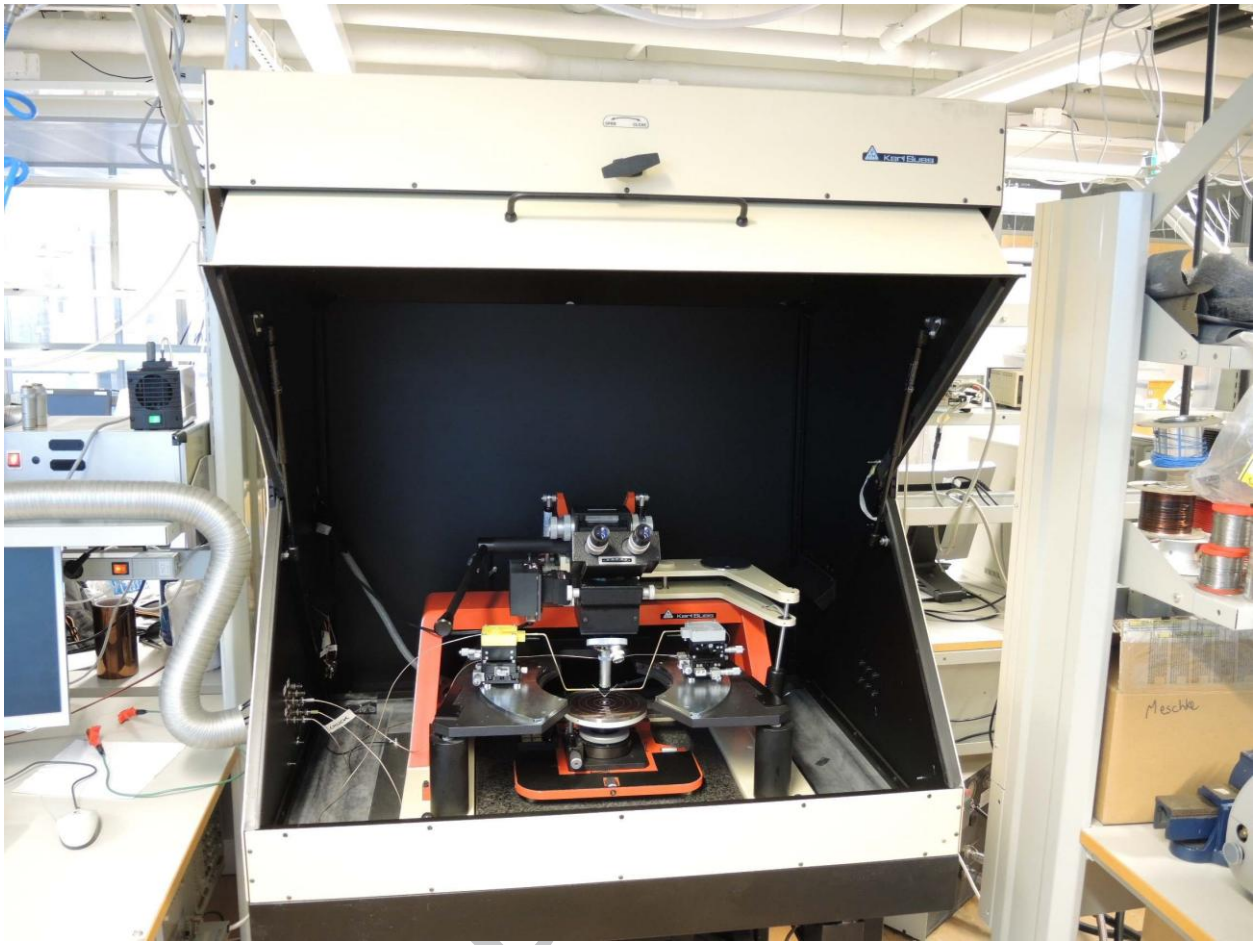


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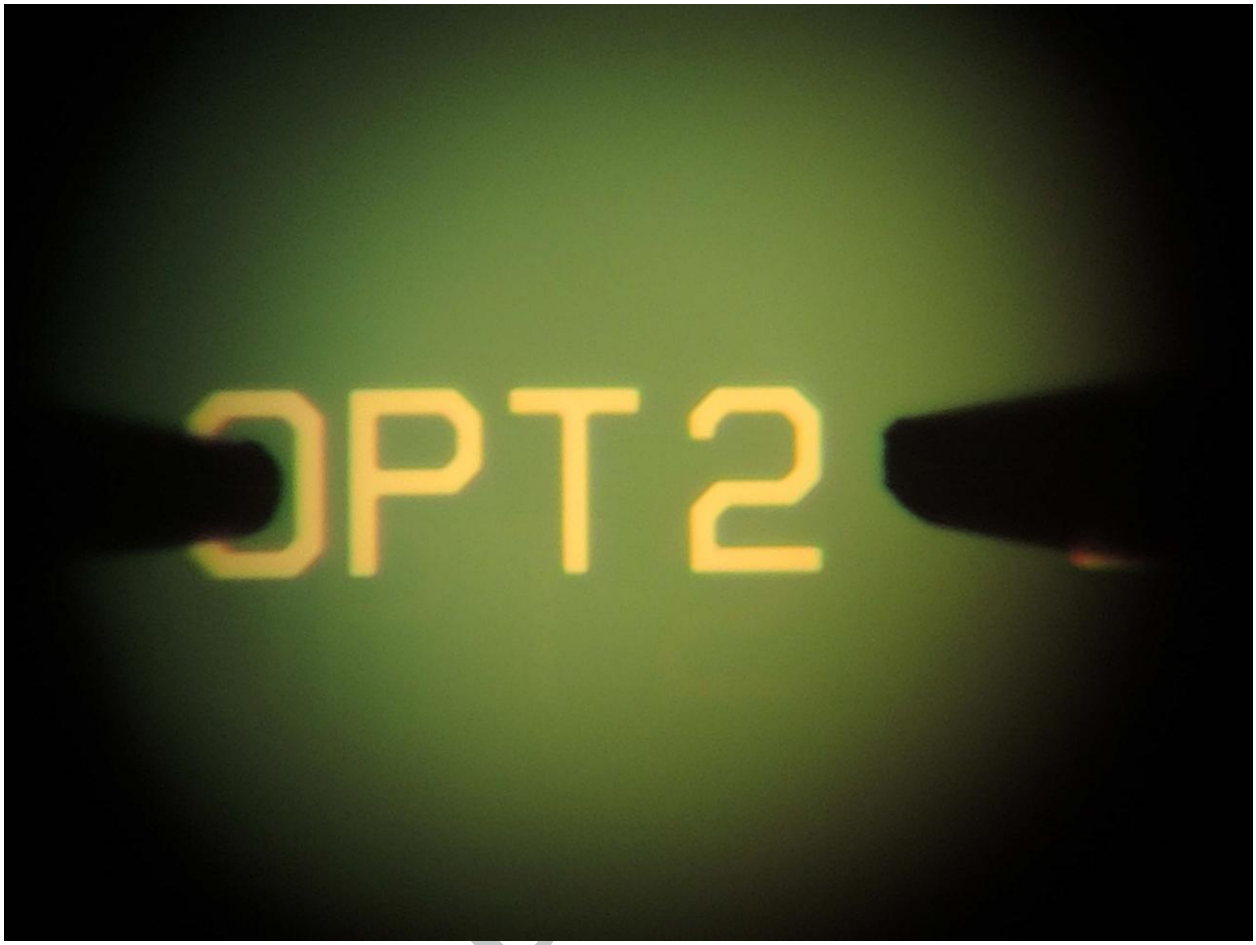


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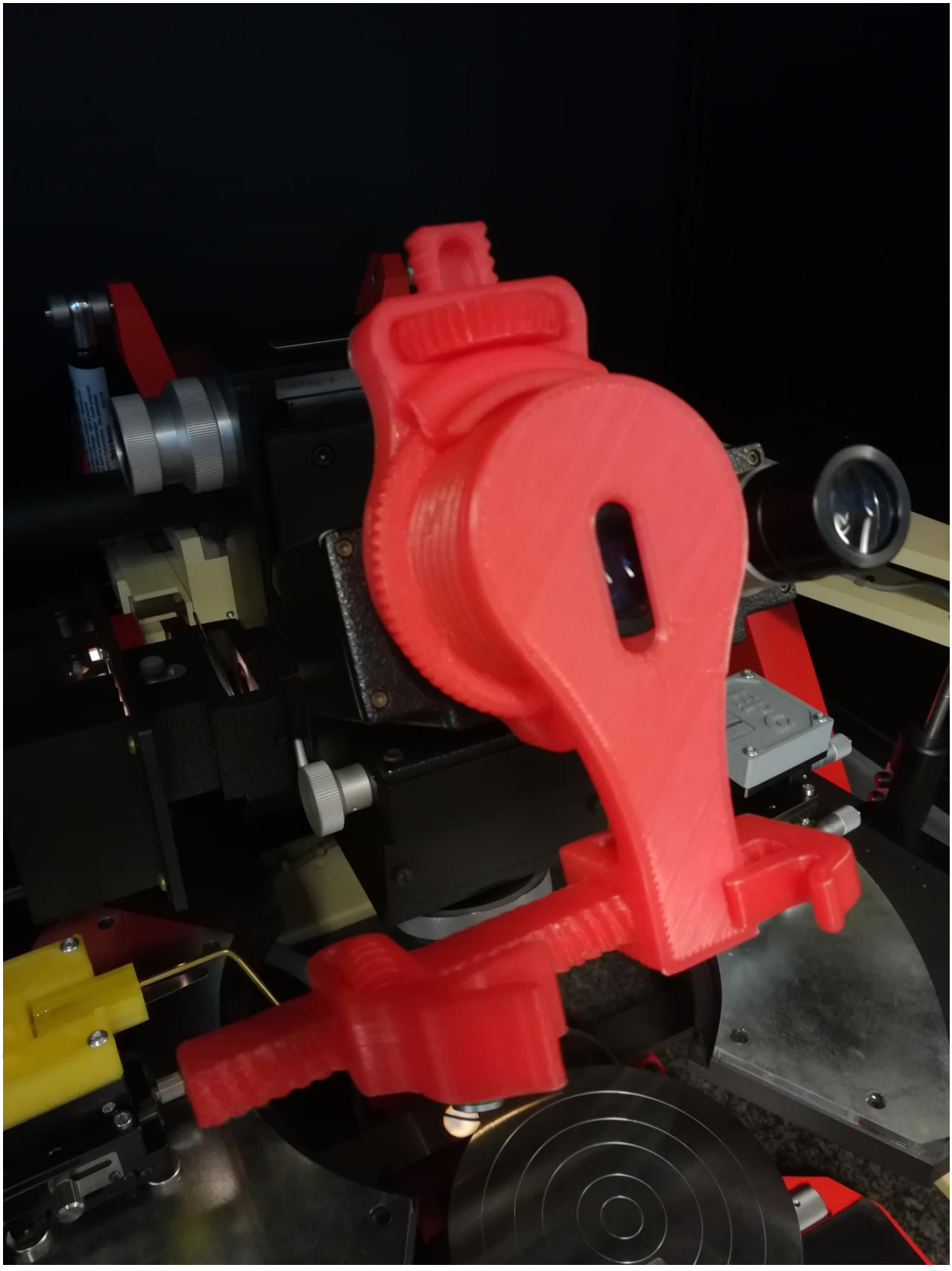

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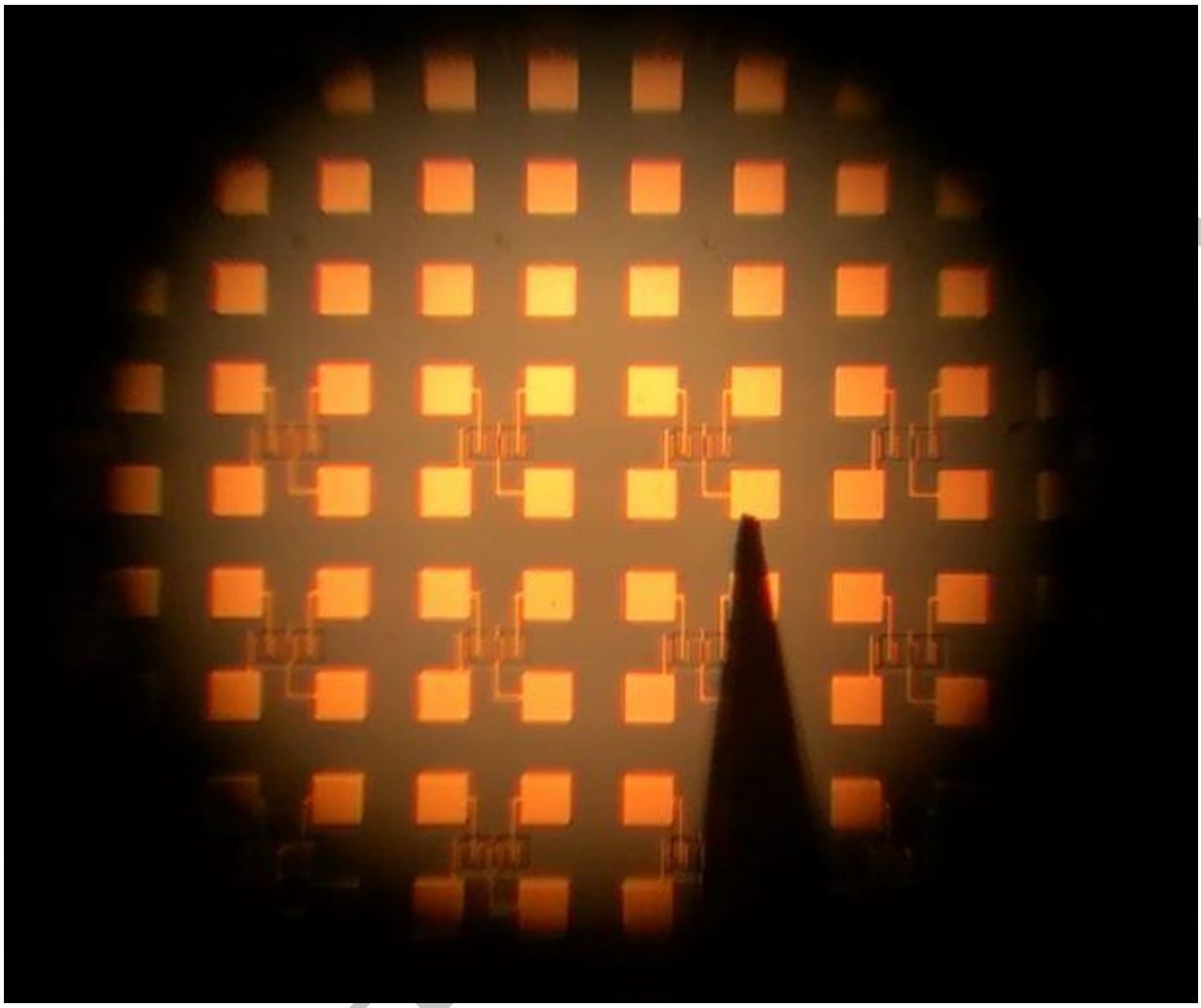

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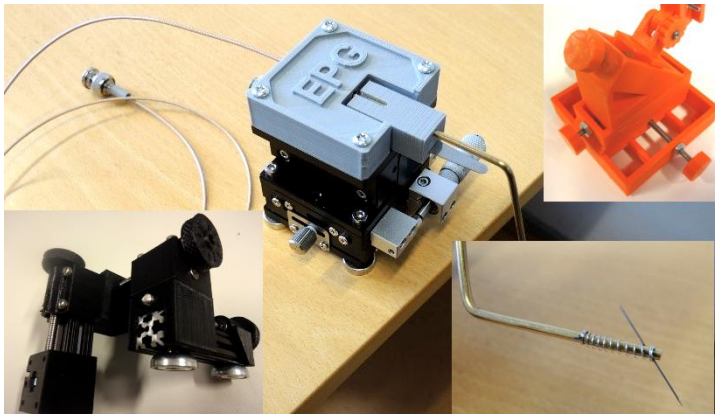


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