FAB@HOME MODEL 3: A MORE ROBUST, COST EFFECTIVE AND ACCESSIBLE OPEN HARDWARE FABRICATION PLATFORM

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Abstract

Solid Freeform Fabrication is transitioning from an industrial process and research endeavor towards a ubiquitous technology in the lives of every designer and innovator. In order to speed this transition Fab@Home Model 3 was created with the goal of expanding the user base of SFF technology by lowering the skill and price barriers to entry while enabling technology developers to leverage their core competencies more efficiently. The result is a device, which is modular with respect to tool heads, fabrication processes, and electronics controls, costs under $1000, and requires only a simple tool set to assemble.

Introduction

Over the last few years, we have seen an explosion in the personal 3D printer market. Companies in The United States, Europe, China and elsewhere are offering new options to consumers. Many of these devices are descendants of the early open hardware 3D printers. Most of these new units are being offered as cheap DIY kits that allow the user to assemble their own machine. The overwhelming majority of personal 3D printers use FDM manufacturing to make plastic objects; few attempt any other material, process or functionality natively. This limits the scope of potential users. While some early adopters and technology enthusiasts have a need to rapidly fabricate simple plastic components, few other potential users of personal 3D printers have the same need. To them it remains a curiosity rather than a useful tool.

In order to expand the user base of personal 3D printing technology, it is necessary to transform single material 3D printers into general-purpose personal manufacturing devices. Such personal fabricators would leverage the infrastructure of 3D printers to accomplish more traditional manufacturing processes. By combining additive and traditional manufacturing capabilities on the same machine, it is possible to dramatically expand the potential user base.

Further limiting the adoption of 3D printing by new user groups is the cost, technical skill requirements, and ease of access of a printer. Most of the kits on the market require substantial technical skill to assemble and operate. A natural solution to this problem may be to offer fully assembled units; however, the complexity and technical requirements of the printer designs leads to extremely high labor costs, often putting the assembled units out of the price range of most potential users. (Makerbot Industries)

Most of the current generation of personal 3D printers are in the vein of the first Model 1 Fab@Home units and traditional commercial machines. They are designed as a single integrated system, requiring the developer to develop novel electronics, chassis, tool heads and control software. (Makerbot Industries) (3D Systems) (pp3dp) This limits the speed of development and forces manufacturers to be well versed in mechanical, electrical, and software engineering. The diversity of skills required will inevitably lead to higher development costs and therefore higher product costs. In order to advance the transition to SFF ubiquity the Model 3 Fab@Home system must once again lower the user's barriers to entry, increase the ease of modification, and expand the usage scope of the machine.

Background

The Fab@Home Project began as an open hardware project in 2005 under Hod Lipson and then doctoral student Evan Malone. The Model 1 Fab@Home was introduced in 2007 as one of the first low cost 3D printers. (Evan Malone, 2007) It was similar to traditional SFF devices in that it was an integrated system with the path planning and motion control software, electronics, chassis and tool head all tightly integrated. Unlike other 3D printers, it was capable of using a wide variety of materials. In 2009, the Fab@Home Project released the Model 2 3D printer design. It focused on lowering the barrier of access by dropping the cost, and was the first system to decouple the tool head from the chassis to ease the modification process. (Lipton, et al., 2009) Several hundred Model 1 and Model 2 units have been by users. These were self-reported by users on the Fab@Home website.

Open Hardware is a nascent concept akin to the open software movement, which began in the 1980's. In 2011, an international community of developers accepted the first definition of open hardware. According to the first definition,

> Open source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design. The hardware's source, the design from which it is made, is available in the preferred format for making modifications to it. Ideally, open source hardware uses readily-available components and materials, standard processes, open infrastructure, unrestricted content, and open-source design tools to maximize the ability of individuals to make and use hardware. Open source hardware gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs. (Open Hardware Summit)

Fab@Home has been operating under this model since 2007. The designs are released under the BSD license and rely on off the shelf parts, and manufacturing processes which are widely available for individual usage, specifically laser cutting.

The Fab@Home project is currently working on the Fab@School project. The Fab@School project aims to revolutionize STEM education by introducing engineering into the classroom to integrate science technology and math education into a tangible activity. The project uses digital fabrication technology to enable students and teachers to make abstract notions in mathematics tangible. The program will begin in the second grade and build up towards high school.

For a personal fabrication device to be successfully integrated into an elementary school classroom it must meet strict safety concerns and must be accepted by the teachers. The Curry School of Education in UVA uses a principle of least change. In order to ensure that teachers will migrate to a new method, it must build a bridge from current methodologies. Most classrooms use Elision die cutters and other forms of 2D paper fabrication. Therefore, the potential user base of elementary school students and teachers must have a bridge built between their current usage of manufacturing technology and 3D fabrication as described in the introduction.

Methods: Barrier to Entry

The Model 3 needed to reduce the difficulty of assembling the unit by reducing the skills required and by reducing the time required to build a unit. A universally accepted standard for low skill assembly is IKEA. IKEA produces items, which often require only a hex wrench set to assemble. The Model 2 Fab@Home required a soldering iron to be used install thermoplastic inserts. This proved to be intimidating to many non-technical people. Therefore, the Model 3 needed to eliminate the thermoplastic inserts in order to ensure the maximal amount of people would be comfortable with attempting assembly of a unit.

In order to reduce the build time of a Fab@Home, the system needed to be made as simple as possible. This was accomplished by having fewer screws and interlocks. Screws and interlocks on the Model 2 have been a source of frustration and failure. These spots often are the sources of cracking in acrylic. Variation in the thickness of the acrylic would often require the users of the Model 2 to file the pieces to ensure a proper fit.

The system was designed to reduce the amount of laser cutting required, use more cost effective parts, and electronics other than the JrKerr SnapMotor system were adopted in order to lower costs of ownership. Laser cutting time was reduced by attempting to minimize the perimeter of all parts. This leads to geometrically simpler parts. The reduction in the number of screws used greatly aided this process by eliminating the holes for the screws and nuts from the interior and exterior perimeter of many parts. Laser cutting times were recorded by cutting the parts out of 6mm acrylic on a 35-watt Epilog Legend laser-cutter at 3% of maximum speed and at full power.

With the Model 2 Fab@Home system, ease of access was a major barrier to user adoption. Often those community members providing kitting services were unable to stock the necessary parts from the vendors. Users in countries other than the United States often had problems ordering the parts from American vendors, and could not find suitable replacements in their own countries. Since the Model 2 had been designed around specific parts from specific vendors this often created delays for users who wanted to adapt the system design to locally available parts. Therefore, the system needed a more flexible chassis design, which would allow for a more flexible supply chain. By under-constraining the dimensions of parts, it is possible to make a system, which will be more adaptable.

Methods: Ease of Modification

The Model 2 Fab@Home successfully decoupled the printer chassis from the tool heads. This lead to a wide variety of tool heads on the Model 2 system. Unfortunately, the space of possible tool heads was limited by the tight integration of the JrKerr SnapMotor system into the chassis of the Model 2. This necessitated the use of SnapMotors for the tool heads. These motors drove up the cost and limited innovation. For Model 3 it was necessary to separate the selection of motors and electronics control systems from the chassis. Other 3D printers have had interchangeable controller boards; however, they always required use of specified motors. In RepRap designs, the NEMA stepper motor standards were always specified in the chassis design. However, the electronics were easily changed. In order to ensure that the system could work with as wide a range of motor as possible, the Model 3 system uses interchangeable motor bays.

These bays allow for the mounting of various motors onto the chassis without the need for extensive modification of the machine's design.

Methods: Expanded functionality

Fab@Home systems are, in essence, a 3-axis robotic gantry system with interchangeable tool heads. The robotic nature of the Fab@Home naturally leverages itself to other forms of manufacturing aside from deposition. With the Model 2, the system was extended into CNC fabrication using a Dremel flex-shaft mount tool head. In order to build the bridge between potential users' current needs and Solid freeform fabrication system, the Fab@Home's set of tools was expanded to included: vinyl cutting, pen plotting, foam cutting, pick and place assembly, microscopy, automated pipetting, 8 material printing, and plastic printing. These tools were designed to use a variety of different motors and leverage the interchangeable mounting system developed in the Model 2 and the motor selection flexibility of the Model 3

For the elementary school environment, one needs to add additional safety features, which are not typically used in a hobbyist or research environment. In order to mitigate the smells from the fabrication process and prevent users from putting their body parts in the machine during operation, a safety hood was developed which can enclose the Model 3. This allows users to customize the safety level of their machine. In the event that a user does obstruct the machine's motion with their body, the system can be equipped with tension-limiting devices that ensure the system can apply a maximum force on the user below the point of causing bodily harm.

Results: Barrier to Entry

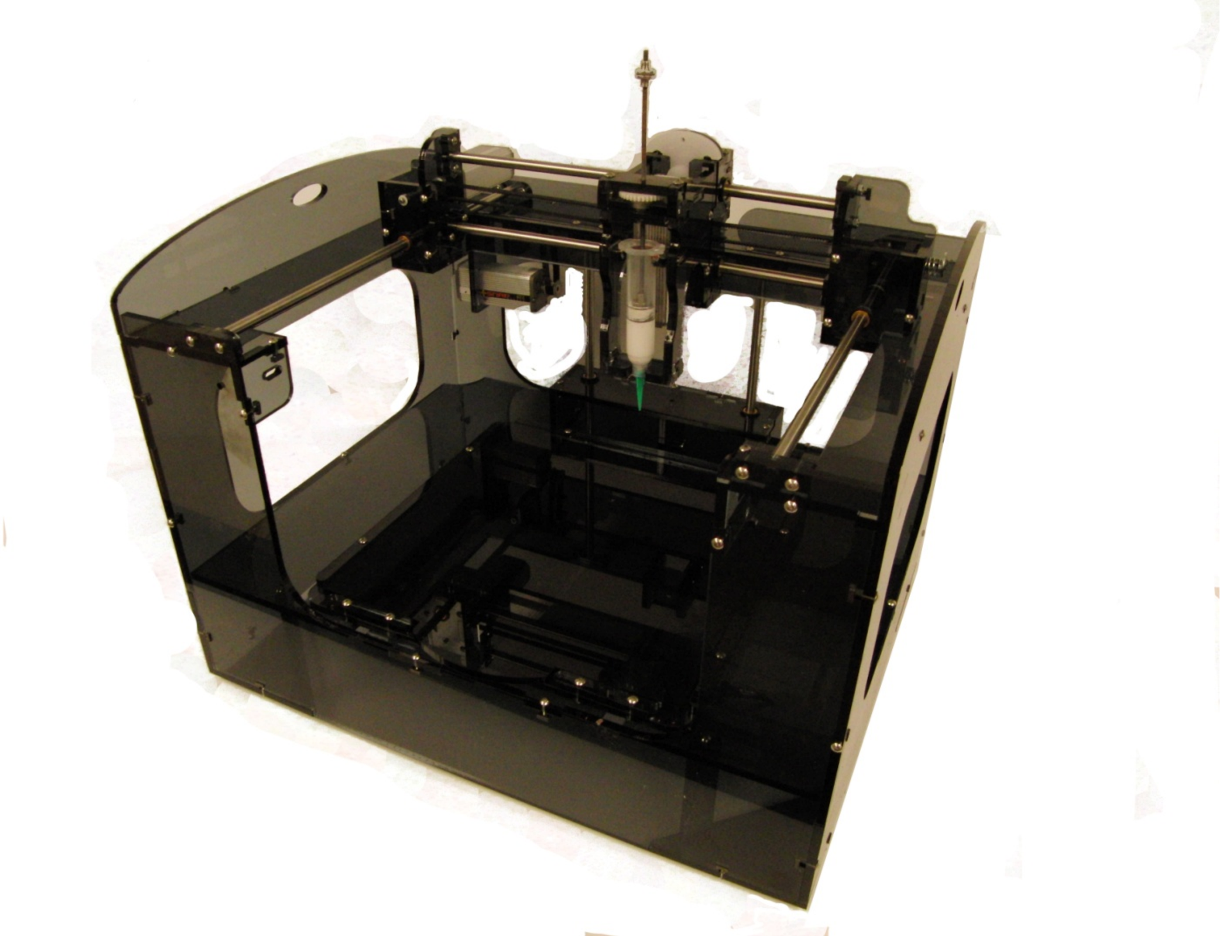


Figure 1: The Model 3 Fab@Home with JrKerr SnapMotors and a Single syringe displacement tool

The techniques employed greatly reduced the assembly difficulty of the Model 3 relative to the Model 2. The Model 3 requires hex wrenches, Philips screwdrivers, scissors and a c-clamp to assemble. These are all tools that almost any individual would feel comfortable using. Belt attachment mechanisms were decoupled from their assemblies to allow for easier adjustment and installation of the belt drives. The system was designed to be made in distinct sub-assemblies, which could be made in parallel and then integrated together.

The simplification of the design allowed an individual to build a prototype of the Model 3 using the JrKerr SnapMotors in a little over one hour of work. This individual was the designer of the Model 2 and Model 3 Fab@Home systems. He typically required 6-8 hours to assemble a Model 2 fabricator. Many users reported needing approximately 20 person-hours to assemble a Model 2 unit, 2.5 times as long as it took the designer. Therefore, it should take a naive user about 3 hours to assemble a Model 3, provided they had all the relevant documentation. This is a dramatic improvement over the average two-day build process of other machines.

By reducing the perimeter of the parts and replacing the bottom plate of the Model 2 with a multiple plate system , it was possible to reduce the cutting time to 298 minutes on the Epilog Legend, without using edge doubling. The Model 2 often took upwards of 400 minutes to laser cut on the same machine. This should help reduce the cost of laser cutting for users who do not have access of their own laser cutter.

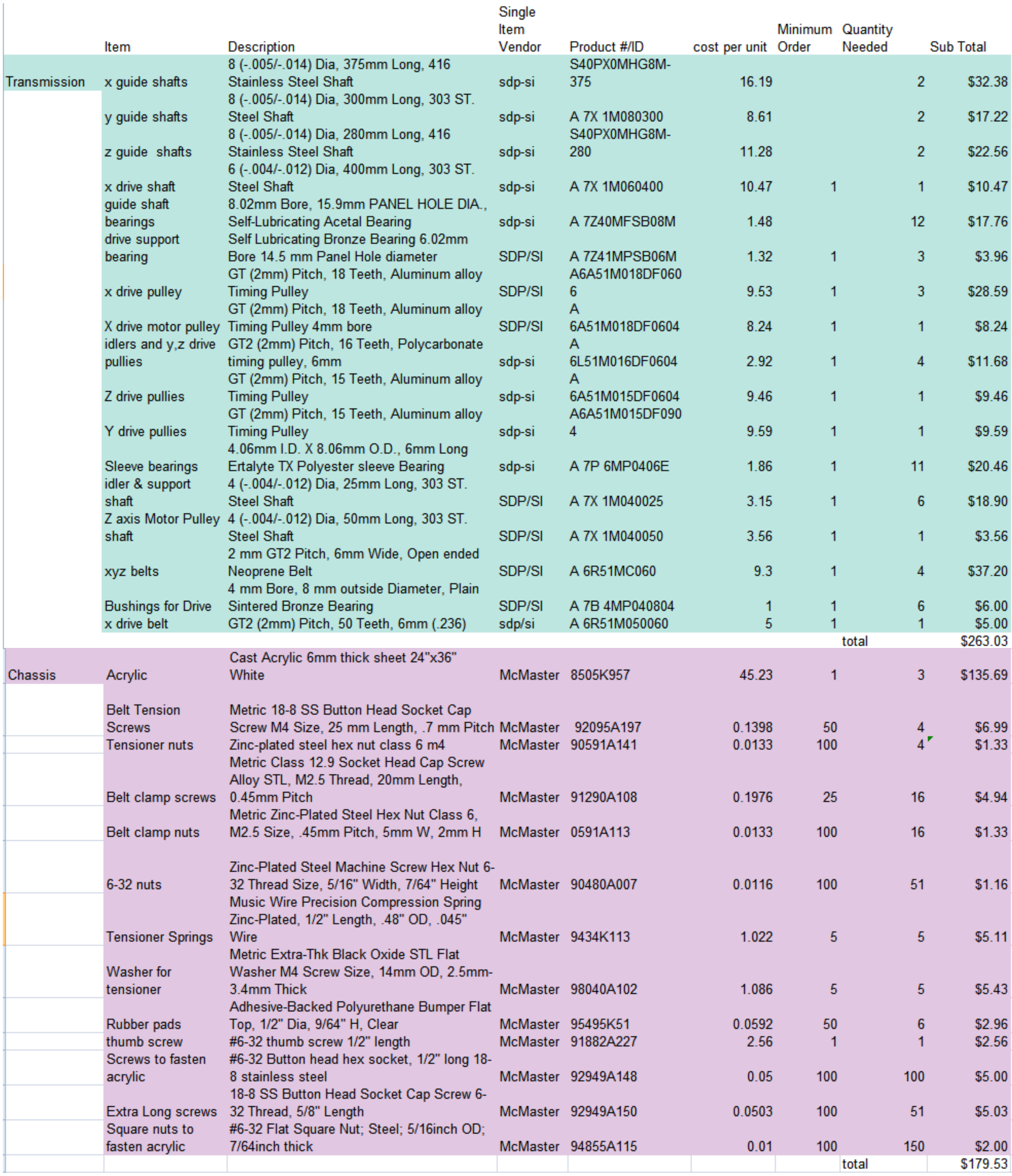
The Model 3 has significantly lower transmission and chassis costs than the Model 2. By changing more pulleys to plastic pulleys, switching to 8mm shafts, and using sleeve bearings rather than ball bearings, the Model 3 transmission costs were reduced to $263 from $399 for the Model 2 a 34% cost reduction for the same functionality. The removal of inserts and the adjustable base pads allowed the Model 3 chassis to cost $179.53 compared to $221.97 for the Model 2, a savings of 19%. (Lipton, et al., 2009)

The most substantial savings come from the interchangeable nature of the motors. This allows the system to use a variety of different more cost-effective motion systems. While the JrKerr SnapMotors are the simplest to install for a novice user, they are expensive. Other motion systems, including the new hobby servo based electronics developed by the Fab@Home Team, are half as expensive for a 3 axis motion system, and nearly a third as expensive for a 5 motor system(see figure 2). In total, a Model 3 using a dual-syringe displacement tool and the servo electronics should cost $935 plus laser cutting and shipping costs. A Model 2 with a dual-syringe displacement tool costs $1600 plus laser cutting and shipping.

With the Model 2, the metal pulleys from SDP/SI often caused supply chain issues. The design of the Model 3 idler pulley system allows the idlers to vary by upwards of 5mm in length and 3mm in diameter. This will allow users to adapt the system to the locally available parts. Additionally the modularity of the motor system allows for the deployment of locally available motors without significant modification to the systems design.

Electronics Package	Makerbot Gen 4	TechZone	JrKerr SnapMotors	Servo Electronics
Electronics costs	370	240	160	315
3 motors	103	63	480	18
5 motors	145	105	800	30
3 axis system	473	303	640	333
5 motor system	515	345	960	345

Figure 2: Costs of 3-axis electronics plus motors from various suppliers



	Item	Description	Single Item Vendor	Product #/ID	cost per unit	Minimum Order	Quantity Needed	Sub Total
Transmission	x guide shafts	8 (-.005/-.014) Dia, 375mm Long, 416 Stainless Steel Shaft	sdp-si	S40PX0MHG8M-375	16.19		2	$32.38
	y guide shafts	8 (-.005/-.014) Dia, 300mm Long, 303 ST. Steel Shaft	sdp-si	A 7X 1M080300	8.61		2	$17.22
	z guide shafts	8 (-.005/-.014) Dia, 280mm Long, 416 Stainless Steel Shaft	sdp-si	S40PX0MHG8M-280	11.28		2	$22.56
	x drive shaft	6 (-.004/-.012) Dia, 400mm Long, 303 ST. Steel Shaft	sdp-si	A 7X 1M060400	10.47	1	1	$10.47
	guide shaft bearings	8.02mm Bore, 15.9mm PANEL HOLE DIA., Self-Lubricating Acetal Bearing	sdp-si	A 7Z40MFSB08M	1.48		12	$17.76
	drive support bearing	Self Lubricating Bronze Bearing 6.02mm Bore 14.5 mm Panel Hole diameter	SDP/SI	A 7Z41MPSB06M	1.32	1	3	$3.96
	x drive pulley	GT (2mm) Pitch, 18 Teeth, Aluminum alloy Timing Pulley	SDP/SI	A6A51M018DF0606	9.53	1	3	$28.59
	X drive motor pulley	GT (2mm) Pitch, 18 Teeth, Aluminum alloy Timing Pulley 4mm bore	SDP/SI	A 6A51M018DF0604	8.24	1	1	$8.24
	idlers and y,z drive pullies	GT2 (2mm) Pitch, 16 Teeth, Polycarbonate timing pulley, 6mm	sdp-si	A 6L51M016DF0604	2.92	1	4	$11.68
	Z drive pullies	GT (2mm) Pitch, 15 Teeth, Aluminum alloy Timing Pulley	sdp-si	A 6A51M015DF0604	9.46	1	1	$9.46
	Y drive pullies	GT (2mm) Pitch, 15 Teeth, Aluminum alloy Timing Pulley	sdp-si	A6A51M015DF0904	9.59	1	1	$9.59
	Sleeve bearings	4.06mm I.D. X 8.06mm O.D., 6mm Long Ertalyte TX Polyester sleeve Bearing	sdp-si	A 7P 6MP0406E	1.86	1	11	$20.46
	idler & support shaft	4 (-.004/-.012) Dia, 25mm Long, 303 ST. Steel Shaft	SDP/SI	A 7X 1M040025	3.15	1	6	$18.90
	Z axis Motor Pulley shaft	4 (-.004/-.012) Dia, 50mm Long, 303 ST. Steel Shaft	SDP/SI	A 7X 1M040050	3.56	1	1	$3.56
	xyz belts	2 mm GT2 Pitch, 6mm Wide, Open ended Neoprene Belt	SDP/SI	A 6R51MC060	9.3	1	4	$37.20
	Bushings for Drive	4 mm Bore, 8 mm outside Diameter, Plain Sintered Bronze Bearing	SDP/SI	A 7B 4MP040804	1	1	6	$6.00
	x drive belt	GT2 (2mm) Pitch, 50 Teeth, 6mm (.236)	sdp/si	A 6R51M050060	5	1	1	$5.00
							total	$263.03
Chassis	Acrylic	Cast Acrylic 6mm thick sheet 24"x36" White	McMaster	8505K957	45.23	1	3	$135.69
	Belt Tension Screws	Metric 18-8 SS Button Head Socket Cap Screw M4 Size, 25 mm Length, .7 mm Pitch	McMaster	92095A197	0.1398	50	4	$6.99
	Tensioner nuts	Zinc-plated steel hex nut class 6 m4	McMaster	90591A141	0.0133	100	4	$1.33
	Belt clamp screws	Metric Class 12.9 Socket Head Cap Screw Alloy STL, M2.5 Thread, 20mm Length, 0.45mm Pitch	McMaster	91290A108	0.1976	25	16	$4.94
	Belt clamp nuts	Metric Zinc-Plated Steel Hex Nut Class 6, M2.5 Size, .45mm Pitch, 5mm W, 2mm H	McMaster	0591A113	0.0133	100	16	$1.33
	6-32 nuts	Zinc-Plated Steel Machine Screw Hex Nut 6-32 Thread Size, 5/16" Width, 7/64" Height	McMaster	90480A007	0.0116	100	51	$1.16
	Tensioner Springs	Music Wire Precision Compression Spring Zinc-Plated, 1/2" Length, .48" OD, .045" Wire	McMaster	9434K113	1.022	5	5	$5.11
	Washer for tensioner	Metric Extra-Thk Black Oxide STL Flat Washer M4 Screw Size, 14mm OD, 2.5mm-3.4mm Thick	McMaster	98040A102	1.086	5	5	$5.43
	Rubber pads	Adhesive-Backed Polyurethane Bumper Flat Top, 1/2" Dia, 9/64" H, Clear	McMaster	95495K51	0.0592	50	6	$2.96
	thumb screw	#6-32 thumb screw 1/2" length	McMaster	91882A227	2.56	1	1	$2.56
	Screws to fasten acrylic	#6-32 Button head hex socket, 1/2" long 18-8 stainless steel	McMaster	92949A148	0.05	100	100	$5.00
	Extra Long screws	18-8 SS Button Head Socket Cap Screw 6-32 Thread, 5/8" Length	McMaster	92949A150	0.0503	100	51	$5.03
	Square nuts to fasten acrylic	#6-32 Flat Square Nut; Steel; 5/16inch OD; 7/64inch thick	McMaster	94855A115	0.01	100	150	$2.00
							total	$179.53

Figure 3: Model 3 Chassis and Transmission Bill of Materials

Results: Ease of Modification

The development of motor bays, allows the same chassis to be coupled to several different types of motor assemblies. In Figure 4, we see a Model 3 with servomotors and an identical chassis with a SnapMotors attached to the system. This should allow any system of reasonable sized motors and controllers with sufficient torque to interface with a Model 3 chassis.

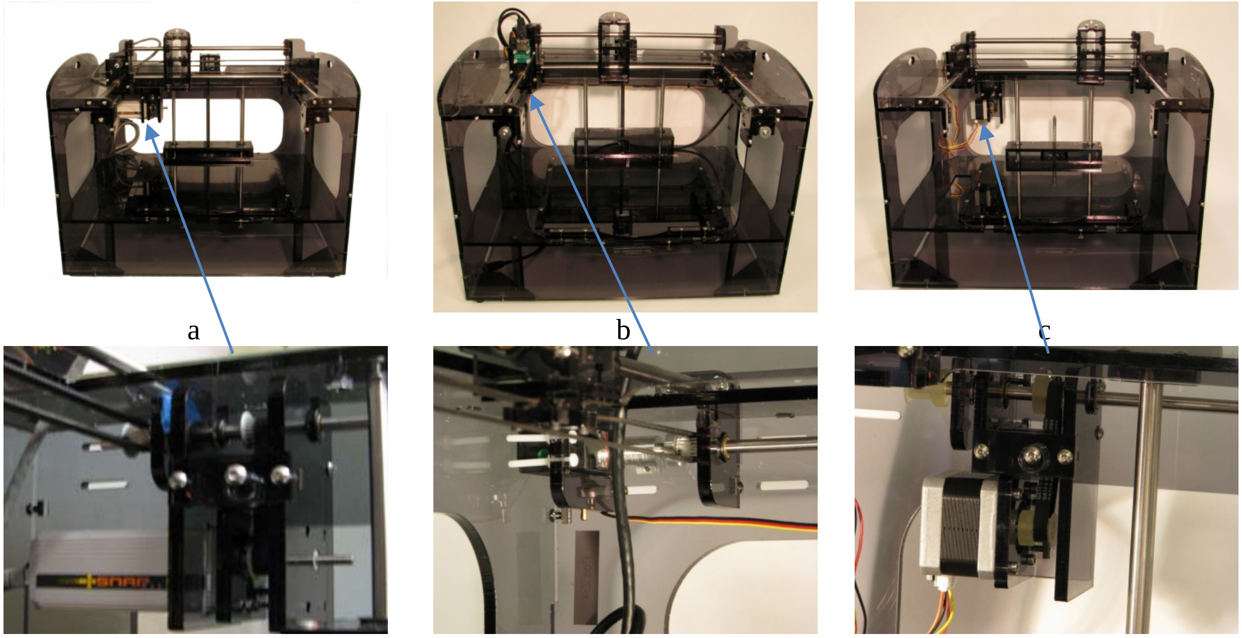


Figure 4: The Fab@Home Model 3 can be equipped with different types of motors including JrKerr SnapMotors (a)(d), servos with magnetic encoders (b)(e), or stepper motors(c)(f). This allows for a wide variety of mounting systems to connect different motors to the transmissions. Larger motors can be linked via secondary belt drives (d)(f), smaller ones can be direct drive(e)

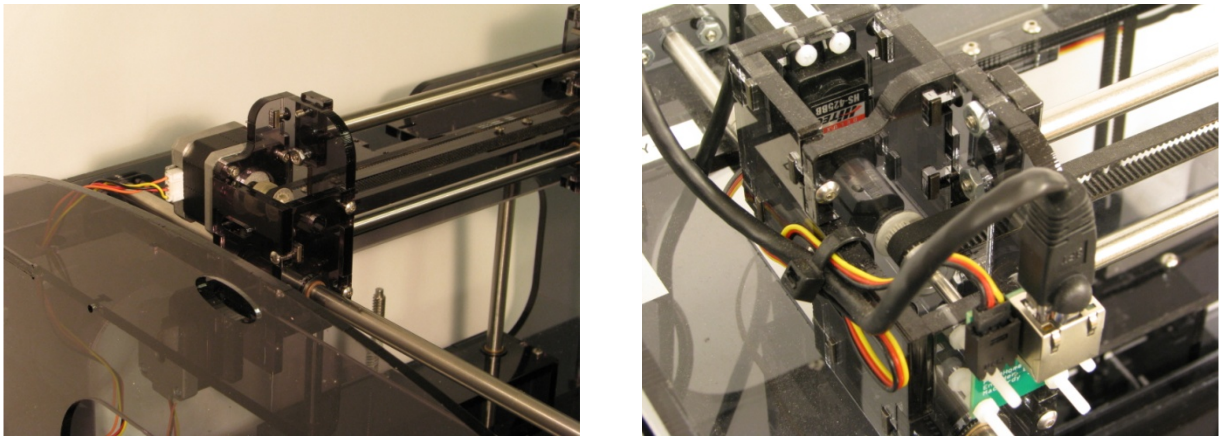


Figure 5: The Y axis of the printer can be configured for multiple electronics sets. Stepper motors(a) and servo motors(b) require slightly different y-axis configurations.

Results: Expanded Functionality

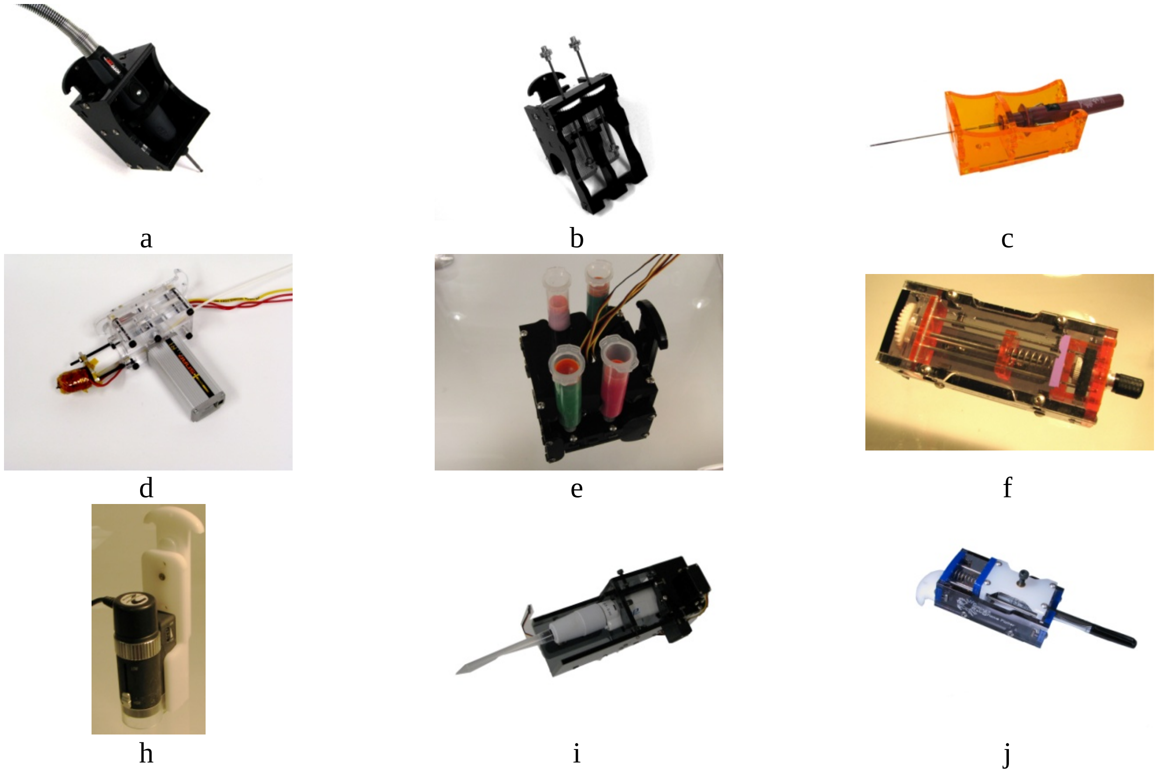


Figure 6: Tool heads which work on the Model 3 Fab@Home include: a Dremel mount (a), a dual-syringe tool(b), Foam cutter(c), plastic deposition(d), 4 material pressure driven tool(e), a vinyl cutter(f), a USB microscope(h), a pipetting tool(i), and a pen plotter(j)

The expansive variety of tool heads that are now compatible with the Fab@Home system will ensure that anyone interested in fabrication will be able to find a use for a Model 3. In figure 6 we can see nine tool heads, two of them use servos in the actuation system and would only be suitable for Model 3 system. Two of them use JrKerr Snap motors and would be compatible with Model 3 or 2. The remainders contain no onboard actuation, and are compatible with Model 2 and 3.

a b

Figure 7: Fab@School Safety additions include a Safety hood (a) which shields the user from the machine and vents the gasses from the printer through activated carbon, and added compliance in the belt drive that limits the force the machine can apply. A spring system(b) applied a tension to the belt proportional to the compression of the spring. If the driving motor applies a force greater than the springs, the spring will compress and cause the belt to skip.

The Model 3 can easily be modified to meet the safety requirement of an elementary school. The safety hood, seen in figure 7a, has been successfully fielded with students in the UVA pilot program. This system allows the Fab@Home to be the first low cost 3D printer which can be safely used in an elementary school environment. The acrylic walls prevent students from being harmed by the moving parts, and the ventilation system ensures that all of the fumes pass through activated charcoal to contain the smells from non-toxic processes. The system is hinged at all joints between the vertical walls, and the top plate latches into place, making the system very portable. The added compliance from the spring based tensioning system ensure that the system cannot apply any force over a set maximum. When the limit is reached, the spring compresses and the belts will skip rather than apply further force on the moving assemblies.

Conclusions

The Model 3 Fab@Home system is the most versatile Personal Fabricator thanks to its plethora of tool heads, its optimization for modifiability, and its low barriers to entry. The new modular motor design contributes significantly to the systems supply chain flexibility and decreased costs. The systems simplicity helped to reduce the price while lowering the technical barriers to entry and build time. Model 3 should help bring new users into the SFF user community. Educators and young children now have a machine that can meet their specific needs. It is the next step in making SFF towards ubiquitous.

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Bibliography

3D Systems. (n.d.). Retrieved 7 2, 2011, from Bits from Bytes: http://www.bitsfrombytes.com/

Evan Malone, H. L. (2007). Fab@Home: The Personal Desktop Fabricator Kit. *Rapid Prototyping Journal* , Vol. 13, No. 4, pp.245-255.

Lipton, J. I., Cohen, D., Heinz, M., Lobovsky, M., Parad, W., Bernstien, G., et al. (2009). Fab@Home Model 2: Towards Ubiquitous Personal Fabrication Devices. *Solid Freeform Fabrciation Symposium.* Austin TX.

Makerbot Industries. (n.d.). *Makerbot.com*. Retrieved 07 10, 2011, from www.makerbot.com

Open Hardware Summit. (n.d.). *Open Source Hardware (OSHW) Statement of Principles.* Retrieved 7 11, 2011, from OSHW: http://freedomdefined.org/OSHW

pp3dp. (n.d.). *UP!* Retrieved July 2011, from Personal Portable 3D Printer: http://pp3dp.com/