Fab@Home Model 2: Towards Ubiquitous Personal Fabrication Devices

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Abstract:

The open-architecture, open-source Fab@Home platform has proven to be an important system within the SFF community. In order to facilitate wider spread of the Fab@Home platform and SFF throughout the world, we aimed to improve critical aspects of the system, and business model. By changing the electronics package and streamlining the mechanics, the cost of the system was brought from $2500 to $1600. By changing the business model we hope to transform the SFF market and spur innovation.

Introduction:

Solid Freeform Fabrication (SFF) has the potential to transform the world. Personal Fabrication devices, “fabbers”, can enable the individual to manufacture complex objects on demand. Fabbers change the methods used to design, make, deliver, and use products. They eliminate the barrier to production that often stifles personal innovation. Rather than needing larger capital investment, or extensive skill sets, the end user can immediately transmute a CAD representation into a functional physical object. The fabber revolution could be as important, and transformative, as the digital revolution by allowing for the “democratization of invention”. (1) The goal of the Fab@Home project is to spark innovation and development of personal SFF systems.

The majority of SFF systems on the market today are large, expensive proprietary machines. Few are below the $20,000 mark. These high cost machines limit the spread of SFF technologies by erecting a barrier to personal ownership. They stifle innovation, by making systems technologies proprietary. The business model of most printers is similar to that of the old mainframe computers from before the digital revolution. They use a vertical business model, where a single company makes all material, hardware and software for the system. Fab@Home seeks to transform all of this, by establishing a cheap open-source platform. Rather than using a vertically integrated business model, the Fab@Home project seeks to transition to a horizontal model, similar to the modern PC era, where different companies, and make the materials, hardware, and software. (2)

Background:

The objective of the model 1 Fab@Home was to lower the cost of involvement in SFF, and encourage others to develop and invent new technologies. To this end the model 1 has been extremely successful. The cost of a Model 1 printer brought the cost of ownership to $2300 for parts. This price reduction has made it possible for individuals, schools, and startups to purchase their own printers. Printers have been deployed across several continents. (3) Several companies have formed around the Fab@Home idea and begun to manufacture and distribute them. Additionally the model 1 has helped to spark interest in the general public about SFF technologies. It attempted to make a printing system similar to the standard business model of printers; the hardware and software of the Fab@Home were integrated into a single platform.

Several limitations of the Fab@Home printer platform have presented themselves over its life. Though the printer is significantly less expensive than most commercial printers, the price mark is still a barrier for many people who are interested in the project. Since it is an open-source community backed program, a high price tag is prohibitive since there is no one to return a kit too if one is dissatisfied; trust and faith are required. Additionally the difficulty of assembly and modification has frustrated many users and hurt the projects dissemination. The community has been poorly lead, and since its inception, has not grown significantly. There has been no direction or guidance, only limited support.

The Reprap project has been extremely successful in cultivating an open source community. It has given direction, guidance, and updates to the community on a regular basis. As a result they have an active user base and community. While its high skill level requirement tends to limit the community to more technically inclined users, these users are the ones who develop and further open-source projects. Like all other printers on the market, it is based on a vertical business model. (4)

Methods: ***Hardware***

In order to improve the quality and cost of the Fab@Home system, new hardware needed to be developed. The largest cost in the Fab@Home Model 1 kit were the transmission, at $662.52, and electronics with motors ($367.78+ $610.59) (3). These systems were responsible of the limitations in quality, speed, and complexity of the Fab@Home. Complete redesign of the transmission and motors necessitated the redesign of the entire model 1 chassis system.

The Motors and electronics of the model 1 limit the system to low speeds. At higher speeds, the system begins to drift as a result of the stepper motors loosing steps. This error creates a print speed cap at 10 mm/s. There is no error correction in the system, so all errors compound. This causes long builds to be difficult. The drivers associated with this system are not perfectly stable; often the drivers will crash and require the complete restart of the host computer. The assembly of this system, ad its exposed design often intimidates would be users.

The electronics and motors were replaced with an integrated single supplier commercial system. The Snap Motor system combined the controls, amplifier, motor and optical encoder into a single unit. (5)The Cabling was accomplished by use of standard cat5 cables. The systems commercial drivers ensured support for the platform's electronics.

In order to improve the transmission, the system was switch from lead screws to timing belts, and the parts were homogenized. On the Model 1, each axis used different linear bearings , and different shafts. This increased the complexity and cost of the kit. In order to reduce complexity, the system was designed to use identical shafts and bearings for each axis. Transmission was accomplished using timing belts, pulleys and idlers. This system inherently costs less and eliminates the need to purchase an interface between the transmission and the chassis, rather that parts are made entirely from acrylic. Additionally all but one, non critical component of the system was switched to metric. This enabled a more global appeal to the model 1 since outside of the United States, standard parts are difficult to acquire.

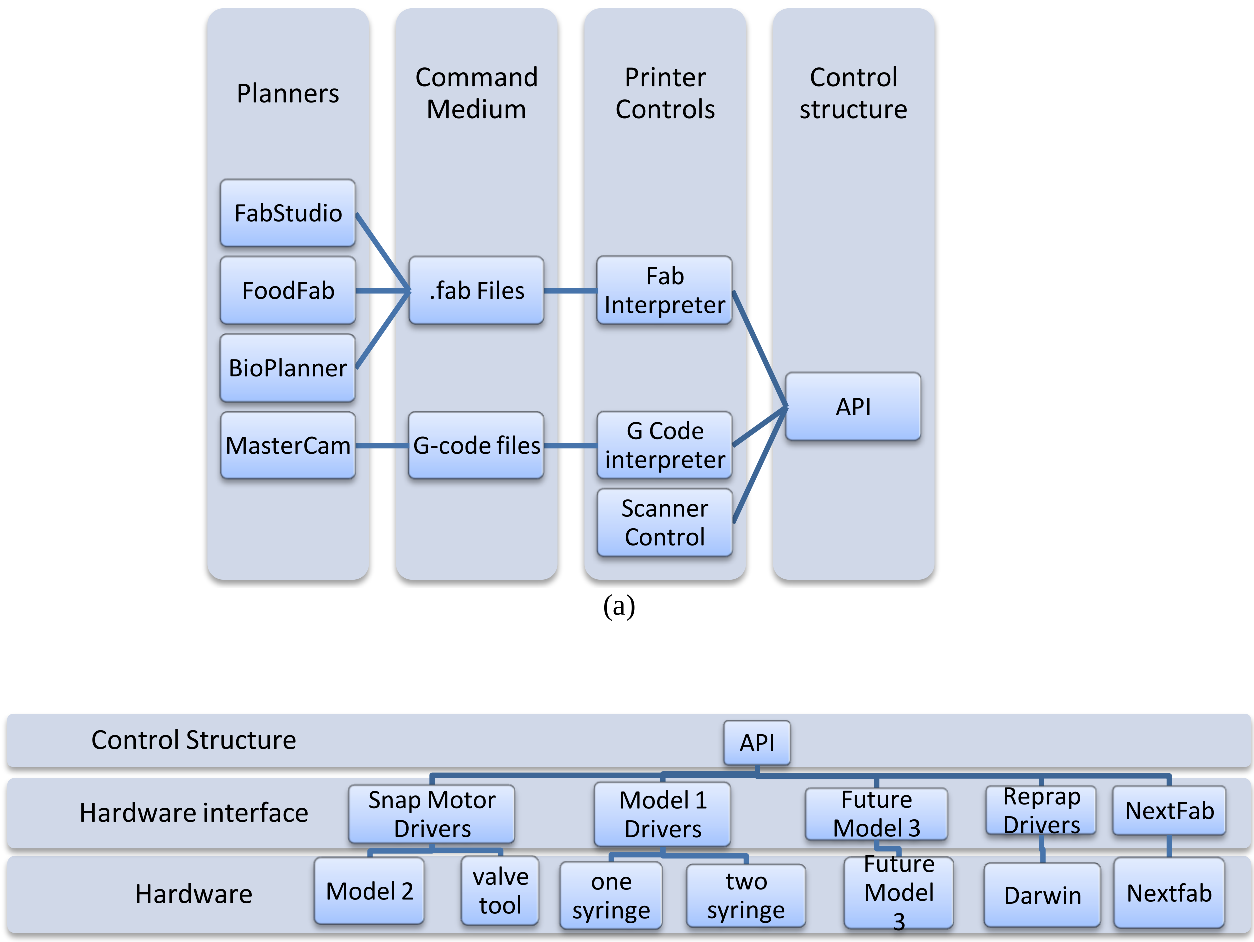
New tool heads were designed to give the printer more versatility. Aside from a traditional syringe based displacement tool. A pressure and valve based tool was developed. A pressure source forces material from the syringe reservoir at a fixed rate while the valve is open. Additionally a Dremel mount was developed for the printer.

Methods: *Software*

Redesigning the software was critical to forwarding a horizontal business model. The old system had a fully integrated print planning and printer control program. A change to any aspect of the system required extensive rewriting of the software. We sought to enable the interoperability and independent development of several layers of programming. This was accomplished by dividing the software as seen in figure 1. In order to test this model, the FabStudio, .Fab files, and FabInterpreter were created.

A ".fab" file type was designed as an XML based file which allows for the efficient transfer of commands and information. XML was selected because of its hierarchical nature and widespread usage. A ".fab" file contains relevant information about the tool, material settings, and paths in the form of tagged information. It was designed to allow future interpreters and planners to add commands and sequences that have not been predicted. XML's nature allows for parsers to ignore unknown commands. These commands may include flow control such as loops, or logical structures such as "if" statements.

The API provided with The Snap Motors was used temporarily to build the interpreter (5). This allowed for the rapid development of the initial control hardware. The interpreter allows for the operation of the Model 2 printer and can convert the information in a .fab file into commands to the printer with result in physical objects. The client program, named FabStudio, uses path planning algorithms to convert an STL, tool and material information into a .fab file. It was created by modifying the model 1 program and removing all hardware interactions.



(b)

Figure 1: The new printer control scheme(a) could enable a transition to a horizontal business model for SFF devices. If SFF systems controls could conform to a set API structure, it would be possible to separate the hardware and software entirely. Just as AMD and Intel processors do not require different operating systems, SFF software would operate any number of printers and tool heads (b).

Methods: *Community Development*

In order to encourage community growth and interest in the project, a new website was designed. The old wiki based website's visual appeal was lacking. It did not immediately draw a new user into the project. The information on the site was disorganized and often unhelpful. The new website was designed to educate and entice new users, while organizing information in useful ways for established users.

The site was divided into two main parts. The front end of the site was made as a static page powered by Drupal. (6) It was filled information and visuals that encourage visitors to become users. It was designed to be a manifestation of the guidance and leadership in the project that was lacking. The Back end of the site was made from a wiki with integrated blog and forum. Previously the wiki and forum were separate. The goal of integrating them into a single site was to encourage a sense of organization and community. The blogging was added to the website in order to encourage users to return to the site frequently, and to consolidate information about the end users activities.

Results: *Hardware*

The design of the model 2 reduced the price and build-complexity of the Fab@Home system, while increasing its aesthetic appeal. figures 3 shows various parts of the Model 2. The positioning of the motors and elimination of custom wiring, along with the reduced visual impact of the transmission gave the Model 2 a cleaner design. Table 1 shows the components and cost of the Model 2. The modification of the electronics and transmission greatly reduced the cost and number of parts.

The skills required to build a Fab@Home have been greatly reduced. In order to build a Model 2 from a kit, one needs only a hex wrench set and a soldering iron for thermoplastic inserts. One need not program a microcontroller, or strip and solder any wires since the Snap Motor system is preprogrammed and uses cat 5 cables.

The optical feedback eliminated drift provided that the transmission is properly tightened. A single encoder count corresponded to 0.006 mm of travel in the x direction, 0.0035 mm in y, and 0.0036mm in z. The error correction built into the motors allowed for the system to automatically return the system to its proper position after an error was induced by exerting a force on the deposition tool during a print.

The printer has been successfully used with a top movement speed of 100mm/s with an acceleration of $100mm/s^2$. This is a significant improvement over the maximum speed of the model 1 at 25 mm/s theoretically, and 10mm/s in practice. Objects have been printed on the Model 2 at twice the build speed of the Model 1. The speed ceiling of the Model 2 appears to be at 20mm/s during a print, though with further refinement it may go higher.

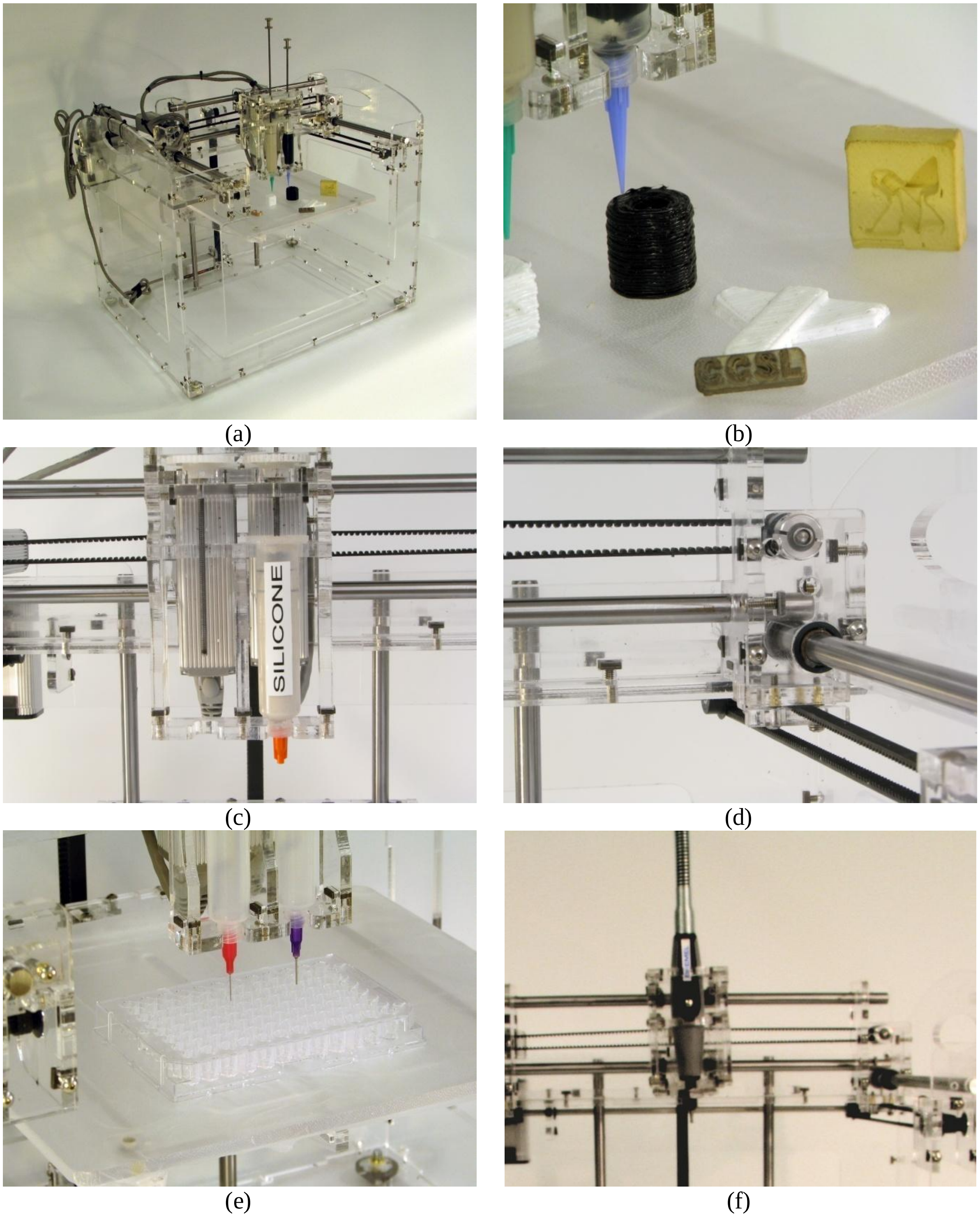


Figure 2: The model 2 Fab@Home (a) comes with a two syringe displacement based deposition tool (c) , and uses the same shafts and bearings(d). The machine is multi use since it can be used as a bio experimentation platform, using standard tool heads, (e) or as a CNC machine by attaching a Dremel mount (f).

Item	Description	Purchase from	Product #	Cost Per Unit	Min order	Quantity	Sub Total
x guide shafts	10 (-.005/-.014) mm Dia, 375mm Long, 416 ST. Steel Shaft	SDP/SI	S40PX0MHGAM-375	25.02	1	2	50.04
y/z guide shafts	10 (-.005/-.014) mm Dia, 300mm Long, 303 ST. Steel Shaft	SDP/SI	A 7X 1M100300	19.11	1	4	76.44
guide shaft bearings	Self Lubricating Bronze Bearing 10.02mm Bore 15.9mm Panel Hole diameter	SDP/SI	A 7Z41MPSB10M	1.53	1	12	18.36
drive shaft	6 (-.004/-.012) Dia, 400mm Long, 303 ST. Steel Shaft	SDP/SI	A 7X 1M060400	10.47	1	1	10.47
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	GT2 (3mm) Pitch, 18 Teeth, Polycarbonate timing pulley	SDP/SI	A 6Z53M018DF0906	5.19	1	2	10.38
idlers and y/z pullies	3mm (HTD) Pitch, 10 Teeth, Polycarbonate timing pulley	SDP/SI	A 6Z23M010DF0904	4.29	1	6	25.74
Ball bearings	Flanged- no sheild ball bearing. 4mm Bore Dia. 8mm Outer Diameter, Stainless/ISO 6, Beacon 325 Lubrication	SDP/SI	A 7Y 5MF0804G	8.33	10	10	83.3
X axis coupler	Rigid Coupling with bores of 4 / 6MM on Opposite Sides	SDP/SI	A 5X 9M0406	8.91	1	1	8.91
idler & support shaft	4 (-.004/-.012) Dia, 35mm Long, 416 ST. Steel Shaft	SDP/SI	S40PX0MHG4M-035	4.24	6	6	25.44
z belt	GT2 (3mm) 600mm 9mm wide	SDP/SI	A 6R53MC090	12.07	1	1	12.07
xy belt	GT2 (3mm) 600mm 6mm wide	SDP/SI	A 6R53M200060	18.4	1	2	36.8
Acrylic	24" x 24" 6mm thick extruded Acrylic	McMaster	8589K83	26.94	1	6	161.64
Belt clamp Screws	Metric 18-8 SS Button Head Socket Cap Screw M4 Size, 16 mm Length, .7 mm Pitch	McMaster	92095A194	0.0994	100	24	9.94
normal inserts	Metric Brass Threaded Insert for Thermoplastc Tapered, M4-.7 Internal Thread, 4.7mm Length	McMaster	94180A351	0.1278	100	24	12.78
base pad inserts	1/4-20 brass threaded inserts; 0.3inch length	McMaster	93365A160	0.3332	25	4	8.33
base pad	Rubber Foot; 1/4-20 X1/2inch thread; 1inchdiameter 25lb rated	McMaster	9377K53	1.36	1	4	5.44
Screws to fasten acrylic	#6-32 Button head hex socket, 1/2" long 18-8 stainless steel	McMaster	92949A148	0.0497	100	130	9.94
Square nuts to fasten acrylic	#6-32 Flat Square Nut; Steel; 5/16inch OD; 7/64inch thick	McMaster	94855A115	0.01	100	130	2
Motor mounting screws	M2 Hex Socket 10mm length .4mm pitch 3.8 mm head	McMaster	91292A011	0.0381	100	20	3.81
plunger rod	Metric Class 4.6 Plain Steel Threaded Rod, M3 size, 1 meter length, .5 mm Pitch	McMaster	98861A040	1.57	1	1	1.57
plunger connector	Metric 18-8 SS Round Knurled Thumb Nut, M3 screw, 12mm Head Dia, .5mm Pitch	McMaster	90368A150	1.62	1	10	16.2
gear on syringe drive	6mm bore, 28mm pitch dia. 16mm hub dia.	SDP/SI	A 1P 2MYD08035D	8.53	1	2	17.06
gear on tool motor	4mm bore, 28mm pitch dia. 16mm hub dia.	SDP/SI	A 1P 2MYD08035B	8.53	1	2	17.06
material drive bearing	mm Bore, 6mm Outside Dia., 440C Stainless / ISO 6 Ball bearing, lube with Grease (Beacon 325)	SDP/SI	A 7Y 5MFSS0603G	14.12	1	2	28.24
Motors	SM062 motor	JRKERR	SM062	160	1	5	800
Hub	snap hub (SM-HUB6)	JRKERR	SM-HUB6	160	1	1	160
						Total	**1615.92**

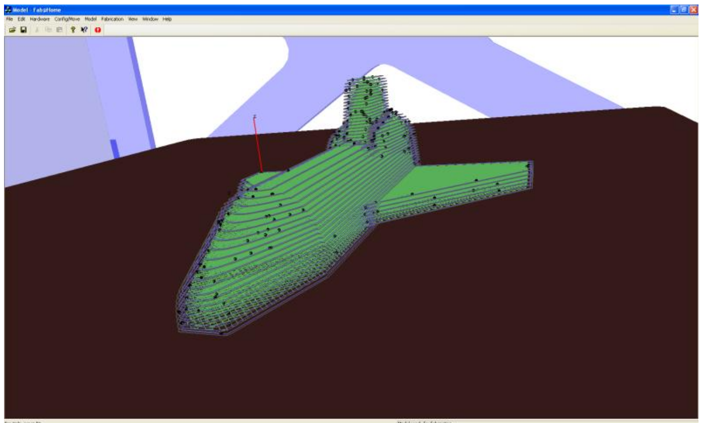
Table 1: The parts list with prices for the current version of the Model 2 Fab@Home printer

Printer Metric	Model 1	Model 2
# parts	484	415
# part types	90	26
chassis Cost (USD)	651.73	213.88
Electronics cost (USD)	978.37	960
Transmission cost (USD)	662.52	442.04
Theoretical speed (mm/s)	25	134.16
Actual Jog speed (mm/s)	10	100
Maximum print speed (mm/s)	10	20
Maximum theoretical resolution (mm) x/y/z	0.015 / 0.015 / 0.015	0.006 / 0.0035 / 0.0036

Table 2: Comparison of printer metrics between model 1 and 2.

Results: *Software*

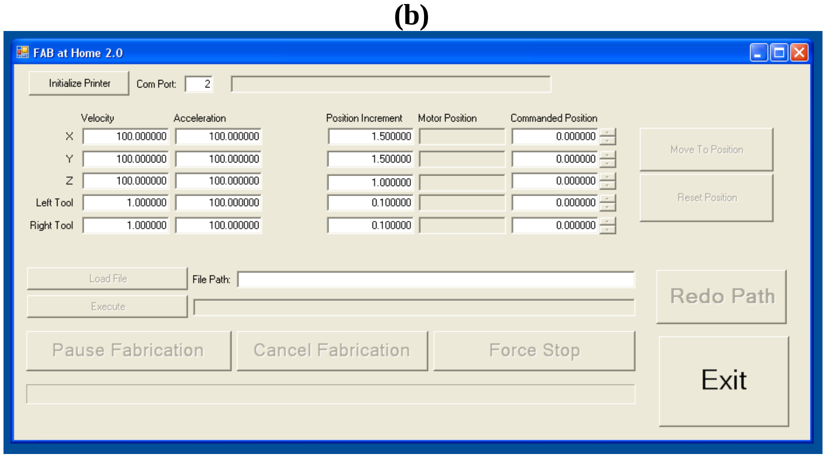
The stratification of the software was successful. The planner has created dozens of .fab files. These files were stored to allow for instant access by the interpreter. A standard text editor can be used to edit the paths and print parameters generated during planning. This has been used as a mean of error correction. Occasionally the planner will add unnecessary paths, or paths that are too small, and manual editing can correct planning errors. The interpreter was used to convert .fab files into objects.



(a)


```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>
<fabAtHomePrinter>
    <tool>
        <!--Name of the tool.-->
        <name>10ccGreenTaper-ClearSilicone.tool</name>
        <!--Top speed in millimeters/second for this tool during execution of path.-->
        <pathSpeed>10</pathSpeed>
        <!--Width of the path in millimeters.-->
        <pathWidth>0.8</pathWidth>
        <!--(millimeters of plunger motion)/(millimeters tool travel) along deposition path.-->
        <depositionRate>0.0035</depositionRate>
        <!--Seconds of early dispensing to start flow quickly.-->
        <pushout>0.2</pushout>
        <!--Seconds reverse plunger motion to stop flow quickly.-->
        <suckback>0.13</suckback>
        <!--Seconds to delay suckback by.-->
        <suckbackDelay>0</suckbackDelay>
        <!--Millimeters of clearance between tip and last layer when traversing.-->
        <clearance>2</clearance>
        <!--Number of paths after which to trigger an automatic pause.-->
        <pausePaths>30</pausePaths>
        <!--no comment-->
        <pitch>0.000397</pitch>
    </tool>
    <path>
        <!--The name of the tool that executes the path.-->
        <executeToolName>10ccGreenTaper-ClearSilicone.tool</executeToolName>
        <point>
            <x>14.6</x>
            <y>14.6</y>
            <z>0.7</z>
        </point>
```


(b)



(c)

Figure 3: The Fab@Home control software has been divided into a two independent pieces of software, the planner, FabStudio (c), and the controller call FabInterpreter (a). These communicate via .fab files (b).

Results: *Community Development*

The new site successfully provides a visually appealing lure which draws users to the project. Figure 5 shows the sitemap of the website. All front pages are used to connect visitors with the relevant information on the wiki, and discussions on the forum. The site has not gone active yet, and is still under construction.

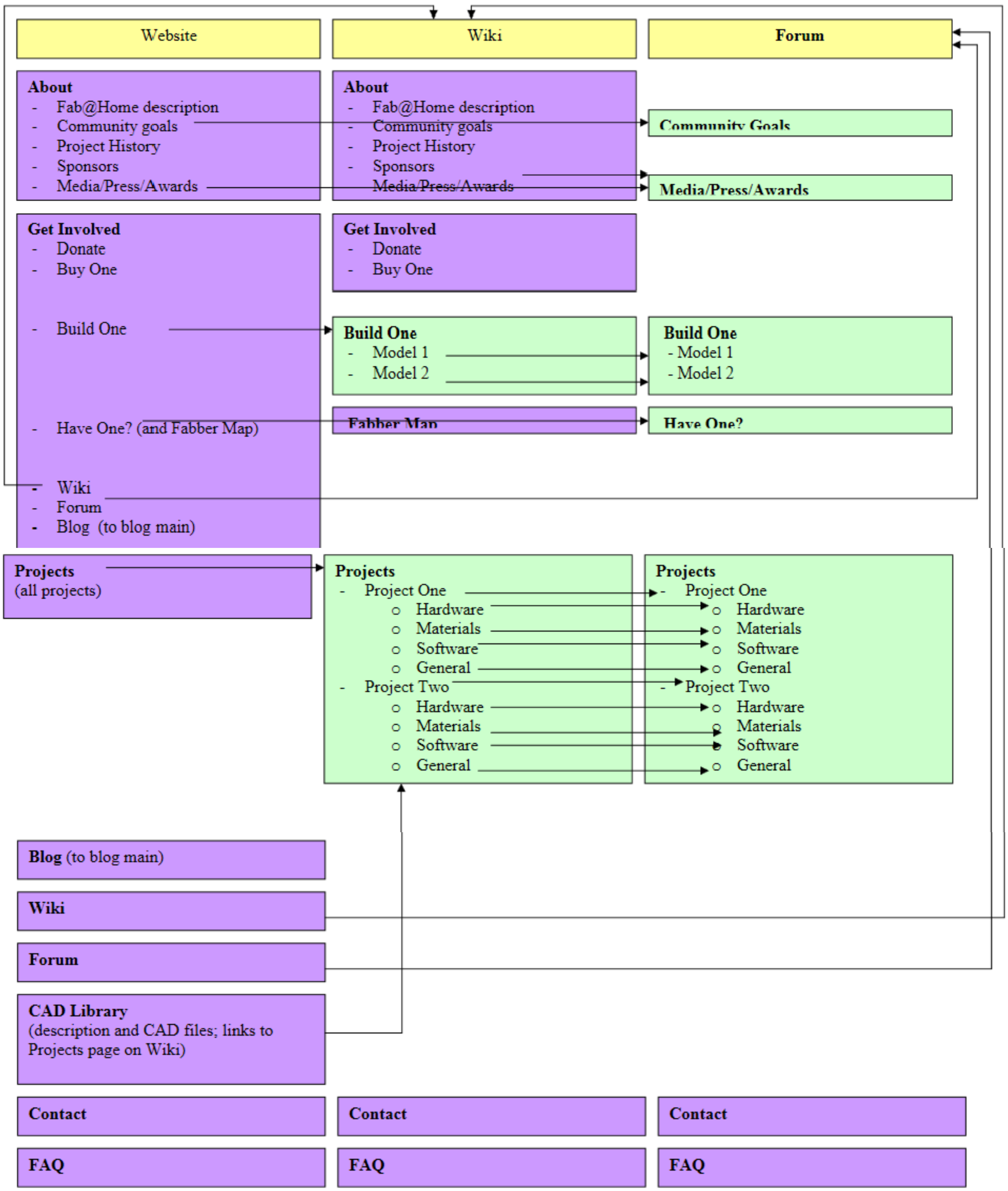


Figure 4: The sitemap for the Fab@Home community was designed to attract new users and guide the project. Arrows represent links.

Discussion:

The transition to a horizontal business model for SFF devices began of the Fab@Home system with model 1. The syringe based deposition tool used on the model 1 allowed any material to be extruded. Kraftmark is an independent materials supplier who invented two different types of materials for 3d printers. (7) One of which, FabUno^tm is provided in the standardized syringe container. Had Kraftmark sought to innovate on printing materials prior to the model 1, they would have need to invent and entire printing platform. The separation and standardization of the Fab@Home software allows each aspect of the software to be developed independently, provided it follows interaction standards.

The FabStudio and FabInterpreter programs demonstrate the ability to separate the development of printer controls from print planning. The Fab@Home has been used in biological experiments, cake decorating and SFF. Each of these uses could benefit from different planning programs, algorithms and commands, but could use the same control software. Future standardization of software hardware interactions would enable interoperability of printers. Ideally corporations, individuals, and other open source groups would develop the separate aspects of the printing process.

While the new software and business model will remove the barriers to innovation once involved in SFF, the Model 2 printer will remove the barriers to involvement. The key barriers to involvement are price, skill level, and belief in usefulness. The price reduction from the chassis and transmission redesign will enable more individuals and corporations to invest in SFF technologies. The newly designed motor and electronics system reduces the skill level needed. The Dremel attachment will ensure a minimal usefulness level to the system. Engravers and CNC mills are a well established field. People understand their usefulness. By incorporating this functionality into the device, people will have confidence to invest in a printer for personal use. A strong community will give people confidence in the longevity and support for their investment in SFF devices.

Future Work:

Working towards personal fabrication devices will demand a great deal of effort. The next step for the Fab@Home project is to develop a support infrastructure based in Cornell University and around the world. An undergraduate project team should be created in order to provide support and constant innovation to the Fab@Home project. Using the resources of a project team and a resuscitated community new tools and software, and hardware should be developed. This will include a filament based deposition tool to enable plastic printing similar to Reprap and other low cost printers. Additionally, higher capacity reservoirs based around a valve powered tool to encourage extended use of a printer to create large objects. A custom electronics and motor option should be created. While this would deviate from the Fab@Home projects use of exclusively off the shelf parts, it would help reduce the entry cost for experienced users and commercially deployed machines. A new independent API standard should be developed in collaboration with other open-source printers to encourage standardization and stratification of SFF device development.

Conclusion:

The spread and advancement of personal fabrication technologies requires that barriers to ownership and innovation be dramatically degraded. In order to accomplish this, a new printer, and business models, and revitalized community were needed. The new printer design greatly reduces the price and skills level barriers while improving technical performance. The new website will help translate interest into participation in the community. By standardizing hardware and software interactions, innovations in any aspect of printing technology can be instantly transferred across all printer platforms. Together these advancements forward us towards ubiquitous personal fabrication.

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Works Cited

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