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Multi-material additive and subtractive prosumer digital fabrication with a free and open-source convertible delta RepRap 3-D printer

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Introduction

RepRap (a portmanteau of self Replicating Rapid prototyper) 3-D printers were introduced as an open source technology (Jones, et al., 2011), essentially freeing 3-D printing from the frequently innovation-stifling effects of intellectual property law (Heller & Eisenberg, 1998; Takalo & Kanniainen, 2000; Boldrin & Levine, 2002; 2008; Pearce, 2013; Jaffe & Lerner, 2011; Chu, Cozzi & Galli, 2012). RepRap designs are freely available and open-source, following the increasingly popular free and open-source software paradigm (Lakhani & Von Hippel, 2003). The distinguishing feature of RepRap 3-D printers is that they are purpose-designed to employ as many printed components in their assembly as is possible (Sells et al., 2010). Structural components, gears, pulleys and any other part, be it high value or trivial, that can be printed by the printer itself are integral features of the designs, yielding the self replicating portion of the RepRap philosophy. RepRaps are acknowledged to have exceptionally high value (Wittbrodt, et al., 2013) as a result of this self-replicating feature and the fact that the designs are open-source and freely available. Since their introduction, RepRaps have been used for personal fabrication (Stemp-Morlock, 2010; Betts, 2010; Wittbrodt, et al., 2013), project-based education (Kentzer, et al., 2011; Irwin et al., 2014), the development of scientific tools, scientific visualization and experimentation (Partridge, Conlisk & Davies, 2012; Pearce, 2012; Anzalone, Glover, & Pearce, 2013; Zhang, et al., 2013; Pearce, 2014), and production of open-source appropriate technology for sustainable development (Pearce, et al., 2010).

There are presently two common RepRap printer designs; the Cartesian design having linear actuators parallel to each of three orthogonal planes, and the delta design (Rocholl, 2012) having three linear actuators arranged vertically around a circle. The Cartesian design is presently the most common of the two with many commercial products based upon it. Computer Numerical Control (CNC) and inexpensive microcontrollers (specifically the open-source Arduino and derivatives) are technologies that have made the printers possible. The ability to automatically and precisely control movement of the print head is what makes the platform a compelling candidate for repurposing. RepRaps typically print in polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS). The recent development of the recyclebot, which is an open-source waste plastic extruder (Baechler, DeVuono, & Pearce, 2013), and the commercialization of the entry-level extruders of similar design, not only showed a route to more environmentally friendly 3-D printing materials (Kreiger & Pearce, 2013; Kreiger, et al., 2014), but also to expanded materials selection and composites. There is commercial RepRap-compatible filament available made from: nylon, polycarbonate (PC), polyvinyl alcohol (PVA), high impact polystyrene (HIPS), high-density polyethylene (HDPE), polyether ether ketone (PEEK), polyphenylsulfone (PPSF or PPSU), polyetherimide (PEI), polyoxymethylene (POM) and a number of polymer composites. In addition, since its inception, the RepRap community has been actively engaged in exploring possibilities beyond just printing polymer-based parts. Milling of printed circuit boards and experimentation with paste-based printing media have been underway on the RepRap wiki (http://reprap.org/) for years and many conventional printers have been retrofitted with apparatus that permit these capabilities.

As Cartesian 3-D printer designs are more common, most of the modifications have been based upon that platform. In nearly all Cartesian designs, the print head is one of the moving components and it moves parallel to the print bed in a simple x-y axis for each layer. Since the hot end of the extruder is typically low mass, machine designs are typically not required to be exceptionally rigid. This presents a problem when retrofitting relatively heavy tools to the moving print carriage. Movement precision can degrade as a result of the additional mass. Insufficient frame rigidity manifests itself as uncontrolled movement during rapid changes in direction and the increased force required to accelerate the tool can cause motors to stall or slip. It also tends to be difficult to interchange tools with this platform. Thus, the ability to print with a wider selection of materials is limited because of the difficulty in switching heads – RepRap printers are optimized normally for one type of material printing.

A recent innovation to the delta printer design turns the printer upside-down such that the tool is fixed in place and the workpiece moves below it (Anzalone, et al., 2013; Haselhuhn, et al., 2014), which presents a solution: A convertible platform that is able to switch between a moving tool mode (e.g. conventional RepRaps) and a fixed tool mode.

The objective of this paper is to investigate a new a convertible RepRap platform capable of both moving and fixed tool operation. The bill of materials, basic assembly and description are provided as free and open source hardware. As the tool remains stationary in the stage configuration, a tool having much greater mass can be fit above the build platform, expanding the catalog of tools and thus materials available for both additive and subtractive manufacturing on the delta platform. The convertible delta RepRap is then tested with a variety of tools including: a thermoplastic extruder, a caulk/silicone extruder, a syringe pump extruder, a micro mill spindle and a tool holder used for vinyl cutting and plotting. Performance and capital costs are compared against single material commercial systems and the results are discussed. Future work is outlined for further enhancing both RepRap applications and materials selection in the burgeoning prosumer and maker communities.

Materials and Methods

The MOST (Michigan Tech Open Sustainability Technology Lab) Delta 3-D printer (MOST, 2014) was modified with replacement carriages having magnetic mounts facing both upwards and downwards and the closed top of the printer was replaced with an open ring. These changes permit conversion of the printer from its normal polymer-based printing configuration, in which the end effector with a hot end moves above a fixed build platform, into a 3-axis stage having the workpiece fixed to the end effector. One of the vertical boards on the printer was then replaced by a rigid aluminum rectangular tube to which a magnetic tool mount was attached, permitting easy and rapid swapping of tools positioned above the end effector. The magnetic mount, the design of the 3-D printed housing of which is shown in Figure 1a and 1b, consists of three high strength ring magnets encased in a 3-D printed housing attached to the fixed tool mount on the printer. The magnets are rated to hold 1.6 kg. The magnets are held stationary by the 3-D printed casing and used to affix the tools. The surfaces of the magnets for the stationary tools are mated directly with the holder magnets.

As seen in Figure 2, the surface of the magnets on the end effector that attach to the steel balls of tie rods are lubricated with white lithium grease. To disengage a tool head it is manually removed from the end of the tie rods. A tool head can then be immediately manually placed in the same location if the orientation (end effector down or end effector up remains the same). If switching between down/up orientation the tie rods are completely removed from the system manually and moved in the opposite position (end effector down or end effector up). Then the new tool head/substrate holder is positioned on them.

<insert Figure 1a>
<insert Figure 1b>

Figure 1. a) OpenSCA*D rendered image of fixed tool magnetic mount base and b) top of base.*

Tools are affixed to the magnetic mount by steel ball bearings that are integrated into the 3-D printed tool or tool holder. The bills of materials for conversion of a MOST Delta RepRap to a convertible RepRap is shown in Table 1 and for the magnetic base in Table 2.

<insert Table 1>
<insert Table 2>

The bills of materials for the tools demonstrated, a syringe pump, an extruder designed to accept products delivered in caulk tubes, and a micro mill spindle holder are provided in Tables 3, 4 and 5, respectively.

<insert Table 3>
<insert Table 4>
<insert Table 5>

Finally, a 3-D printable end effector was designed that permits easy swapping of tools using a smaller version of the fixed-tool mount. Tool holders for fixing pens and a vinyl cutter were designed and printed. Bills of material for the end effector and tool holders is provided in Table 6 and Table 7, respectively.

<Insert Table 6>
<Insert Table 7>

The entire software tool chain is open-source and freely available. Franklin printer firmware (Wijnen, et al., 2015) is configured for each of the tools, setting tool offset, extrusion rate and other parameters necessary. Three dimensional models for printing were sliced with Cura (software.ultimaker.com). Printed circuit boards were designed with kicad (kicad-pcb.org) and converted to g-code using pcb2gcode (sourceforge.net/projects/pcb2gcode/). Scalable vector graphics (SVG) line art files were converted to g-code using Inkscape (inkscape.org) and the Gcodetools plugin (github.com/cnc-club/gcodetools) for pen plotting, vinyl cutting and eventually for engraving.

Results

The MOST Delta RepRap was successfully converted to a convertible RepRap using the materials shown in Table 1 and 2 while still maintaining the ability to print with plastic in the stationary substrate configuration as shown in Figure 2. In this configuration the RepRap functions as a standard polymer 3-D printer, the extremely small increase in the mass of the double sided replacement carriages had no impact on speed, resolution or reproducibility of PLA prints.

<Insert Figure 2>
Figure 2. Digital Photograph of Assembled Convertible RepRap in mobile tool mode with 3-D printer end effector for printing thermo polymers with conventional fused filament fabrication.

In this configuration, the printer can be used to produce a number of other tools including the plastic parts listed in Tables 3-7. Tools too large to fit on the moving end effector were designed with steel ball bearings that mate with a magnetic base attached to the aluminum vertical board. The magnetic mount makes for rapid and easy tool interchange. This tool interchange is a manual operation.

The platform is reconfigured to stationary tool mode by removing the end effector, inverting the tie rods in their carriages and attaching a stage mount end effector. The additional limit switches are moved into position below the carriages to establish a home position. In this configuration a modified syringe pump following the design of Wijnen, et al. (2014) consisting of the components shown in Table 3 was fabricated and mounted as shown in Figure 3. Syringe pumps of different sizes can be used as a 3-D print head for viscous materials. Note that the polymer print head is simply set aside in the bottom left of Figure 3 and can easily be replaced (in less than a minute) if the convertible printer is needed to print a PLA object. The syringe pump is shown extruding an ornament in porcelain slip in Figure 4.

<Insert Figure 3>
Figure 3. Digital photograph of Convertible RepRap in stationary tool mode with a syringe pump extruder mounted on the fixed tool mount.

<Insert Figure 4>
Figure 4. Close up digital photograph of the Convertible RepRap with the syringe pump extruder operating to produce an ornament made from porcelain slip.

For larger viscous prints, using common materials an extruder designed to accept standard-size caulk tubes ("caulkstruder", BOM in Table 4) containing a variety of viscous sealants and cements was fabricated. The caulkstruder mounted on the convertible printer is shown in Figure 5. This is a significantly larger and heavier tool meant to print in any material available in hardware stores in standard caulk tubes. In the inset of Figure 5, the caulk extruder, with white silicone caulk loaded, is shown printing a custom silicone orthotic (Nettleton, 2013).

<Insert Figure 5>
Figure 5. Digital photograph of the Convertible RepRap with the caulkextruder mounted. The inset shows a custom orthotic being printed in silicone caulk. The caulk extruder tool is attached to the fixed tool mount.

All of the tools were designed to use as many 3-D printed parts as possible, in keeping with the RepRap philosophy. All of the printed parts were produced on the machine they were to be attached to and only require hardware ('vitamins' in RepRap parlance). For example, note the 3-D printed (printed in the stationary substrate configuration) planetary gearbox in the upper-right hand corner of Figure 5 is also an open-source parametric file that can be customized using OpenSCAD (MTU-MOST, 2014).

The convertible Delta RepRap can also be used for subtractive manufacturing and prototyping. In Figure 6, the results of assembling the components listed in Table 5 are shown to make a lightweight micro mill. The micro mill spindle is shown placed the tool mount being used to produce the circuit boards shown in inset of Figure 6.

<Insert Figure 6>

Figure 6. Digital photograph of the Convertible RepRap with the micro mill tool mounted. Inset: Digital photograph of printed circuit boards milled with the micro mill tool. The micro mill spindle is just visible in the top of the inset.

The platform can also be used as other conventionally 2-D tools when it is reconfigured to mobile tool mode with the tool end effector in place on the working end of the tie rods. A tool end effector for mounting small, low mass tools on the moving end effector was designed using a similar, but much smaller magnetic mount (Table 6). A spring-loaded tool mount (Table 7) for holding cylindrical tools was fabricated and tested for functionality. For example, the spring mounted tool was outfitted with a tangent knife and a tacky cutting mat was placed on the glass build platform. Vinyl was secured to the mat and patterns were cut as shown in Figure 7. Using the same setup, a marking pen can be affixed to be used as plotter for graphics as shown in Figure 8.

<Insert Figure 7>
Figure 7. Digital photograph of the Convertible RepRap in mobile tool mode with the tool effector in place fitted with a tangent knife cutting a pattern in pressure sensitive adhesive-backed vinyl.

<Insert Figure 8>
Figure 8. Digital photograph of the tool effector fitted with a permanent marker plotting a graphic on plain, white paper.

In all cases, the platform performed well as compared to its single-purpose, commercial counterparts, producing useful and usable products. Of particular merit was the fact that the platform performed the different functions predictably, i.e. when converting from fixed tool mode to mobile tool mode for 3-D printing, which requires inversion of all tie rods, no adjustments were required and the quality of the printed part was unaffected. The use of magnetic mounts greatly facilitated interchanging tools and conversion from stationary tool to mobile tool modes.

Table 8 summarizes the functions demonstrated by the convertible delta RepRap and compares the cost of the function provided by the open-source RepRap to commercial equivalent devices. It should be noted that the plotter is not listed as this technology has been largely been replaced by conventional 2-D printers. The total cost of the convertible delta RepRap with all of the tools shown in Figures 2-8 is less than $1,000, which is striking compared to even a single purpose proprietary tool. The total capital expenditure reductions when using the convertible delta RepRap compared to single-purpose tools for only the functionality demonstrated in this study are between $7,000 and $29,000. This represents a savings to prosumers of between 90 and 97%. It should be pointed out that smaller RepRap 3-D printers can be purchased for under $500, that the delta RepRap shown here is not only comparable in cost for thermo polymer printing alone, but also capable of the full set of additional functionalities (e.g PCB milling) demonstrated in Figures 2-8.

<Insert Table 8>

Discussion

As with most comparisons of multi-purpose tools to the purpose-built tools they are designed to compete with, shortcomings are apparent. Although, the convertible RepRap performed adequately at all tasks considered in this evaluation, it is clear refinements can be made and can be expected following the open source model of technical development. In some cases the RepRap, when tuned, can even out perform the commercial equivalents. This was demonstrated previously in a study of the tensile strength of 3-D printed parts using PLA and ABS (Tymrak, et al., 2014).

Of the applications investigated here, PCB milling proved to be the most challenging. This can be seen in the micrographs of printed circuit boards produced by a commercial PCB mill and the convertible platform shown in Figure 9a and 9b, respectively, demonstrate more chattering is occurring with the convertible RepRap.

<Insert Figure 9a>
<Insert Figure 9b>

Figure 9. Digital micrographs of traces milled in printed circuit boards produced by a) a commercial PCB milling machine and b) the Convertible RepRap.

However, considering the very preliminary nature of this evaluation and the fact that the platform is an order of magnitude less expensive than most commercial, purpose-built PCB mills, even with all of the additional tools evaluated, it is clear that the convertible RepRap is an exceptional value. With this new functionality prosumers may improve technical sophistication and begin to fabricate smart objects or electrically functional objects from the use of entry level open-source making machines.

This study confirms the high-value of custom distributed manufacturing (or home manufacturing) (Wittbrodt, et al., 2013). For example, the pair of custom orthotics in the inset of Figure 5 can cost consumers over $500 a pair. Printing out only two pairs with a tube of caulk can economically justify the entire convertible RepRap and all of the additional tools. The flexibility afforded by the platform is unparalleled and the opportunity for continuous improvement of the open-source design ensures that it will be refined and that additional capabilities will be added to it's already significant list of features, ensuring that the platform remains valuable. Unlike digital designs for objects that are not capable of self-replication the value of the RepRap designs is difficulty to quantify (Pearce, 2015). However, even modest conservative estimates of the number of applications of this process would result in substantial economic value (Pearce, 2015).

From the perspective of driving innovation, the affordability of the convertible RepRap and its intrinsic extensibility allows both professionals and tinkerer-makers to explore their ideas with much greater freedom. RepRaps currently dominate entry-level 3-D printing in the maker community (Moilanen & Vadén, 2012). As the many RepRap variants all share a common core technical infrastructure, the tools (e.g. print heads) can be shared between them. This is a major advantage over closed source development of rapid prototyping and manufacturing tools, which are normally designed specifically to avoid functioning with competitors products. Given the platform's predictable behavior, workflows for producing different items can be optimized, compressing time for prototyping and allowing more rapid evaluation of concepts. With this platform, more people can do more prototyping faster than might be possible with multiple, conventional, purpose-built tools. In addition, prosumers can make more expensive, more complicated products as they harness more sophisticated means of production with entry-level investments. The commercial behavior observed in conventional RepRap 3-D printing, where open-source tools first radically reduced costs and then commercial variants began to lower costs and provide solutions, can be expected to occur in multi-machines as well. Already commercial, multi-purpose prototypers are being developed (Molitch-Hou, 2013; 2014; *ZeGo Robotics, 2014).*

As Campbell, Bourell & Gibson (2012) point out when discussing the future of additive manufacturing: “where materials advances are foreseen to occur will be by do-it-yourselfers”, which will drive an increase in demand and the concomitant reduction in feedstock costs. They believe that this demand will accelerate the entry of major suppliers into the marketplace with their new and improved materials and even more functionality. This prediction can already be seen to be coming true in the fourth column of Table 8. Proprietary feedstock for fused filament fabrication 3-D printers costs about $200/kg and proprietary prosumer filament $53/kg, while generic filament currently costs about $35/kg and recyclebot filament costs less than $0.10/kg for makers producing it themselves from their own household waste. Groups such as the Plastic Bank and the Ethical Filament Foundation have already begun to work with major materials suppliers to develop mass-production of social plastic/ethical filament gathered by waste pickers in the developing world (Feeley, et al. 2014). Multi-purpose tools like the one described here will enable prototyping and manufacturing with an even wider range of materials, thus providing the opportunity to expand this form of high-value recycling to additional materials.

Future Work

The functionality of the standard delta RepRap has been greatly expanded by this study, yet there are still many applications that are left for future development. Using the same tool head holder as the plotter the system could be used for engraving a variety of materials. The system can also be used as a bioprinter (Hock et al., 2014) or food printer (Cohen et al., 2009) by overcoming former limitations of standard RepRaps. For example, with the syringe head it could be used to decorate cakes and cupcakes, make custom pancakes, sandwiches or yet unknown digital culinary masterpieces. The platform can be utilized by artists, for personalization or for prototyping logos on products. For example, it could be used to paint conventional pictures, make stop action movies, or the standard hot end could be used without filament as a wood burner. By developing the ability to map arbitrary substrates to tolerate complex geometries, the system could be used to prototype skins on 3-D objects made for decorative or functional purposes. Considerable work is still needed to understand the process parameter effects on standard RepRaps (Lanzotti, Martorelli, & Staiano, 2015) and this work will need to be expanded to these multi-functionality RepRap designs.

For electronics prototyping, in addition to the PCB milling demonstrated here, the platform could be used to print conductive, semiconducting (e.g. light emitting, photovoltiac, etc.) or magnetic inks, as a pick and place tool or for solder paste placement (masking). With further development, this tool could then fulfill much of the RepRap goal of becoming self-replicating to a larger extent than is currently possible. This tool can also be expanded to provide other forms of rapid prototyping. For example, for prototyping heat exchangers, this system could be adapted with a fiber laser to perform forward conduction welding to make expanded microchannel polymer heat exchangers (Denkenberger, et al., 2012).

Given the precise motion control capabilities of the platform, it can be useful for the development of open source scientific hardware (Pearce, 2014). For example, the platform could be developed as a low-cost microscope stage with heavy optical microscopes attached to the fixed tool mount or inexpensive USB digital microscopes attached to the tool effector. In addition, it could be adapted to serve as a low-cost micro-manipulation platform wherein users control motion while observing results in a magnified view. Open source labs could also benefit from utilizing the platform for profilometry, both contact and non-contact modes. The applications of such a tool to open-source labs is as varied and as expansive as all of the experimental sciences.

Conclusions

Open-source RepRap 3-D printers and their derivatives dominate the entry-level rapid prototyping landscape. The novel collection of extensions of the capabilities of RepRaps with the convertible delta RepRap investigated here expands affordable prototyping into new domains. The delta printer design performed a variety of manufacturing tasks and all of the tools were largely manufactured by the printer itself. The bill of materials, basic assembly and description are provided as free and open source hardware. This study has shown that as the tool remains stationary in the stage configuration, a tool having much greater mass can be fit above the build platform, expanding the catalog of tools and thus materials available for both additive and subtractive manufacturing on the delta platform. The convertible delta RepRap was then tested and profound to perform well with a variety of tools including: a thermoplastic extruder, a caulk/silicone extruder, a syringe pump extruder, a micro mill spindle and a tool holder used for vinyl cutting and plotting. The multi-functionality of this <$1000 multi-material additive and subtractive fabrication tool was provided with cost savings of between 90-97% when compared to single-purpose tools with equivalent functionality.

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Biographical Details

Gerald (Jerry) C. Anzalone received a B.Sc. in metallurgy from the Colorado School of Mines, Golden, CO, USA and a M.S. in civil engineering from Michigan Technological University, Houghton, MI, USA. He is a lab supervisor and research scientist at Michigan Tech, investigating a number of materials-related research areas including utilizing open-source hardware and software solutions for scientific investigations.

Bas Wijnen earned Master's degrees in physics and teaching at the University of Groningen, the Netherlands. He is currently doing his Materials Science and Engineering Ph.D. research on RepRap 3-D printers at Michigan Technological University. He specializes in computer programming, and is a strong supporter of free and open source hardware and software, in particular in educational environments. This fuels his interest in 3-D printing, along with its potential to decentralize production.

Joshua M. Pearce received his Ph.D. in Materials Engineering from the Pennsylvania State University. He then developed the first Sustainability program in the Pennsylvania State System of Higher Education as an assistant professor of Physics at Clarion University of Pennsylvania and helped develop the Applied Sustainability graduate engineering program while at Queen's University, Canada. He currently is an Associate Professor cross-appointed in the Department of Materials Science & Engineering and in the Department of Electrical & Computer Engineering at the Michigan Technological University where he runs the Open Sustainability Technology Research Group (MOST). His research concentrates on the use of open source appropriate technology to find collaborative solutions to problems in sustainability and poverty reduction. His research spans areas of electronic device physics and materials engineering of solar photovoltaic cells, and 3-D printing, but also includes applied sustainability and energy policy. He is the author of the *Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs*.

Table 1. Bill of materials to convert a standard MOST Delta RepRap to a convertible 3D printer/stage

Description	Quantity	UOM	Function	Source	Price	Sold in units	Total Price
Printed convertible carriage	3	ea	Permit relocation of tie rods	Printed			$2.07
Printed limit switch mounts	3	ea	Add limit switches under carriages	Printed			$1.10
Printed stage effector	1	ea	Attach workpiece	Printed			$0.92
Printed horizontal brace	1	ea	Tool mount	Printed			$1.33
Printed vertical brace	1	ea	Tool mount	Printed			$1.61
Printed insert	2	ea	Traps nuts for mounting horizontal and vertical braces	Printed			$1.01
3/8" ring magnet	12	ea	Ball joints	https://www.kjmagnetics.com/proddetail.asp?prod= R622CS-P	$1.17	2	$7.02
Limit switch	3	ea	Additional limit switches for stage mode	http://www.digikey.com/product-detail/en/SS-3GLPT/SW767-ND/664728	$1.11	1	$3.33
24ga twisted pair	3	m	Additional limit switch wiring	http://www.amazon.com/Cat5e-Ethernet-Cable-000ft-Cat-5e/dp/B0092TG310/ref=sr_1_2?ie=UTF8&qid=1410357915&sr=8-2&keywords=cat+5+cable+bulk	$48.99	1524	$0.10
1" x 3" rectangular Al tubing	1	m	Tool mount	http://www.amazon.com/gp/product/B003U6I99U/ref=oh_details_o08_s00_i00?ie=UTF8&psc=1	$40.63	1.8	$22.57
M6 x 60mm hex head cap screw	4	ea	Mounting Al horizontal	http://www.boltdepot.com/Product-Details.aspx?product=5810	$0.46	1	$1.84
M6 hex nut	4	ea	Mounting Al horizontal	http://www.boltdepot.com/Product-Details.aspx?product=4776	$0.08	1	$0.32
M6 flat washer	4	ea	Mounting Al horizontal	http://www.boltdepot.com/Product-Details.aspx?product=4516	$0.06	1	$0.24
Proto board	1	ea	Mounting 4-pin header for "extruder" motor	http://www.amazon.com/gp/product/B00ARTP1J4/ref=oh_details_o06_s00_i02?ie=UTF8&psc=1	$7.42	10	$0.74
20ga wire	2	m	Mounting 4-pin header for "extruder" motor	various			
4 pin male header	1	ea	Mounting 4-pin header for "extruder" motor	http://www.pololu.com/product/965	$0.99	1	$0.99
34cm od x 26cm id plywood ring	1	ea	Replacement printer top	various			
						Total Price	$45.20

Table 2. Bill of materials for fixed tool magnetic mount

Description	Quantity	UOM	Function	Source	Price	Sold in units	Total Price
Printed cage top	1	ea	Protect magnets	Printed			$0.78
1” diameter x 1/2” ring magnet	6	ea	Hold tool	https://www.kjmagnetics.com/proddetail.asp?prod=RX038DCB-N52	$13.91	1	$83.46
M4 x 25mm countersunk machine screw	6	ea	Secure magnets to structure	http://www.boltdepot.com/Product-Details.aspx?product=5116	$0.13	1	$0.78
M4 flat washer	6	ea	Secure magnets to structure	http://www.boltdepot.com/Product-Details.aspx?product=4514	$0.05	1	$0.30
M4 hex nut	6	ea	Secure magnets to structure	http://www.boltdepot.com/Product-Details.aspx?product=4774	$0.05	1	$0.30
#6 x 1/2” countersunk wood screw	3	ea	Mounting cap to cage	http://www.boltdepot.com/Product-Details.aspx?product=3953	$0.08	1	$0.24
						Total Price	$85.86

Table 3. Bill of materials for syringe pump tool

Description	Quantity	UOM	Function	Source	Price	Sold in units	Total Price
Printed syringe pump body	1	ea	Motor end and bearing cage	Printed			$3.25
Printed syringe retainer	2	ea	Secure syringe to pump	Printed			$0.28
Printed syringe pump idler	1	ea	Idler end	Printed			$0.83
Printed carriage	1	ea	Plunger carriage	Printed			$0.32
Printed plunger trap	1	ea	Retainer plunger on carriage	Printed			$0.14
Printed plunger retainer	1	ea	Retainer plunger on carriage	Printed			$0.05
625z ball bearing	2	ea	Idler bearing	http://www.amazon.com/Miniature-Shielded-Deep-Groove-Bearings/dp/B008LTIFX6/ref=sr_1_2?ie=UTF8&qid=1405991639&sr=8-2&keywords=625z	$6.76	5	$2.70
NEMA17 motor	1	ea	Drive	http://www.kysanelectronics.com/Products/Detail.php?recordID=7850	$12.50	1	$12.50
6mm x 6mm shaft coupling	1	ea	Drive-screw coupling	http://www.amazon.com/Motor-Shaft-Coupler-Flexible-Coupling/dp/B00DCAISM2/ref=sr_1_1?ie=UTF8&qid=1405991920&sr=8-1&keywords=5mm+shaft+coupling	$7.57	1	$7.57
M3 x 10mm socket head cap screw	6	ea	Guide rod clamps and plunger retainer	http://www.boltdepot.com/Product-Details.aspx?product=6380	$0.06	1	$0.36
M3 x 14mm socket head cap screw	4	ea	Syringe retainer screws	http://www.mcmaster.com/#91292a027/=sxuvqf	$5.60	100	$0.22
M3 x 16mm socket head cap screw	4	ea	Motor mount screws	http://www.boltdepot.com/Product-Details.aspx?product=6382	$0.06	1	$0.24
M3 x 20mm socket head cap screw	3	ea	Attaching ball cage	http://www.boltdepot.com/Product-Details.aspx?product=6383	$0.07	1	$0.21
M3 hex nut	13	ea	Various	http://www.boltdepot.com/Product-Details.aspx?product=4773	$0.05	1	$0.65
M5 threaded rod	0.2	m	Drive	http://www.mcmaster.com/#90024a060/=sxuwfc	$9.24	1	$1.85
M5 hex nut	3	ea	Captive nut, idler jam nuts	http://www.boltdepot.com/Product-Details.aspx?product=4775	$0.05	1	$0.15
6mm A2 tool steel	0.4	m	Guide rod	http://www.mcmaster.com/#8116k35/=sxuwsm	$9.54	0.9144	$4.17
LM6UU linear bearing	2	ea	Carriage	http://www.amazon.com/10pcs-Linear-Bearing-Bushing-linear/dp/B00AGCIS74/ref=sr_1_2?ie=UTF8&qid=1405992161&sr=8-2&keywords=lm6uu	$15.50	10	$3.10
1” diameter G25 ball bearings	3	ea	Magnetic mount	http://www.amazon.com/gp/product/B000FMULLG/ref=oh_details_o04_s00_i00?ie=UTF8&psc=1	$13.75	10	$4.13
						Total Price	$42.71

Table 4. Bill of materials for caulk extruder

Description	Quantity	UOM	Function	Source	Price	Sold in units	Total Price
Printed 5.45:1 planetary gear	3	ea		Printed			$0.14
Printed 5.45:1 sun gear	1	ea		Printed			$0.23
Printed 5.45:1 input annulus gear	1	ea		Printed			$0.46
Printed 5.45:1 output annulus gear	1	ea		Printed			$0.55
Printed 5.45:1 planetary carrier	1	ea		Printed			$0.46
Printed gearbox motor mount	1	ea		Printed			$0.69
Printed gearbox output end	1	ea		Printed			$0.92
Printed piston	1	ea		Printed			$0.37
Printed 23-tooth gear	1	ea		Printed			$0.92
Printed 49-tooth gear	1	ea		Printed			$1.29
Printed lead screw retainer	1	ea		Printed			$0.69
Printed caulk idler end	1	ea		Printed			$2.53
Printed caulk output end	1	ea		Printed			$2.07
Printed caulk tube backer	1	ea		Printed			$1.01
Copper tube adapter	1	ea		Hardware store			$4.00
NEMA17 motor	1	ea		http://www.kysanelectronics.com/Products/Detail.php?recordID=7850	$12.50	1	$12.50
1/4" hose clamp	2	ea		Hardware store	$0.79	1	$1.58
M8 threaded rod	1.5	m		http://www.mcmaster.com/#90024a080/=sxuxk0	$10.50	1	$15.75
M8 hex nut	10	ea		http://www.boltdepot.com/Product-Details.aspx?product=4778	$0.13	1	$1.30
M8 flat washer	4	ea		http://www.boltdepot.com/Product-Details.aspx?product=4518	$0.08	1	$0.32
608zz ball bearing	3	ea		http://www.amazon.com/Set-608ZZ-Radial-Bearings-Printer/dp/B00C7BJTU2/ref=sr_1_3?s=industrial&ie=UTF8&qid=1405992309&sr=1-3&keywords=608zz	$6.00	9	$2.00
2" PVC pipe, split lengthwise	0.21	m		http://www.homedepot.com/p/Unbranded-2-in-x-10-ft-PVC-Sch-40-Plain-End-Pipe-531137/100161954	$5.06	3.04801	$0.35
2" hose clamp	5	ea		Hardware store	$1.05	1	$5.25
624z ball bearing	3	ea		http://www.amazon.com/10-Bearing-624ZZ-Shielded-4x13x5/dp/B002BBH45A/ref=sr_1_1?s=industrial&ie=UTF8&qid=1405992358&sr=1-1&keywords=624zz	$15.38	10	$4.61
M4 x 16mm socket head cap screw	3	ea		http://www.boltdepot.com/Product-Details.aspx?product=6396	$0.09	1	$0.27
M4 flat washer	9	ea		http://www.boltdepot.com/Product-Details.aspx?product=4514	$0.05	1	$0.45
M4 nylock nut	3	ea		http://www.boltdepot.com/Product-Details.aspx?product=4793	$0.06	1	$0.18
M8 x 60mm hex head bolt	1	ea		http://www.boltdepot.com/Product-Details.aspx?product=5821	$0.73	1	$0.73
M3 x 30mm socket head cap screw	4	ea	Gearbox	http://www.boltdepot.com/Product-Details.aspx?product=6385	$0.10	1	$0.40
M3 flat washer	8	ea		http://www.boltdepot.com/Product-Details.aspx?product= 4513	$0.05	1	$0.40
M3 hex nut	7	ea		http://www.boltdepot.com/Product-Details.aspx?product=4773	$0.05	1	$0.35
M3 x 10mm socket head cap screw	4	ea	Motor mount	http://www.boltdepot.com/Product-Details.aspx?product=6380	$0.06	1	$0.24
M8 hex nut	15	ea		http://www.boltdepot.com/Product-Details.aspx?product=4778	$0.13	1	$1.95
M8 flat washer	11	ea		http://www.boltdepot.com/Product-Details.aspx?product=4518	$0.08	1	$0.88
M3 x 20mm socket head cap screw	3	ea	Attaching ball cage	http://www.boltdepot.com/Product-Details.aspx?product=6383	$0.07	1	$0.21
1" diameter G25 ball bearings	3	ea	Magnetic mount	http://www.amazon.com/gp/product/B000FMULLG/ref=oh_details_o04_s00_i00?ie=UTF8&psc=1	$13.76	10	$4.13
						Total Price	$70.18

Table 5. Bill of materials for micro mill spindle mount

Description	Quantity	UOM	Function	Source	Price	Sold in units	Total Price
Printed spindle clamp	1	ea		Printed			$1.61
Printed vacuum attachment	1	ea		Printed			$0.69
Printed bearing cage	1	ea		Printed			$1.84
Mill spindle	1	ea		http://www.angelfire.com/az2/proff/	$92.00	1	$92.00
M4 x 16mm socket head cap screw	1	ea	Spindle clamp	http://www.boltdepot.com/Product-Details.aspx?product=6396	$0.09	1	$0.09
M4 hex nut	1	ea	Spindle clamp	http://www.boltdepot.com/Product-Details.aspx?product=4774	$0.05	1	$0.05
M4 flat washer	1	ea	Spindle clamp	http://www.boltdepot.com/Product-Details.aspx?product=4514	$0.05	1	$0.05
M3 x 20mm socket head cap screw	3	ea	Attaching bearing cage	http://www.boltdepot.com/Product-Details.aspx?product=6383	$0.07	1	$0.21
M3 hex nut	3	ea	Attaching bearing cage	http://www.boltdepot.com/Product-Details.aspx?product=4773	$0.05	1	$0.15
M3 flat washer	3	ea	Attaching bearing cage	http://www.boltdepot.com/Product-Details.aspx?product=4513	$0.05	1	$0.15
M3 x 10mm socket head cap screw	1	ea	Vacuum attachment clamp	http://www.boltdepot.com/Product-Details.aspx?product=6380	$0.06	1	$0.06
1” diameter G25 ball bearings	3	ea	Magnetic mount	http://www.amazon.com/gp/product/B000FMULLG/ref=oh_details_o04_s00_i00?ie=UTF8&psc=1	$13.76	10	$4.13
						Total Price	$101.03

Table 6. Bill of materials for tool effector

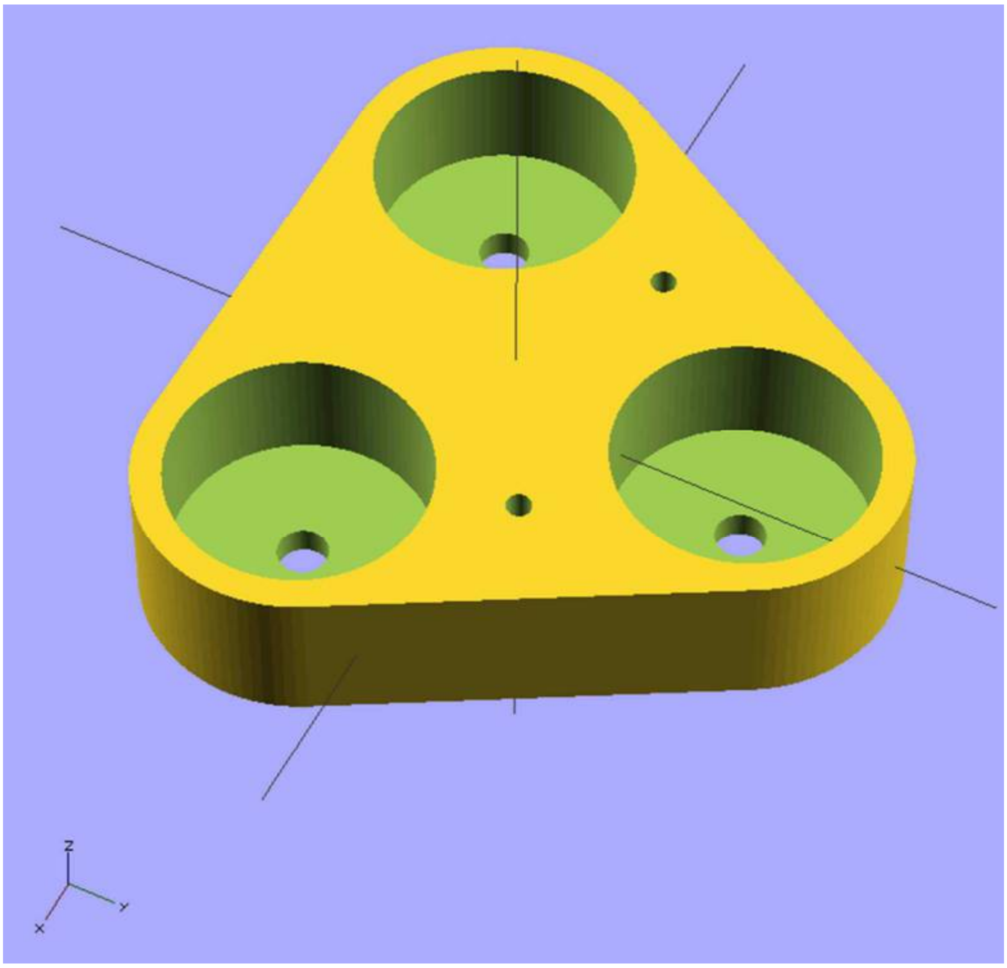
Description	Quantity	UOM	Function	Source	Price	Sold in units	Total Price
Printed tool end effector	1	ea	Effector that accepts tools	Printed			2.07
3/8” ring magnet	12	ea	Magnetic tool mounts and ball joints	https://www.kjmagnetics.com/proddetail.asp?prod=R622CS-P	$1.17	2	$7.02
					Total Price		$9.09

Table7. Bill of materials for tool effector spring mount tool

Description	Quantity	UOM	Function	Source	Price	Sold in units	Total Price
Printed tool mount	1	ea	Mount tool to effector	Printed			$0.92
Printed tool holder	1	ea	Mount tool to effector	Printed			$0.55
3/8" ball bearing	3	ea	Magnetic mount	http://www.amazon.com/Diameter-Chrome-Bearing-Bearings-VXB/dp/B002BBD4SG/ref=sr_1_1?ie=UTF8&qid=1410356832&sr=8-1&keywords=3%2F8%22+ball+bearings	11.15	100	$0.33
M3 x 35mm socket head cap screw	3	ea	Attach holder to mount	https://www.boltdepot.com/Metric_socket_cap_Stainless_steel_18-8_3mm_x_0.5mm.aspx	0.16	1	$0.48
M3 x 10mm socket head cap screw	3	ea	Tool retainer	https://www.boltdepot.com/Metric_socket_cap_Stainless_steel_18-8_3mm_x_0.5mm.aspx	0.06	1	$0.18
M3 nylock nut	3	ea	Attach holder to mount	http://www.boltdepot.com/Product-List.aspx?Units=Metric&Category=Nuts&Subcategory=Hex_lock_nuts_nylon_insert&Material=Stainless_steel&Plating=&Grade=18--8&Finish=&Color=&Thread_direction=Right_hand&Diameter=3mm&Thread_count=&nv=rel	0.05	1	$0.15
M3 nut	3	ea	Tool retainer	http://www.boltdepot.com/Product-Details.aspx?Units=Metric&Category=Nuts&Subcategory=Hex_nuts&Material=Stainless_steel&Plating=&Grade=18--8&Finish=&Thread_direction=Right_hand&Thread_density=Coarse&Diameter=3mm&Thread_pitch=0.5mm&nv=rel	0.05	1	$0.15
5mm x 7mm spring	3	ea	Attach holder to mount	Ball point pens	0.05	1	$0.15
Tangent knife	1	ea	Cut vinyl	http://www.amazon.com/gp/product/B005S2O61E/ref=oh_aui_detailpage_o03_s00?ie=UTF8&psc=1	7.72	1	$7.72
Cutting mat	1	ea	Protect platform and tangent knife	http://www.amazon.com/gp/product/B005VPVW3I/ref=oh_aui_detailpage_o03_s00?ie=UTF8&psc=1	9.4	1	$9.40
						Total Price	$20.03

Table 8. Comparison of the functions demonstrated by the Convertible Delta RepRap to commercial equivalents and the associated costs.

Function	Proprietary Equivalent	CAPEX Cost (US$)	Material Cost (US$)	Notes
Thermoplastic 3-D Printing	Makerbot Replicator Stratasys μPrint SE Plus	$2,900 ~$20,000	$53/kg ~$200/kg	http://www.makerbot.com/ http://www.stratasys.com/
Paste 3-D printer	Foodini	$1,000	N/A	http://www.naturalmachines.com/
Vinyl Cutter/ Plotter	Seiki SK375T	$230	$10/m^2	http://www.joyfay.com/brand-new-375-mm-15-lcd-sign-sticker-vinyl-cutter-cutting-plotter-artcut-sk375t.html?gclid=CJeB7JyZ18ACFRQdaQod51kAjA
Milling	LPKF ProtoMat MITS Eleven Lab Colinbus PCBBox	$8750 $8495 $4,500 (3500€)	N/A	
Total	None	**$8,600-$30,00**		
Convertible Delta RepRap w/ all tools		**$825**		
Savings from RepRap Agglomeration		**$7,775 - $29,175**		



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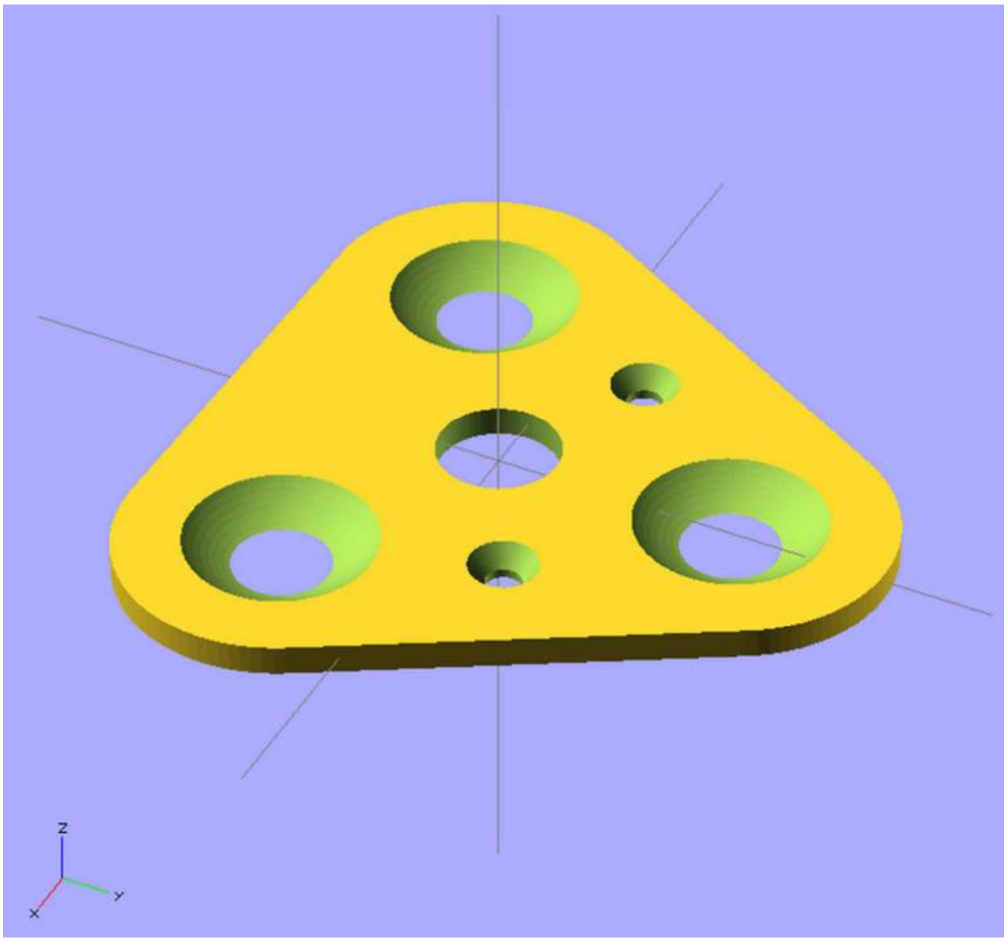

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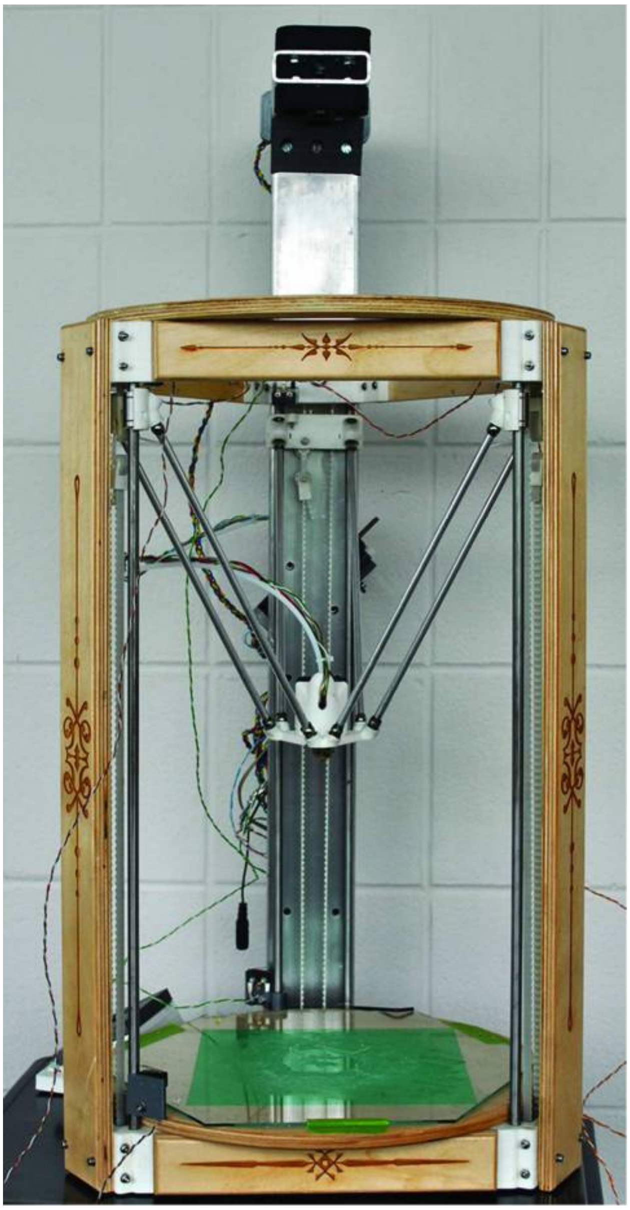

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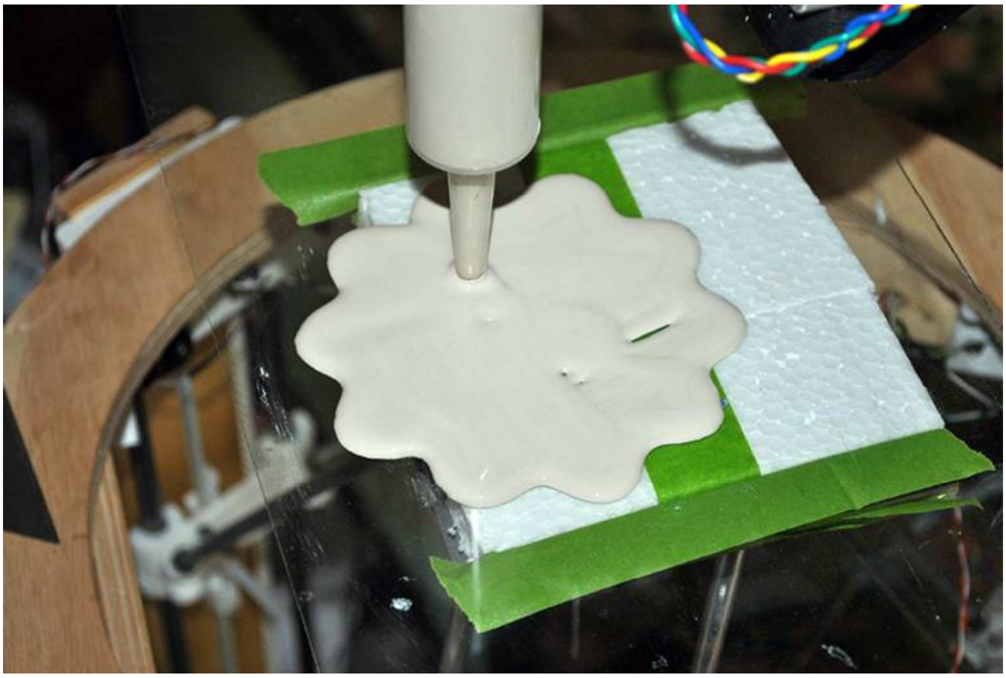

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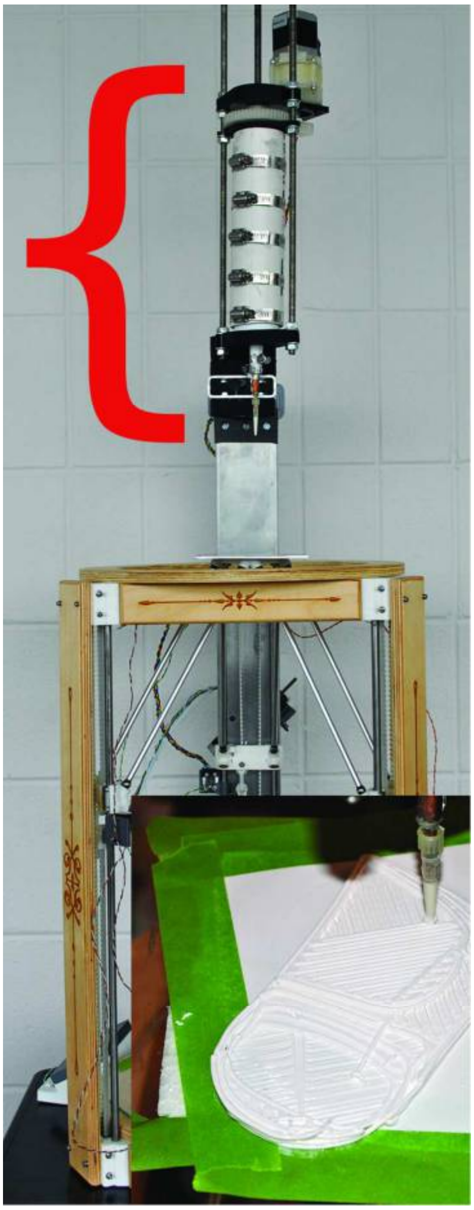

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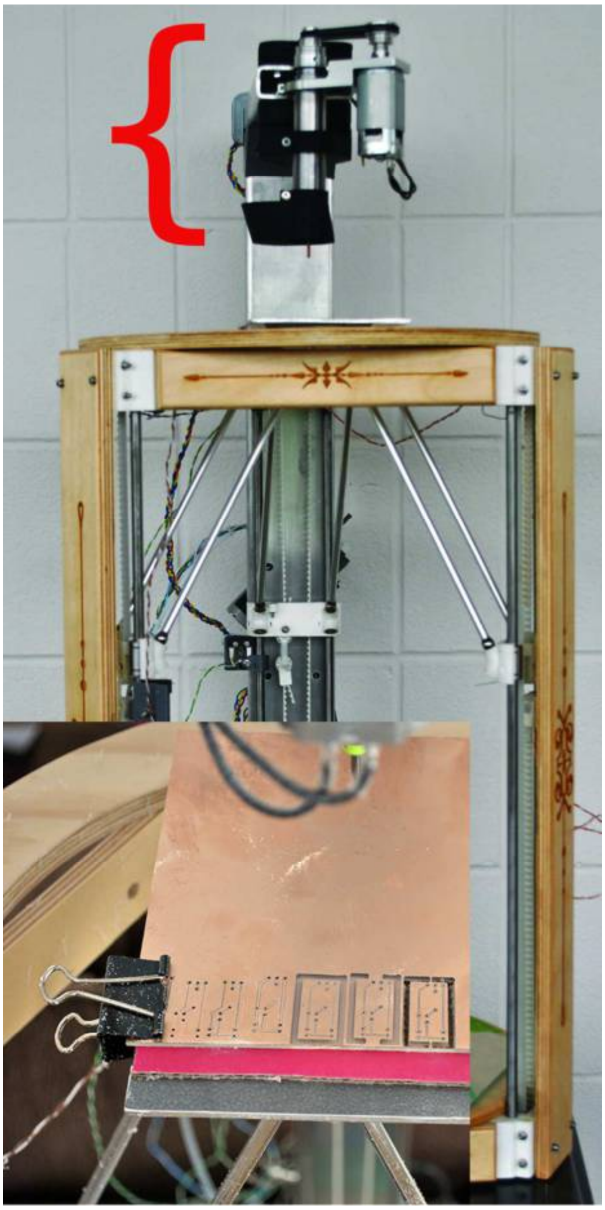

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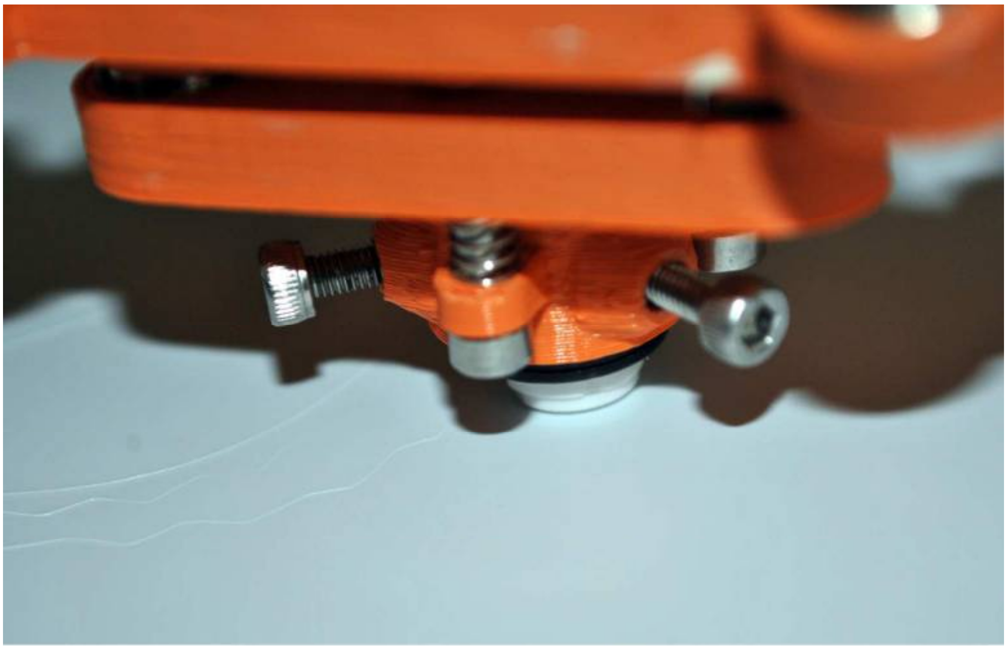

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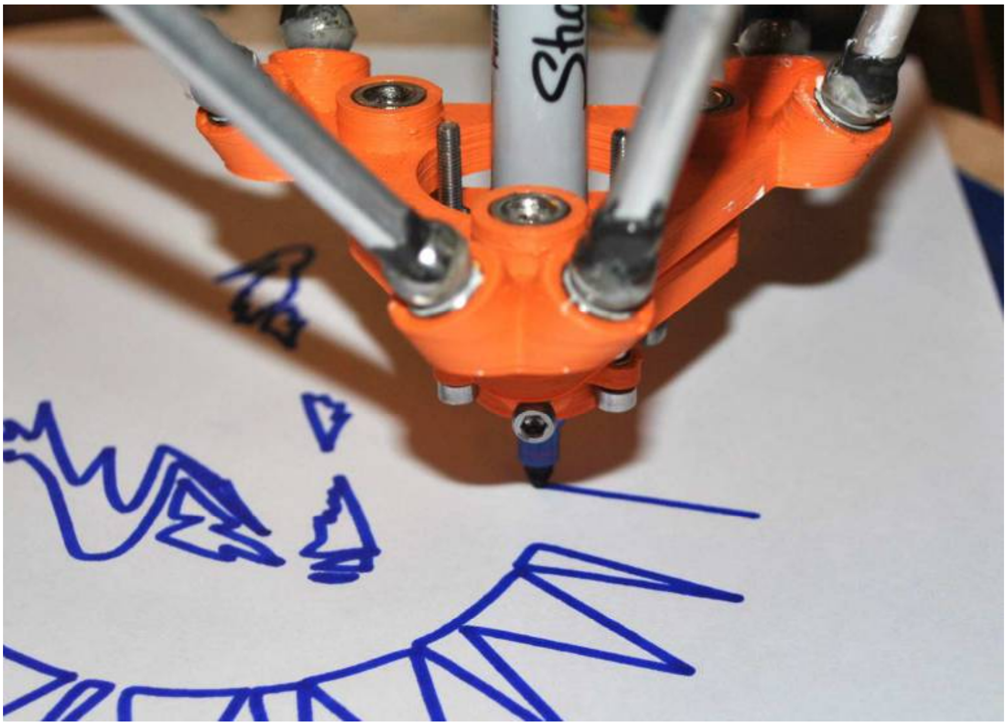

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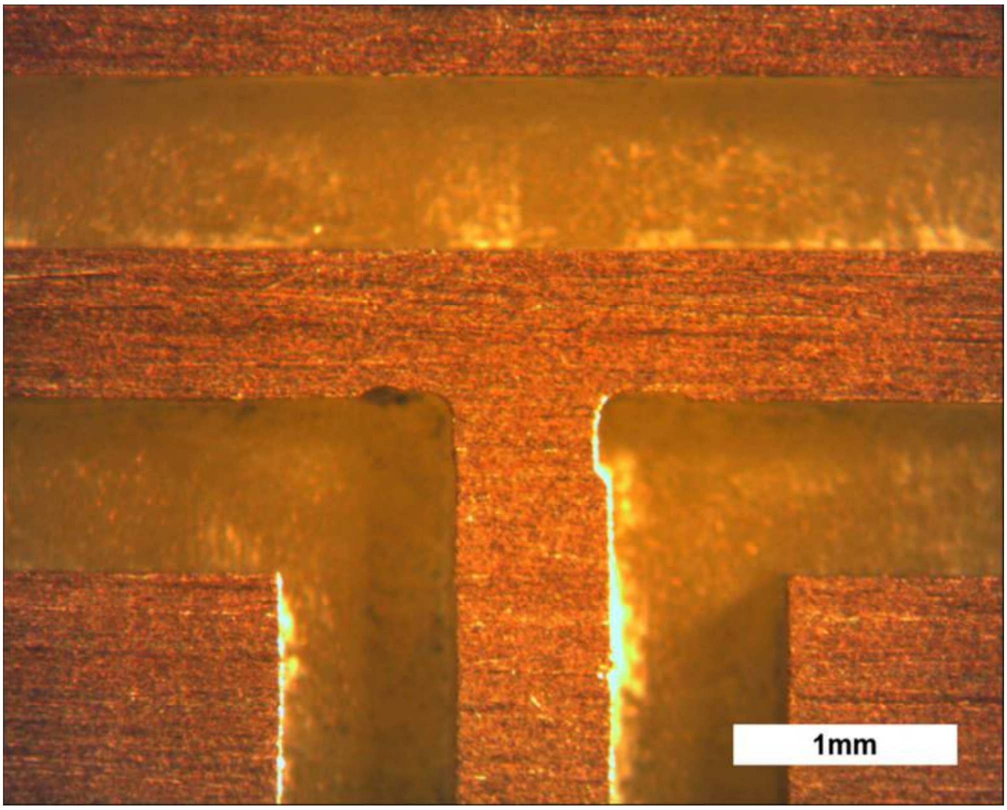

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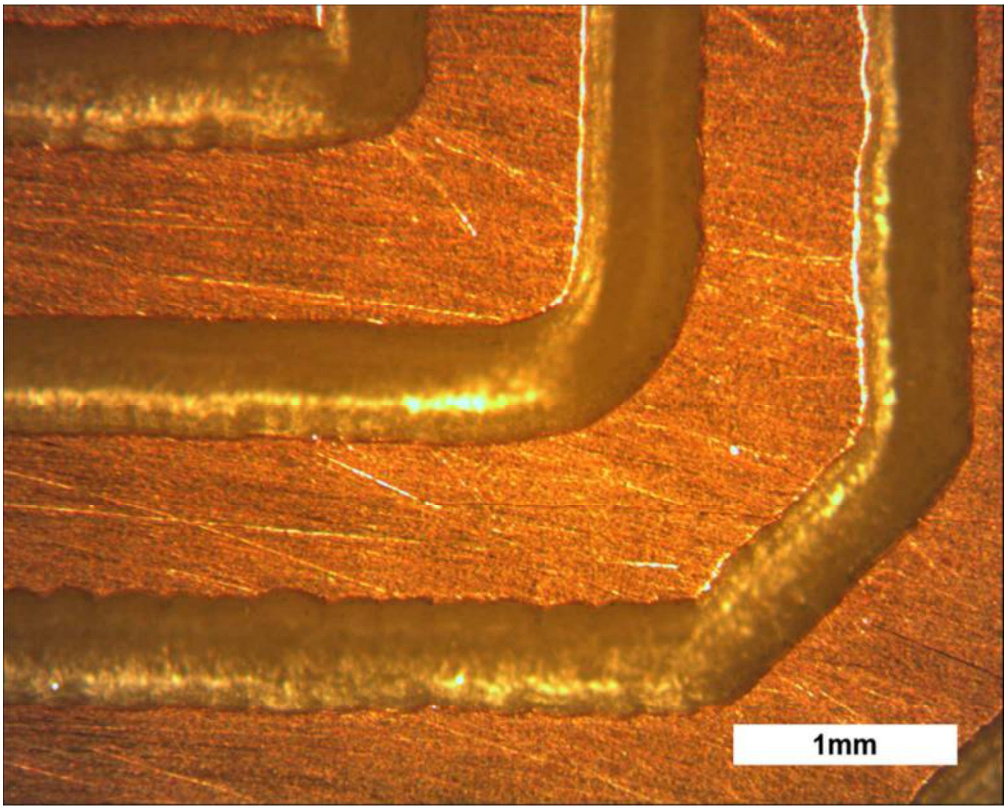

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