Supplemental:

Integrated imaging and bioprinting for scalable, networkable desktop experimentation

Nathan D. Orloff, Cynthia Truong, Nathan Cira, Stephen Koo, Andrea Hamilton, Sean Choi, Victoria Wu, and Ingmar H. Riedel-Kruse

Department of Bioengineering, Stanford University, Stanford, California, USA,

e-mail: ingmar@stanford.edu

Contents

I. Print Cycle Algorithm

We disassembled the printer to understand the native components and identify components that could be modified to reconfigure printer architecture. The printer consisted of many components, which could be thought of as either hardware or electronics. The printer hardware was encased in a plastic housing. A dc motor allowed for the paper to be fed by the paper feed shaft, which was mounted on an aluminum assembly. A timing belt turned the paper feed shaft, which was monitored by an optical rotary encoder. Since the encoder measure the rotations of the shaft and not necessarily the absolute translation, differences in the pitch diameter of the spur gear and paper feed shaft resulted in a slight stretching. As the print head expels ink from multiple nozzles simultaneously, this small error cannot be accounted for by stretching the print document. The printer carriage was driven along an aluminum linear rail by an encoded dc motor. The motors were controlled by a motherboard, which monitored the relative positions with the encoders. The absolute start and stop positions were set by the paper feed slot sensor mounted on the bottom of the printer. This sensor initiated and terminated the print cycle. The optical slot encoder was common design feature in many inkjet printers, which made it attractive as the key component in our design. By understanding how the optical slot encoder functioned, we were able to control the print cycle algorithm.

Once the printer is turned on, the printer initiates a calibration cycle in the printer firmware which rotates the paper feed shaft back and forth to reset the positions of the cartridges and rollers. After a page is sent to the printer, the printer estimates the ink levels. If the number of requested prints exceeds the maximum number of prints allowed, then the printer issues the “no-ink” error. Next, the paper feed motor rotates clockwise to test the paper output tray, which also tests for the “paper-output-tray-closed” error; the paper feed motor then rotates counterclockwise (opposite the print direction) to advance the page. The page is advanced until it triggers the paper feed optical slot sensor into the on state; otherwise, the “out-of-paper” error is reported. The page is then advanced for an additional rotation, placing the page directly under the print cartridge. The page is printed on until the paper feed optical slot sensor is triggered off. During the printing process, the rotary and linear sensors are monitored for errors. Once the paper feed optical slot sensor is triggered off, the page is advanced rapidly in order to eject the paper.

II. Building Instructions

In Section II (Bioprinter Assembly), we describe how to assemble the bioprinter. Here, were provide additional details regarding the fabrication and assembly of the components used to make the bioprinter and imaging platform. First, to build the modified shaft, we cut the original shaft to 100 mm (measured from the end of the shaft nearest the grooved end). We then reduced the diameter of the shaft with an acetone soaked paper towel to 12 mm for 30 mm opposite the grooved end, such that the radial bearing could slide over the shaft. We affixed in the ABS insert from the grooved end of the shaft. The threaded rod was screwed into the insert such that 5 mm remained from the grooved end. We then slid the radial bearing onto the paper feed shaft. The encoder wheel and timing gear were pushed onto the shaft, and then secured with acrylic cement (Weld-On #3). This prevented the timing gear from freely rotating around the shaft. The timing gear and encoder wheel were approximately 37 mm from the grooved end (measured from the face of encoder wheel). Next, we inserted the HF0812 one-way bearing into the ABS sleeve. The sleeve was then pressed into the drive gear. The sleeve was screwed onto the threaded rod opposite the grooved end and fastened on either end with a nut and locking washer. This completed the modified shaft assembly.

The gray plastic body of the printer was retained, because it allowed for the parts to be mounted in their native configuration. We needed to heavily modify this part, removing material in strategic places and drilling a total of eleven holes. To facilitate this step, we created decals from polycarbonate adhesive sheets (Graphix Adhesive Films) cut with an Epilog Mini 18 laser cutter and adhered the decals to the plastic housing. We then cut the plastic housing and drilled/tapped holes where indicated by the decals. We also used the plastic lid from the printer, which decreased the flex of the plastic during the print cycle. Once the plastic housing was fabricated, we screwed on the threaded linear carriage (McMaster-Carr 6709K11) with four M4 bolts onto the bottom of the plastic housing, fastening it with locking washers and nuts. We then attached the ABS mechanical trigger to the plastic housing. The final piece of the plastic housing was the acrylic radial bearing mount. This connects the radial bearing to the plastic housing, maintaining the relative position of the paper feed shaft to the plastic housing. In order to connect this part, we first attached the modified paper feed shaft to the aluminum-mounting bracket and then placed the acrylic radial bearing mount on the bearing. Next, we slid the entire assembly into place and fixed it with screws. The acrylic mount was fastened to the side of the plastic housing with four 4-40 bolts and nuts.

With the main body assembled, we slid the linear carriage onto the guide rail (McMaster-Carr 6709K33), which was bolted to a laser cut 6 mm acrylic base plate (450 mm x 550 mm). The acrylic base plate had specific 1/4-20 tap holes to attach the remaining hardware. The assembly was completed with a main drive rack and a side rail rack. For this design, we opted to route the drive rack to one side of the printer. We found that this could produce torque on the printer assembly, which attributed to the misalignment of the print head. In this configuration, however, we maximized the space under the print carriage. Both racks were fabricated from 6.35 mm laser-cut acrylic. We designed the racks with box joints to facilitate assembly, after which they were permanently bonded with acrylic cement (Weld-On #3). The side rail rack had six 4-40 tapped holes to mount a guide rail (McMaster-Carr #6723K5). The drive rack had two 64 pitch 20 deg pressure angle racks (McMaster-Carr #7854K11). The main drive rack was 320 mm long and the clutch rack was 50 mm long. Both racks were mounted on the underside of the acrylic, which preserved the print direction. We also included a 3.175 mm wide 350 mm long slot alongside of the drive rack. This helped maintain the alignment of the spur gears relative to the drive and clutch racks. After we reassembled the printer hardware and electronics, we needed to fix the aluminum printer carriage to the side guide rail. To do this, we needed to design a fixture to couple the aluminum rail to the linear side rack. We fabricated an ABS fixture the mounted onto a Teflon carriage (McMaster-Carr #6723K5).

III. Step-by-Step Instructions

A. Printer Disassembly

1. Remove the blue tape on the printer.
2. Open the rear paper flap of the printer.
3. Take the flathead screwdriver and insert the end in between the rear paper flap joint and the printer body.
4. Turn the flathead screwdriver to pry the rear paper flap off of the printer.
5. Open the front paper tray. Insert the flathead screwdriver into the rightmost joint and turn to pry the paper tray off. This may break the plastic joint, but this part is not essential.
6. Flip the printer over such that the bottom is face-up.
7. Remove the T10 screw near the right-front of the print. This exposes the optical slot encoder.

8. Find the gray tabs near the middle rear of the printer. Press the tabs, releasing them.
9. Open gray plate. Insert flathead screwdriver in the leftmost joint and turn to pry the gray plate off.
10. Locate and unscrew the T10 screw near the top left front of the printer. Lift the black rectangular piece. The latch will most likely break, but a screwdriver can be used to unhook the assembly. This part is nonessential.
11. Locate and unscrew the two T10 screws near the front of the printer. They should be above the front paper tray.
12. Locate and unscrew the two T10 screws near the rear of the printer. They should below the rear paper flap.
13. Insert the flathead into the lip between the printer lid and body of the printer on the side of the printer with the Energy Star sticker. Twist the flathead and pry the lid off the printer.
14. Open the printer cartridge access tray. Insert the flathead into the left joint of the printer cartridge access tray, and turn to pry the tray off of the printer.
15. Locate the paper ejection roller. Insert the flathead screwdriver into the right joint and turn to dislodge the roller from the printer body. The roller may require more significant force to remove, but the part is nonessential.
16. Locate the three plugs that are connected to the motherboard. One of the plugs has black, yellow, and green wires. The other has red and black. And the last has gray and white wires. Carefully use the wire nippers to pop the three plugs off of the motherboard. Do not to cut the wires with the nippers. To do this, insert the tip of the nippers between the plug and the receptacle on the motherboard. Gently squeeze the plug and pull the plug up to disconnect it from the motherboard.
17. Locate and unscrew the three T10 screws on the motherboard that fasten it two the body of the printer.
18. Locate the small white ribbon facing the front paper tray. Pull the ribbon out of the socket.
19. Tilt the motherboard up and locate the large white ribbon. Pull the ribbon out of the top mounted socket. Place the motherboard to the side.
20. Locate the small board connected to the small white ribbon. Unscrew the T10 screw and place the board to the side.
21. Unscrew the two T10 screws near the half-moon cut outs. And unscrew the T10 screw that was below the motherboard.
22. Remove the printer linear stage and carriage and place to the side.
23. Locate the small black tabs on the linear stage. Take a flathead screwdriver and press the tabs to remove the black plastic paper alignment part, which should be just below the ribbon. There should be three plastic parts that need to be removed.
24. Unscrew the two T10 screws near the waste ink receptacle, which should be a white plastic part opposite where the motherboard was housed. Remove the white plastic part.

25. 25. Unscrew the two T10 screws closest to the plastic body. These fasten the paper feed shaft to the plastic body. Pull the aluminum part up and pry the paper feed shaft off of the housing. This should not require a significant force.
26. Locate the paper feed lever near the rear paper flap. Tilt the lever toward the paper tray to reveal a spring. Unhook the spring with the wire nippers.
27. Locate the two T10 screws on the white cover. The black, green, and yellow wires should route below this piece. Unscrew the T10 screw and remove this piece.
28. Unwrap the black, green, and yellow wires from their fastening points along the body.
29. Flip the printer over and unclip the prongs used to fix the position of the slotted optical encoder. Lift the slotted optical encoder, and be careful not to damage any of the wires or the plug.
30. Flip the printer right-side up.
31. Next to the side of the lever opposite where the motherboard was housed, locate the last remaining T10 screw and unscrew it.
32. Take the flathead screwdriver and insert it into the joint of the paper feed lever nearest to where the motherboard was housed. Turn and pry the lever from the body of the printer.
33. The gear assembly should also be removed when pulling this part out.
34. Take the wire nippers and locate the spring that is located near black plastic printer carriage cleaning assembly.
35. Unhook the spring and slide the carriage back to its rest position (e.g., slide it up the ramp).
36. Lift the carriage up and it should be easy to remove.
37. Remove the black lever in front of the black printer carriage cleaning assembly. This part should be shaped like a wedge.
38. The printer is now disassembled.

B. Scanner Disassembly

1. Open the scanner lid.
2. Disconnect the electrical connector between the lid and body of the scanner.
3. Pull the white lid toward one side. And remove it from the scanner.
4. Turn the scanner glass-side down. Use the Phillips head screwdriver to remove the four black screws from the top of the scanner.
5. Use the flathead screwdriver to press on the tabs connecting the body to top.
6. Open the scanner body and take off the top.
7. The scanner is now disassembled.

C. Baseplate Assembly & Main Guide Rail Mount Assembly

1. Under a fume hood, assemble the interlocking leaves of the baseplate.
2. Use acrylic cement to permanently bond the parts. Let the parts cure overnight.
3. Tap the M4 holes for the main guide rail.
4. Place the two mounting plates onto the base place over the M4 holes.
5. Fasten the guide rail onto the baseplate with M4 screws.

D. Drive Rack Assembly

1. Arrange the acrylic pieces of the drive rack.
2. Place the two struts into the box joint in the center of the middle part such that the flat faces out and the small box joint points down.
3. Affix the middle with struts onto the base, seating them into the box joints.
4. Attach the end caps to the middle and base.
5. Place the top onto the middle. The short series of slots on the top should be on the opposite side of the large circular hole in the middle part.
6. Use masking tape to hold the parts in place or a clamp. The parts should be tightly held together.
7. The support should be bolted in place such that the thru holes in the support and the top parts are aligned. The short series of slots should not be covered.
8. Apply acrylic cement (Weld-On #3) to permanently bond the parts. If done correctly the joint should appear clear where bonded. An additional small amount of Weld-On #16 can be placed in the corner joints to improve rigidity.
9. Let the parts cure overnight.
10. Remove the masking tape from the drive rack mount.
11. Put a washer and nut on each of the ten 0.5 inch 0-80 screws.
12. Align the brass drive and clutch racks and fasten the racks in place.
13. Use two 1/4-20 screws to fasten the rack to the base plate. Use washers on both sides to allow for fine alignment.

E. Side Rack Assembly

1. Arrange the acrylic pieces of the side rack.
2. Tap the six 8-32 holes on the top acrylic part.
3. Gently hold the acrylic part in one hand and slowly feed the tap with the drill. Allow the tap to pull the piece but do not allow the part to rotate. As the tap pushes through the hole accelerate the tap to clean up the edges.
4. Afix the middle with struts onto the base, seating them into the box joints.
5. Attach the end caps to the middle and base.

6. Use masking tape to hold the parts in place or a clamp. The parts should be tightly held together.
7. Apply acrylic cement (Weld-On #3) to permanently bond the parts. If done correctly the joint should appear clear where bonded. An additional small amount of Weld-On #16 can be placed in the corner joints to improve rigidity.
8. Let the parts cure overnight.
9. Remove the masking tape from the side mount.
10. Align the aluminum side rail onto the side rail rack.
11. Fasten with six 8-32 screws.
12. Use two 1/4-20 screws to fasten the rack to the base plate.

F. Printer Lid Modification

1. The printer body and lid should be completely disassembled and all the extraneous parts should be removed.
2. Take the printer lid and place a piece of masking tape outlining where the cutting path on the top of the lid (the natural external part of the lid). This should be placed such that the two threaded holes that attach the printer lid to the printer body are not damaged during the cut.
3. Take the lid to the fume hood.
4. Place the lid top side up such that the power button is on the left.
5. Turn the Giles Precision Waxer on by pressing the red toggle switch.
6. Turn the dial to 9 and let the end heat for 1 minute in the holster.
7. Once the Giles Precision Waxer is hot, score the lid with the hot end. Scoring is achieved by light pressing on the plastic lid, but not cutting all of the way through.
8. Turn the Giles Precision Waxer off.
9. Flip the lid over.
10. Use the wire nippers to cut the vertical plastic supports on the printer lid. Be careful to cut the vertical supports on the opposite side of the tape preserving the supports closest to the power button.
11. Bend the printer lid back and forth to fatigue the plastic along the scored path.
12. The printer lid should break in two parts. The first will should have the power button, and the two threaded holes that connect to the printer body.

G. Printer Body Modification

1. Apply decals to the body of the printer.
2. Place the plastic body in a fume hood such that the solid back is facing the back of the fume hood.
3. Turn the Giles Precision Waxer on by pressing the red toggle switch.

4. Turn the dial to 9 and let the end heat for 1 minute in the holster.
5. Once the Giles Precision Waxer is hot, score the printer body with the hot end. Scoring is achieved by light pressing on the plastic lid, but not cutting all of the way through.
6. The sturdiest part of the printer is where the printer carriage and motherboard are housed. The scored bath should leave these regions and the associated vertical supports intact.
7. There should be two openings in the back of the printer.
8. Turn the Giles Precision Waxer off.
9. Cut the cross bar over the paper feed tray with the wire nipper, leaving the threaded hole to connected to the printer body.
10. Cut the vertical supports with the wire nipper.
11. Flip the printer body over and cut the threaded hole near where the paper feed shaft was mounted.
12. Bend the printer body back and forth to fatigue the plastic along the scored path. If there are vertical supports that are still intact cut them with the wire nipper.
13. Once the printer body is broken into two halves, take the smaller half with that housed the printer carriage and motherboard.

H. Modified Shaft

1. Take the original paper feed shaft.
2. Cut the shaft to 90 mm on the side that includes the grooved end. File the edges so that they are smooth and no barbs are on the shaft.
3. Insert the modified shaft-insert into the cut paper feed shaft.
4. Take a 120 mm long 4-40 threaded rod and screw it into the shaft insert. The ABS shaft insert should self-tap. Allow 20 mm of threaded rod to protrude on either side.
5. Use a cloth soaked in acetone to reduce the diameters of the non-grooved end to 12 mm. A handheld drill can be used to rotate the shaft evenly.
6. Slide the two-way bear onto the reduced diameter shaft.
7. Place the white plastic hub shaft mount salvaged from the disassembly onto the shaft opposite its original orientation.
8. Take hub mount (Hub.stl) printed part and insert the one-way bearing, gently tape the bearing into the hub. It should be a snug fit. If it is too tight. Heat the hub mount.
9. Take the 64031 spur gear and align it with the notches in the hub mount. Gently tap the spur gear onto the hub mount such that the spur gear face is flush with the ABS plastic.

10. Slide the spur gear and hub assembly onto the threaded shaft. Use four 4-40 nuts to secure: two for inside the hub mount and two for on the opposite side of the threaded shaft. Over tighten, such that the shaft is one complete component and the gear cannot rotate freely.
11. Slide the second gear onto the threaded rod and into the one-way bearing.
12. The modified shaft assembly is complete.

I. Mechanical Switch

1. Arrange the 3D printed parts.
2. Use an M4 tap to widen the horizontal holes on the slider and housing.
3. Place the slider in between the housing and push the drive shafts (6” 1/8” Dia) through the holes of the housing and slider.
4. Use a 4-40 tap to thread the vertical holes and enable the mechanical switch to be mounted.
5. Take the optical slot encoder and PCB mount. Trim the excess PCB with nippers to reduce the size of the component. Use a drill bit or file to widen the unmodified mounting hole. Use a flat head 4-40 screw to fasten onto the housing.
6. The modified shaft assembly is complete.

IV. Box-in-a-Box Analysis

In Section III (Print Performance), we discussed the box-in-a-box characterization technique. To provide some guidance on how to reproduce this analysis technique we have included the analysis code in the supplemental materials. In this section, we will provide some additional details to help guide the interested reader.

Before we can process the images, it is necessary to ensure that the images are well aligned relative to each other on both the printer and scanner. To help align the pages, we used an acrylic fixture to hold the page in place during the print and scan. Once we were certain the fixture effectively held the pages in place, we printed the box-in-a-box pattern on five separate sheets of paper. We then took scans of the page at each step to ensure that the paper was in approximately the same position on the printer to within 100 µm. We then scanned the images at 600 dpi, and scanned a NIST certified ruler to verify the conversion factor. As additional check, we made movies of the edges of the page to confirm that the page-to-printer-to-scanner alignment was satisfactory.

After we had the images of the box-in-a-box patterns, we imported them into MATLAB. From an image-drawing program (Inkscape), we determined the intended lengths of each box. In this case, there were two widths of the lines used to make the box, and the inside dimension of the box. For any given box in one dimension, this meant three length measurements (excluding the smallest one). Since the boxes had different line widths, this provided seven independent length measurements. For our smallest box, we had to just use the total width of the box, because it made the image processing too challenging. As we know the page did not move significantly during the print and scan, we cropped each image to the same position on the image, removing the strip printed to keep the printer from translated too quickly at the beginning and end of the print cycle. We then converted the cropped image to grayscale, computed a threshold for each image with Otsu's method, and created binary images of the box-in-a-box patterns. To help with edge detection near the boundary of the images, we padded the binary image with zeroes. Next, we removed small objects less than 600 pixels and then dilated and eroded the binary image with a four-pixel disk. These steps enabled us to identify each box in the image, and compute the position, image of the box, and total area. We then used a Sobel filter to find the edges of the boxes. We then summed the binary image of the edges along a given axis. We then took the peak as the representative edge of the box. We used the peaks to compute the seven lengths for the printed image along one axis.

From the image-drawing program, we know where the boxes were intended to be and their intended lengths. We then computed the average and standard deviation in the error over the five pages in the length and position for each position and box in the grid. For a given axis, we then have four parameters for every box and position: the mean of the error in the length, the standard deviation of the error in the length, the mean of the error in the position, the standard deviation of the error in the position. These values could be computed for a single page or over multiple pages. In Fig. 4c,d, we plot the accuracy print-to-print accuracy as a function along each axis for the unmodified and modified printer. The error bars are the precision.

There were a few disadvantages to this approach to calculating the print metrics. First, it was possible that the fixture used to mechanically align the page during the print may have introduced small random errors in the absolute position of the pages. Similarly, another random error could have been introduced during the scanning. From our data analysis, it would appear that these errors were much smaller than our accuracy and precision in the printed image and absolute position on the page otherwise the quantified results would have been much larger than the native values and not followed the expected trends. As a result, these errors had a negligible contribution to the accuracy, precision, and repeatability. We have included the MATLAB analysis script as a supplementary file (bibanalysis.m).

V. Growth analysis

To quantify the area fraction of the colony, we converted the images to grayscale and subtracted the first time point to zero the background. We then used Otsu's method to compute a threshold and to convert the image to a binary, which we used as a mask for the grayscale image. We subtracted the median value of the background and normalized the pixel value to the maximum pixel value in the 100% grayscale time series. The sum of the pixels in the binary mask was then the weighted area. We then divided all of the weighted areas by the maximum area fraction obtained by the 100% grayscale time series. In practice, if the colonies obtained the same area over the same time this would normalize them to the same value. In our experiments, the 100% population had a much larger final area than the other dilutions.

VI. File Types & Fabrication Settings

Since there are several supplemental files, here we will provide a list of all of the file types and some additional information about how we made the different components. We used two file types, Adobe Illustrator (.ai) and Autodesk Inventor (.ipt and .stl), to create all of the parts of the bioprinter. The .stl files were fabricated by a 3D printer, and can also be sent to a 3D print service. We used a Dimension uPrint Plus 3D Printer. The units of the .ipt files were inches. The material settings were solid. The .ai files were fabricated with a CO2 Laser cutter (Epilog Mini 18). We used the following settings for the laser cutter: 600 dpi, 100% power, 1% speed, frequency automatic, and optimized cutting path. The guide rail mount (guiderail_mount.ai) was fabricated from 0.125 inch acrylic. The remaining .ai files were fabricated from 0.250 inch thick acrylic (18 inches x 12 inches). Three custom decals were also fabricated (sticker_cartridge.ai, sticker_plasticbody.ai). The decals were fabricated from Graphix Adhesive Film with the Laser Cutter. In this case, the speed was set at 50% and the power was set to 50%.

VII. Materials, Off-the-shelf Parts, Custom Parts, and Decals

A. Materials

Raw Materials	Qty.	$/Item	Catalog #	Source
1/4-20, 0.375 inch	1	3.34	92196A535	www.mcmaster.com/
1/4-20, 0.50 inch	1	3.22	92196A537	www.mcmaster.com/
1/4-20, 0.25 inch, Low Head	1	5.72	93615A405	www.mcmaster.com/
4-40, 0.50 inch	1	7.27	92196A106	www.mcmaster.com/
4-40, 0.50 inch, Flat Head	1	4.48	92210A110	www.mcmaster.com/
0-80, 0.50 inch	1	7.59	92196A070	www.mcmaster.com/
M4, 12 mm	1	3.26	92855A413	www.mcmaster.com/
M3, 12 mm	1	3.26	92855A313	www.mcmaster.com/
1/4-20 nuts	1	5.05	91845A029	www.mcmaster.com/
0-80 nuts	1	5.02	90480A001	www.mcmaster.com/
4-40 nuts	1	4.90	90545A005	www.mcmaster.com/
1/4-20 washers	1	5.88	93852A102	www.mcmaster.com/
Flat Washer NO. 2 Screw Size	1	1.19	90126A501	www.mcmaster.com/
Low-Friction High-Strength PEEK Washers	1	3.76	93785A300	www.mcmaster.com/
Clear Acrylic Sheet (1/4", 18", 12")	4	13.20	99999	www.tapplastics.com/
Clear Acrylic Sheet (1/8", 18", 12")	2	10.00	99999	www.tapplastics.com/
Foamed PVC Sheets (1/4", 24", 19")	2	10.00	99999	www.tapplastics.com/
Foamed PVC Sheets (1/4", 24", 7")	2	10.00	99999	www.tapplastics.com/
Foamed PVC Sheets (1/4", 18.5", 7")	1	10.00	99999	www.tapplastics.com/
Rosco Cinegel Tough UV Filter	1	10.00	B000I179HI	www.amazon.com/
Grafix Ink Jet Adhesive Film, 6-Pack, Clear	1	7.80	B000S15KDS	www.amazon.com/

B. Off-the-shelf Parts

Part	Qty.	$/Item	Catalog #	Source
HP Deskjet 1000 Printer J110a	1	29.99	CH340A#B1H	shopping.hp.com/
HP Scanjet G3110 Photo Scanner	1	109.99	L2698A#B1H	shopping.hp.com/
The Gold Standard Pinion 31T 64P	2	6.99	64031	www.teamcrc.com/crc/
One-Way Locking Bearings (#HF0812)	1	13.46	6392K42	www.mcmaster.com/
Metric Steel Ball Bearings (#6801)	1	9.52	5972K154	www.mcmaster.com/
Brass Gear Rack 64 Pitch 20 Deg	1	31.98	7854K11	www.mcmaster.com/
Guide Rail, 17 mm Wd, 500 mm Ln	1	5.36	6723K5	www.mcmaster.com/
Carriage, 17 mm Wd	1	25.00	6723K9	www.mcmaster.com/
Threaded Stud 4-40 Thread, 4" Ln	1	10.51	95412A413	www.mcmaster.com/
Drive Shaft 6" 1/8" Dia	2	6.02	1263K38	www.mcmaster.com/
Compact Snap-Together Cable Carrier	1	38.49	55835K411	www.mcmaster.com/
Guide Rail, 15 mm Wd, 460 mm Ln	1	138.00	6709K33	www.mcmaster.com/
Carriage, for 15 mm Rail Wd	1	118.18	6709K11	www.mcmaster.com/

C. 3D Printed Parts

3D Printed Parts	Qty.	Filename
Housing	1	switch_housing.stl
Slider	1	switch_slider.stl
Side Rail Mount	1	siderail_mount.stl
Shaft Insert	1	shaft_insert.stl
Hub	1	hub_mount.stl
Bumper	2	bumber.stl

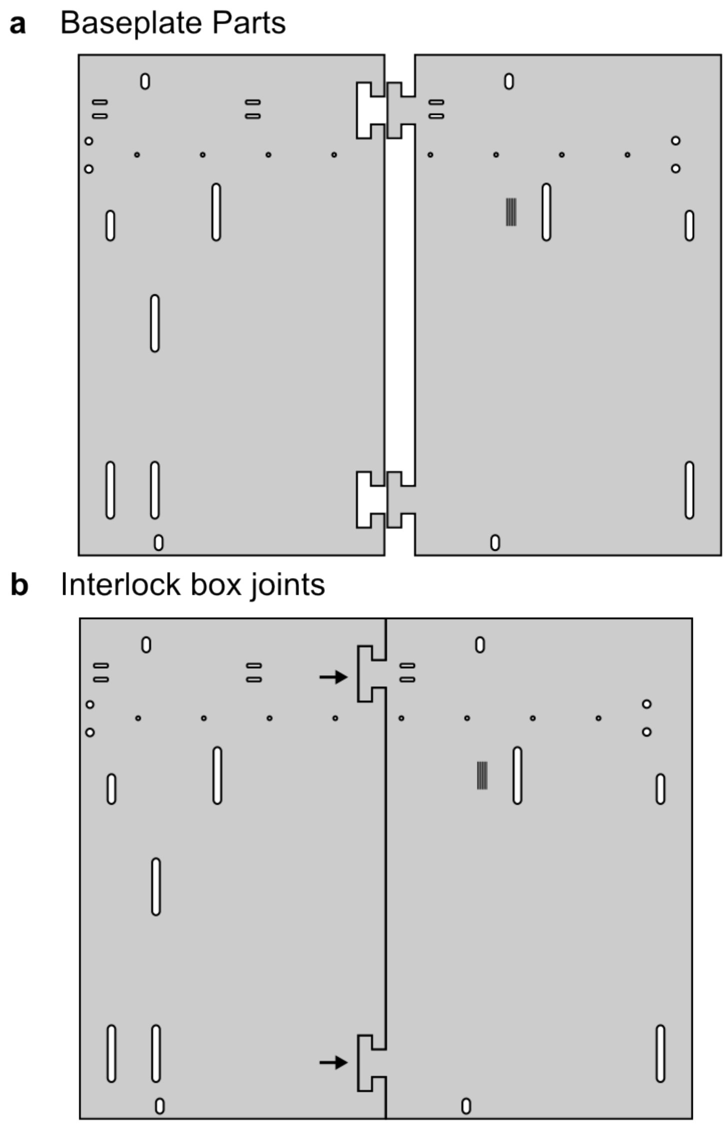
D. Acrylic Parts

Acrylic Parts	Thickness [in]	Filename
Base Plate #1	0.250	base_plate1.ai
Base Plate #2	0.250	base_plate2.ai
Acrylic Parts #1	0.250	short_parts.ai
Acrylic Parts #2	0.125	long_parts.ai

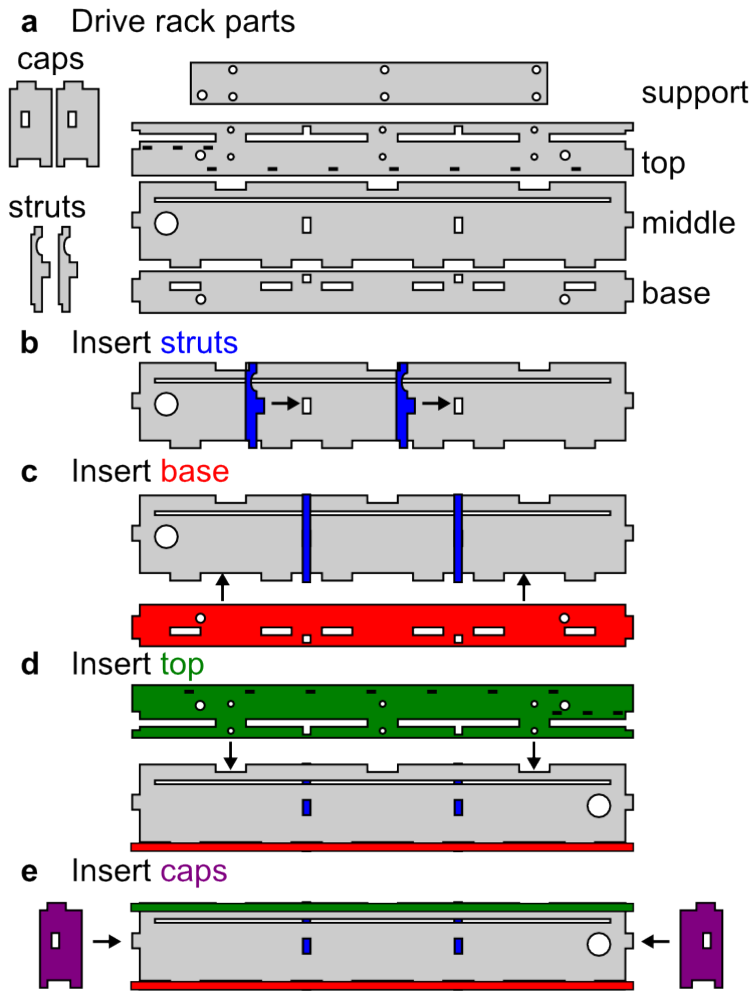
E. Decals

Decals	Qty.	Filename
Printer Body	1	sticker_printerbody.ai

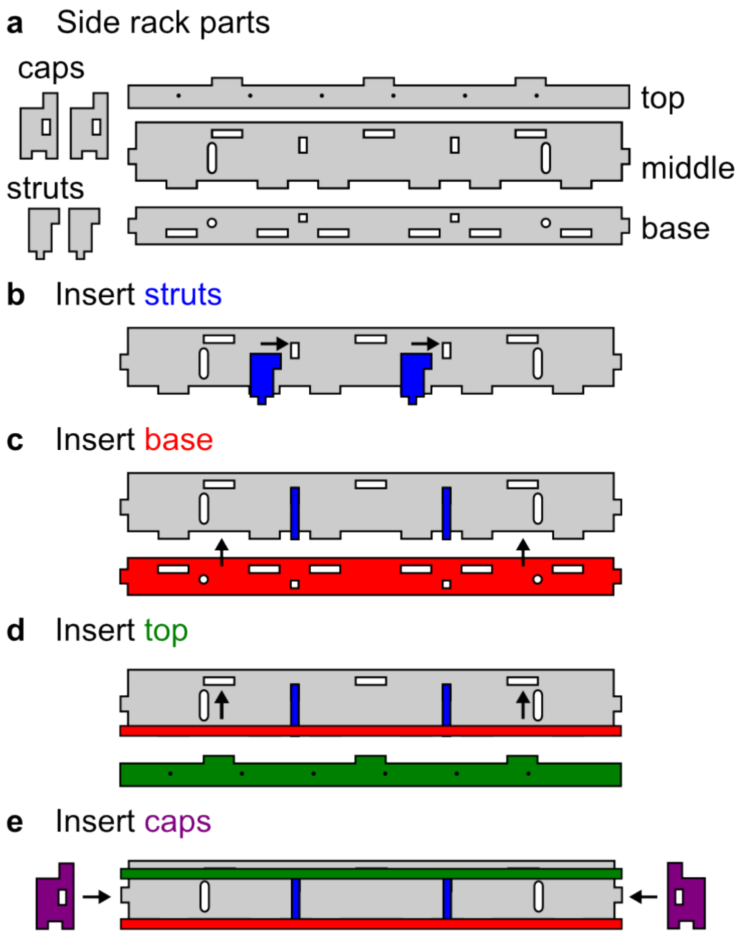
VIII. Figures of the Components



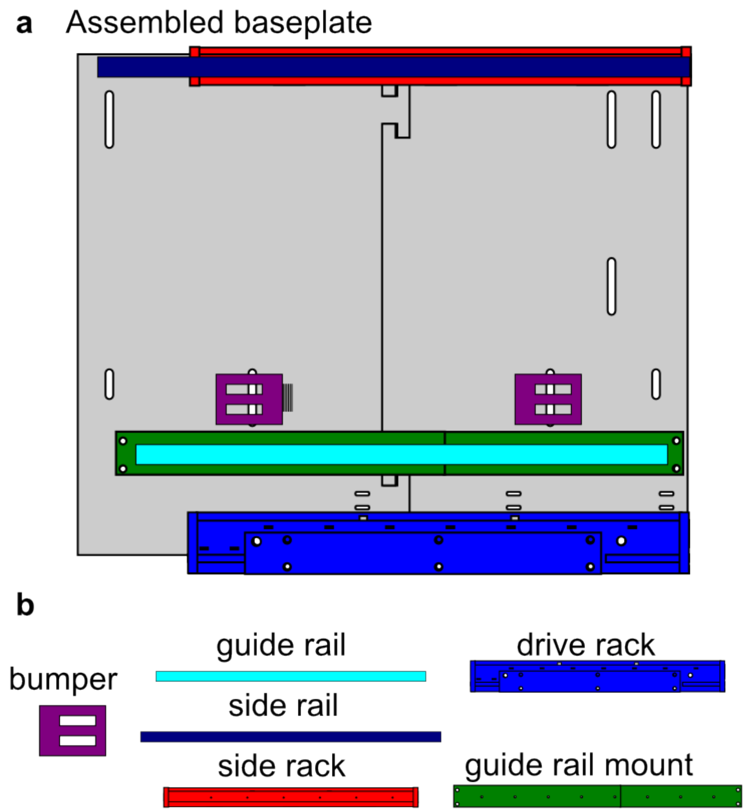
SFig. 1. **A schematic of the parts used to assemble the baseplate.** (a) All the parts from the used to construct the baseplate. (b) We show the step-by-step schematic of the construction of the baseplate.



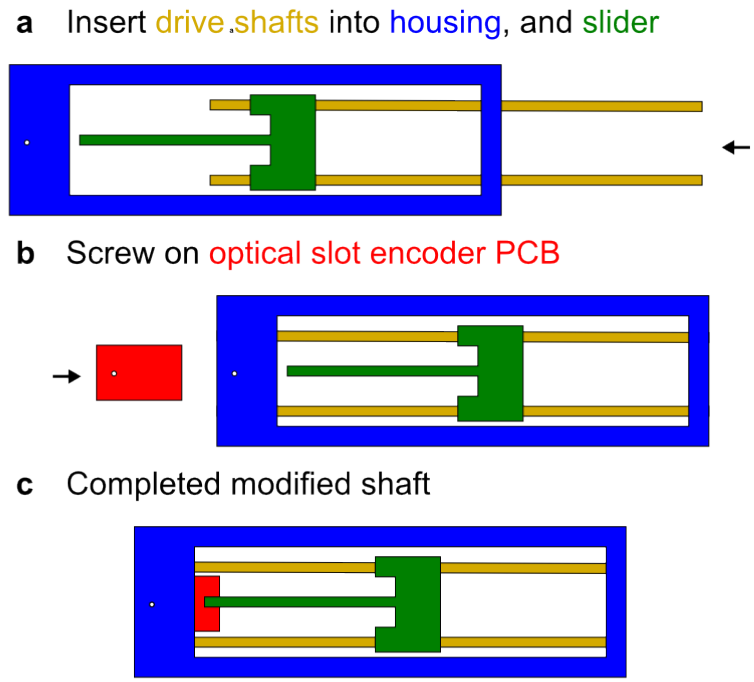
SFig. 2. **A schematic of the parts used to assemble the drive rack.** (a) All the parts from the used to construct the drive rack. (b)-(e)We show the step-by-step schematic of the construction of the drive rack.



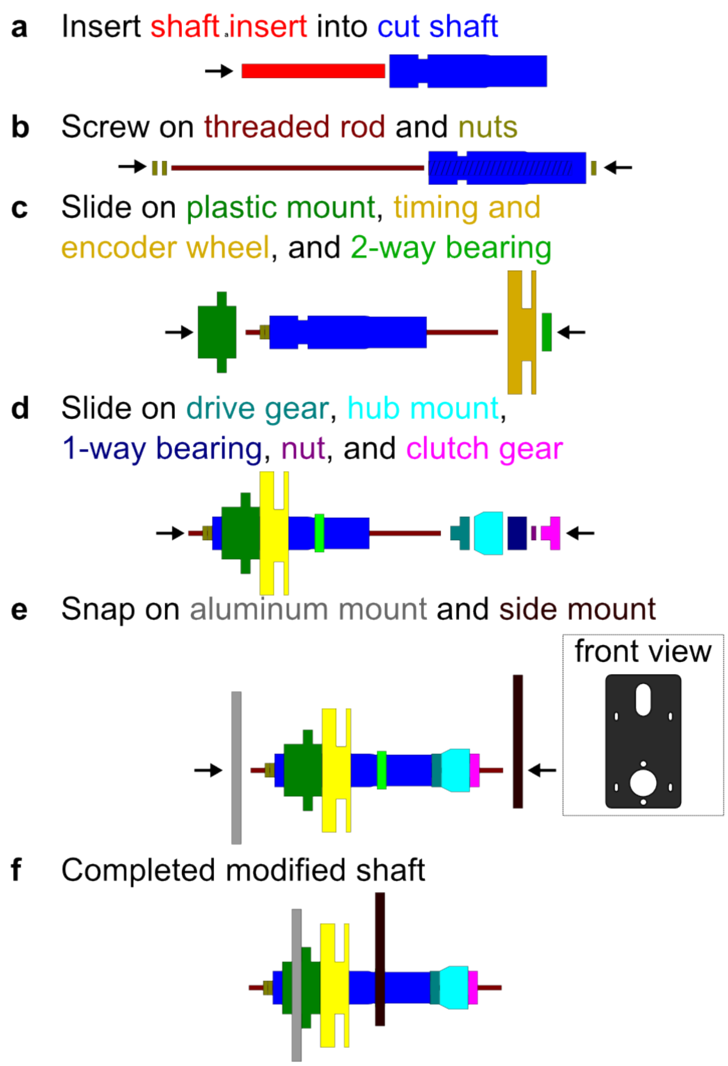
SFig. 3. **A schematic of the parts used to assemble the side rack.** (a) All the parts from the used to construct the side rack. (b)-(e) We show the step-by-step schematic of the construction of the side rack.



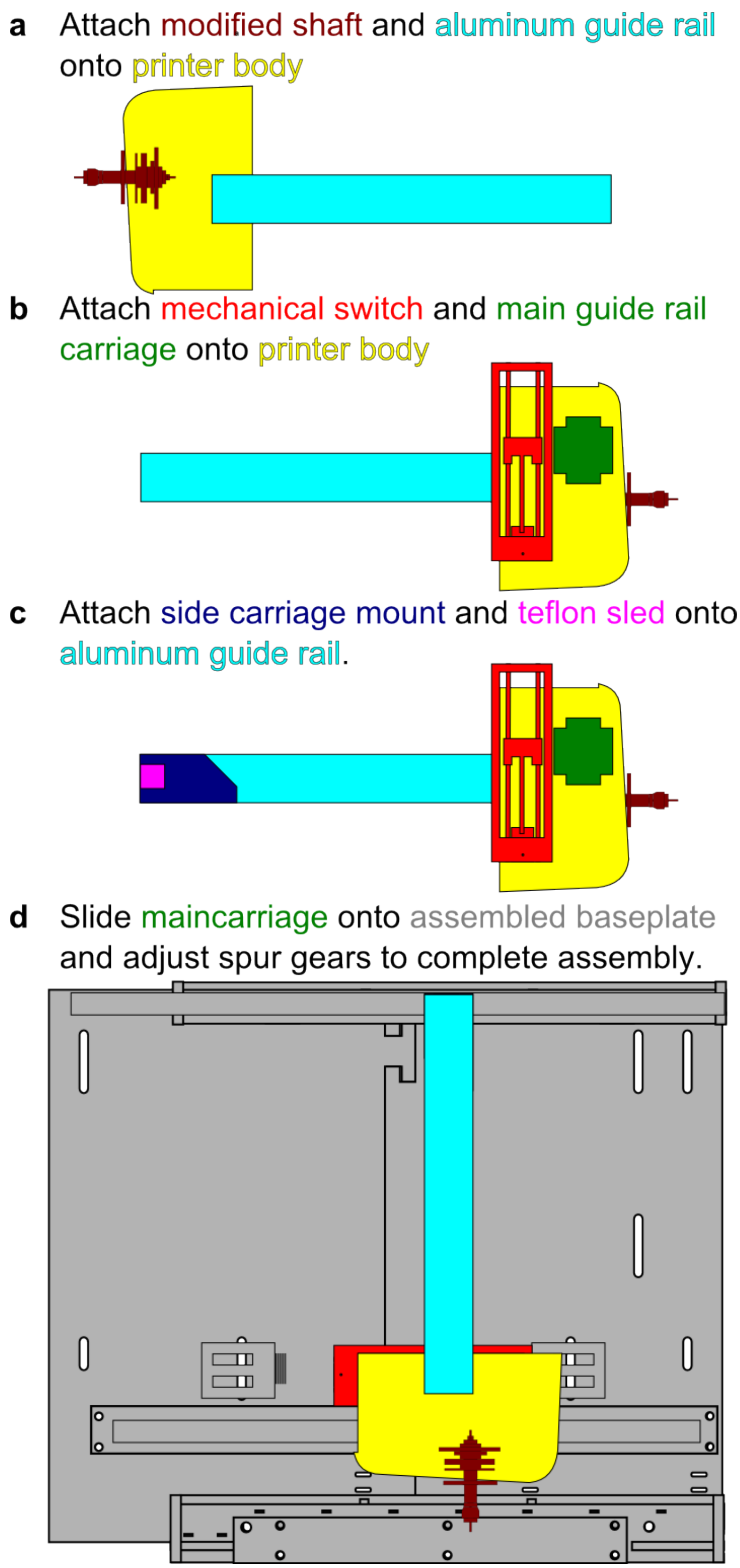
SFig. 4. **A schematic of the parts used to assemble the baseplate with the guide rails, side rack, drive rack, and other parts.** (a) The assembled baseplate with all the parts and locations. (b) We show the parts used to put together the baseplate.



SFig. 5. **A schematic of the mechanical switch.** (a) All the parts from the used to construct the side rack. (b)-(e) We show the step-by-step schematic of the construction of the switch.



SFig. 6. **A schematic of the modified shaft.** (a)-(f) We show the step-by-step schematic of the construction of the modified shaft.



SFig. 7. **A schematic of the modified shaft.** (a)-(f) We show the step-by-step schematic of the construction of the modified shaft.