Object Augmentation for the Visually Impaired Using RP

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Abstract

We demonstrate the application of rapid prototyping technology to augment every-day objects for the visually impaired. A freeform fabricator was used to print a tactile alphabet on multiple surfaces including paper, plastic, and metal. We have identified and experimented with multiple non-toxic materials and analyzed the dimensional tolerance, repeatability, and adhesion characteristics on multiple surfaces. Printing time for 1x1cm embossed letters varied from 14 to 52 seconds. More broadly, these experiments open the door to RP applications that involve custom product adaptation to address disabilities.

Introduction

The goal of this research project was to explore the use of freeform fabrication to augment everyday objects in a way increases their accessibility to the visually impaired. Freeform fabricators, also known as 3D printers or rapid prototyping (RP) machines, are devices that build 3D objects a layer at a time through the sequential solidification of material at points within that layer. There are many ways in which Rapid Prototyping technology could be applied to alleviate difficulties resulting from disabilities. Previous work has explored the use of rapid prototyping technology in surgery (Muller et al., 2003), diagnosis (Kacl et al., 1997), and prosthesis development (Popovic et at., 2001, Lee & Wu, 2003, Tie et al., 2005). This is in line with the traditional view of RP as a way of producing objects *de novo*. Here we propose the use of rapid prototyping technology *in situ* to modify, extend, and label everyday objects in ways tailored to address the specific needs of a person with a disability. For example, it is possible to change or extend the shape of a handle to make an object easier to grasp or manipulate, or to modify other household items to be safer to use or be more easily accessible for a person with limited reach. Other objects may be made to be more visible, less confusing, or more distinguishable from surrounding objects. Such augmentations may prove to be increasingly beneficial as the cost and accessibility of RP systems improve to the point where they are readily available for home use.

In this paper we address the problem of labeling everyday objects such as canned food, books, or switches for the visually impaired. One promising solution to this problem is to use a rapid prototyping machine capable of printing tactile text on various surfaces. Using an appropriate tactile text alphabet, such as the *ELIA Tactile Alphabet*, the printed labels can be read visually or by touch with minimal training. By enabling the blind and those with low vision to label and identify items required for their activities of daily living (ADLs) and instrumental activities of daily living (IADLs), and to access printed text and graphics, this technology may significantly increase their independence as well as their opportunities for employment and leisure activities.

This study was performed on the Fab@Home platform (Malone & Lipson, 2007). The goals were to examine the ability of this platform to print in multiple non-toxic materials on multiple surfaces and characterize the resulting prints. Specifically, we set out to evaluate the dimensional tolerance, repeatability, and adhesion characteristics of letters of various sizes printed using different materials. In order to print the ELIA alphabet, an extension to the previously-existing Fab@Home open-source software was also required to allow the parsing of vector graphics files into the Fab@Home internal representation. Finally, using this conversion software, we aimed to develop a library of import files for printing the ELIA letters as well as a tool to combine these letters into specified sentences.

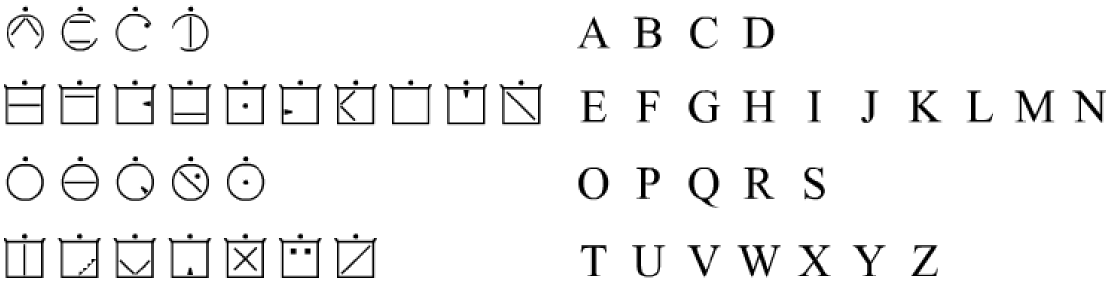
Background

Prevalence of visual impairment

The U.S. Census Bureau estimates that there are 7.9 million people in the United States with a visual impairment, of whom 1.8 million are severely visually impaired (unable to see) (Steinmetz, 2006). Additionally, there are approximately 505,000 new cases of visual impairment per year (McNeil, 1996), a growing percentage of which are elderly. However, less than 4% of those who are severely visually impaired know Braille (Russel and Hendershot, 1997), and adults have a much more difficult time learning Braille than children (Millar, 1994). Thus there is a great demand for a method of labeling everyday objects with tactile text that anyone with a visual impairment would find easy to read.

ELIA Tactile Alphabet

The ELIA Tactile Alphabet (Figure 1a) is a modified alphabet from the Roman Alphabet (Figure 1b) designed specifically for visually impaired people who were previously sighted and learned the Roman Alphabet. Each letter of the ELIA Alphabet uses the major features of the Roman Alphabet design in order to make learning quicker and more effective than if it had no resemblance. Additionally, the ELIA letters are framed with either a square or a circle, which aids the blind reader to orient the letters and read quickly. Research has shown that the ELIA Tactile Alphabet is easier to learn than both Braille and a raised Roman Alphabet (Chepaitis et al., 2004).



(a) (b)

Figure 1. (a) ELIA Alphabet and (b) Roman Alphabet: Features in each ELIA letter are taken from the Roman Alphabet to create a resemblance. Circular and rectangular frames aid the reader in orienting the letters.

The Fab@Home Platform

The Fab@Home Model 1 (Figure 2) uses a three-axis positioning system composed of threaded rods and motors. The printer head rests on these rods which enable it to travel in the *x*, *y* and *z* directions. Combinations of these directions allow the printer head to travel in any path. The printer head contains two deposition tools, which are plastic syringes with pointed tips. In each tool, a linear stepper motor drives a rubber piston down the syringe to deposit the material inside. The printer is no bigger than a microwave, measuring 18.5” by 18.0” by 16.0”. The small size and portability of the Fab@Home makes it to be a convenient desktop device. With a simple USB connection, it can easily attach to a computer and operate like any other printer. The printer software imports STL files and emulates the printing process on the monitor. Parameters for printing can be adjusted for different materials by modifying material files that are integrated into the software, controlling parameters such as deposition rates, extrusion delays and suckback timings.

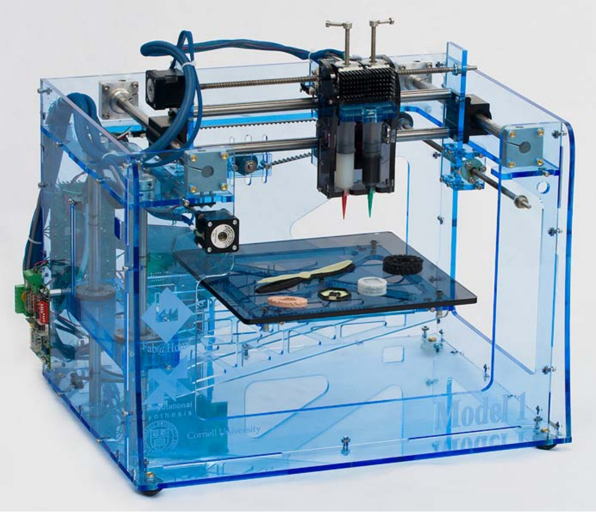


Figure 2. Fab@Home Model 1: An open source multi-material RP system allows direct experimentation with a variety of materials.

Experimental Methods

Before implementing the printing process using the Fab@Home, we manually extruded four different materials: WindowArt – an arts and crafts product by Klutz; GE black silicone – a caulking material for windows and doors; GE white silicone – a caulking material for kitchens and bathrooms; and Crayola’s 3D squeezable paint. These materials were applied on different surfaces that would potentially be used in the printing application, such as paper, cardboard, and tin cans.

In order to start printing letters using the Fab@Home printer, an STL file was needed. We created the ELIA Alphabet letter “e” using a CAD system, designing the letter to be 1cm wide and 1.2 cm high. The thickness of the lines was to be 1 mm throughout the letter. With some experimentation, we found the STL files to be inefficient in printing letters because they required the printer to create an outer contour of the object, resulting in a minimum of two passes. Therefore we modified the printer software to be import and process vector files that contains seuqnces of *x*, *y*, and *z* coordinates, in millimeters, corresponding to paths of multiple points. The printer then prints lines to connect these points in the order in which they are written. A blank line in the text file designates the end of path and start for the next path. Vector files were much more convenient for printing letters because they allowed printing in a single pass an more diret control over letter formation.

After creating a library of vector files for each ELIA letter, we programmed a utility to convert a string of text into vector files. This allows the user to type a word or phrase into the program which then outputs a single vector file to be imported into the printing software. This tool also gives the user the option to print the desired string in 1, 2 or 3 layers to create letters of various heights.

Results

Testing of Manual Extrusions

Through manual extrusions, we tested the consistencies, drying times and surface contact performances of the materials and their compatibilities with different surfaces (Table 1). The materials were loaded into syringes with rubber pistons. Instead of using the linear stepper motor from the printer to push out the material, we inserted a plastic rod and manually pushed the piston down to write out the text by hand. The material was written on paper, finished cardboard, Styrofoam, plastic bottle caps and metal cans. These experiments showed that the WindowArt and 3D squeezable paint dried significantly faster than the black and white silicone. The WindowArt and 3D Squeezable Paint both took approximately 5 minutes to dry while the black and white silicone took 30 to 60 minutes.

Material	Approx. Drying Time (min)	Contact Performance
WindowArt	5	Good except with external paper surfaces
3D Squeezable Paint	5	Good on all five surfaces
Black Silicone	30-60	Good except on Styrofoam
White Silicone	30-60	Good except on Styrofoam

Table 1. Performance of Different Materials: By manually applying different materials on a sheet of paper, data for drying time and evaluation of surface contact was collected.

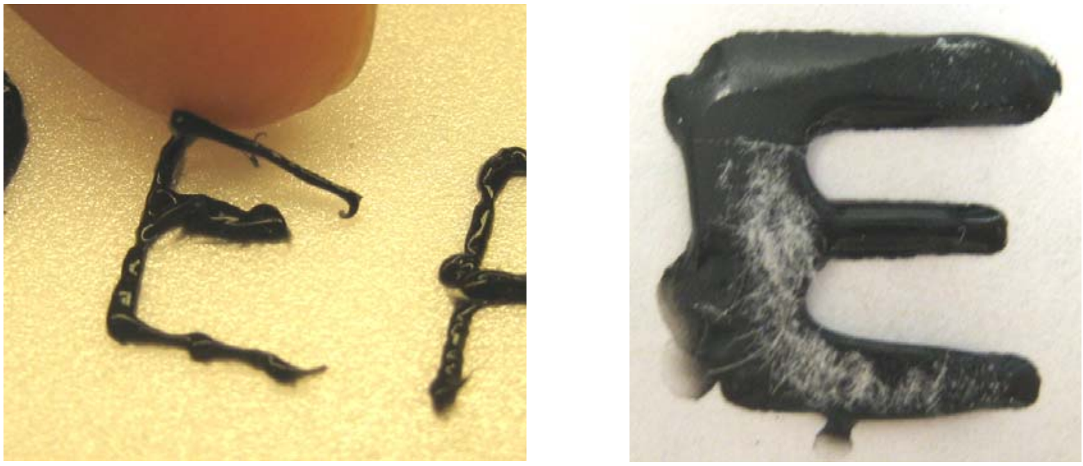
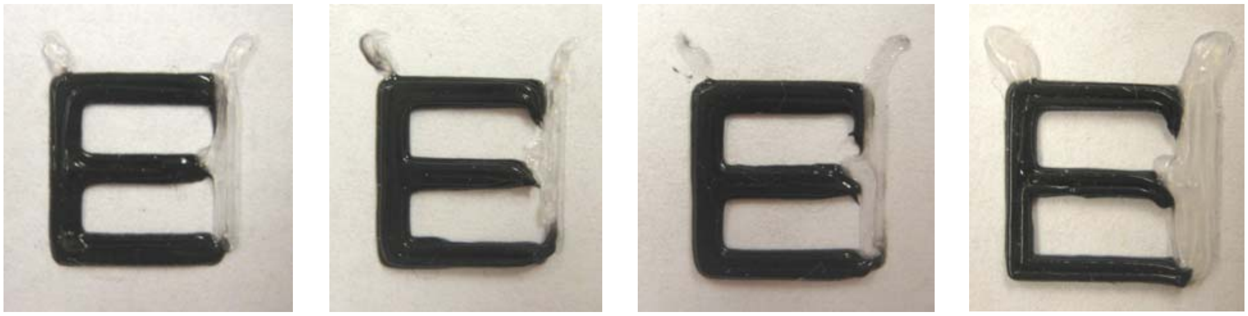

(a) (b)

Figure 3. Durability Issues: (a) Black Silicone on Styrofoam – After weeks of sitting on a Styrofoam surface, black silicone started to peel easily. (**b) WindowArt–paper Contact Performance:** Although fully dried, WindowArt sticks to paper and results in a fuzzy surface, compromising the function of the letter.

The WindowArt and 3D squeezable paint extrusions were more rigid than the silicones, which had a soft rubbery texture. Initially, all the materials had good contact with the different surfaces after drying – even under conditions of the paper being rolled. The other surfaces were not distorted in any way. However, after a month, the black and white silicone did not maintain contact with the Styrofoam and started to peel off the surface due to slight touches (Figure 3a). Another problem that was detected over time was the prolonged sticky effect of WindowArt. Even fully dried, if the WindowArt came in contact with paper – for example, paper lying on top of a printed letter – it stuck to the paper, leaving paper fibers attached to the WindowArt (Figure 3b). This presents a challenge in using WindowArt as a printing material especially in cases where printed pages are piled on top of each other.

STL Files

Using an STL file, we printed the ELIA letter "e" using black silicone and white silicone. We used both materials for one letter in order to create a letter that could be easily read by both for those familiar with either the ELIA or the Roman alphabets. To tune the parameter *DepositionRate* of the black and white silicone, we printed multiple trials of the letter "e" (Figure 4). Comparing the measurements of the different parameters of the letter (Table 2), we concluded that the optimal deposition rate is .0010 mm/s for black silicone and .00083 mm/s for white silicone.



(a) Trial 1:
Black = 0.0015 mm/s
White = 0.00083 mm/s

(b) Trial 2:
Black = 0.0010 mm/s
White = 0.00083 mm/s

(c) Trial 3:
Black = 0.0010 mm/s
White = 0.0093 mm/s

(d) Trial 4:
Black = 0.0010 mm/s
White = 0.0093 mm/s

Figure 4. Double-Pass Trials: The ELIA letter "e" was printed with various black and white silicone deposition rates

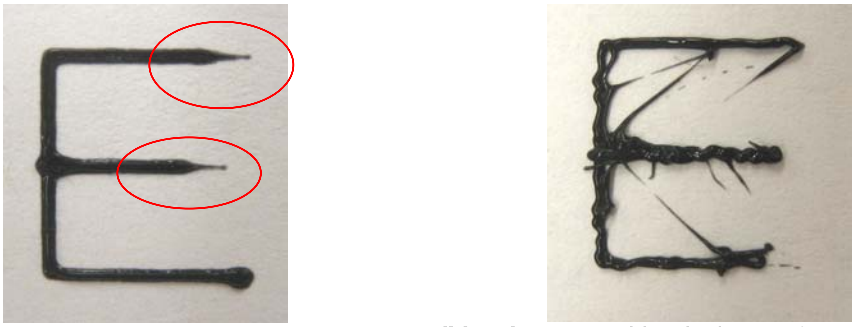
Trial	Silicone Deposition Rates (mm/s)		Width (mm)	% Error	Length (mm)	% Error	Height (mm)	% Error	Thickness (mm)	% Error
	Black	White								
Design	N/A	N/A	10.3	N/A	12.3	N/A	1.0	N/A	1.3	N/A
1	.0015	.00083	10.5	1.94	12.6	2.44	0.5	50.00	1.5	15.38
2	.0010	.00083	10.4	0.97	12.9	4.88	0.8	20.00	1.5	15.38
3	.0010	.00093	10.2	0.97	13	5.69	0.7	30.00	1.2	7.69
4	.0010	.00093	10.8	4.85	13.4	8.94	0.8	20.00	1.0	23.08

Table 2. Deposition Rate-Tuning Measurements: Measurements were taken for different combinations of deposition rates for black and white silicone.

Vector Files

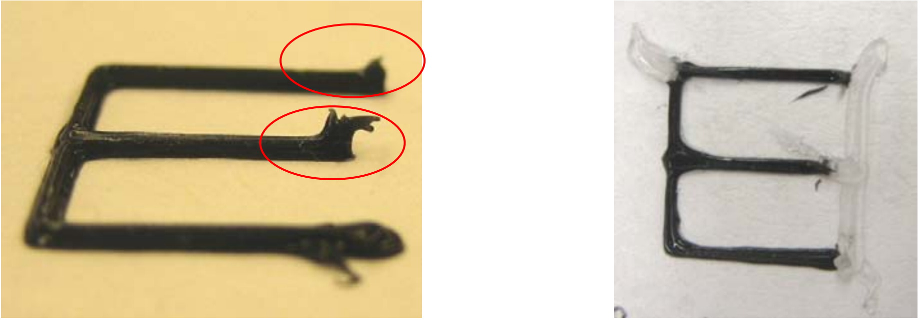
Vector files significantly improved the overall quality of the letters. Since they only required a single pass in creating a path, the lines were cleaner and thinner. In this section we discuss various experiments we conducted to tune the various parameters for printing using vector files.

We printed multiple trials of the Roman letter “e” to find the optimal set of parameters for single pass (Figure 5). Dimensions of the letter were set identically to the ones used in the STL files. In Trial 1, we used the optimal deposition rate that was found in the previous section for black silicone. However, another parameter that needed tuning was the *SuckbackDelay*, which is a parameter that delays *suckback*. Suckback causes reverse plunger motion to stop flow quickly after each path is printed, eliminating problems such as material dripping out of the syringe tip after it leaves the surface. Because the suckback begins while the tip is still printing the end of a line, *SuckbackDelay* is needed to delay the suckback until the appropriate time. Without delaying suckback, the print resulted in unfinished lines (Figure 5a).



(a) Trial 1: No suckback delay resulted in thinning ends at termination of paths.

(b) Trial 2: Suckback delay of 0.2 seconds was too long, resulting in continued flows during path changes.

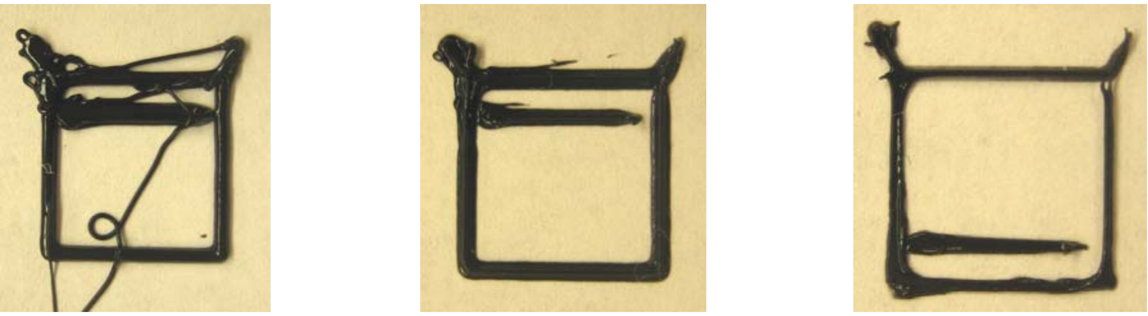


(c) Trial 3: Suckback delay of 0.1 seconds improved the print from Trial 2 but still created messy finished tips.

(d) Trial 4: Suckback delay was decreased further to 0.15 seconds, which showed better finished tips.

Figure 5. *SuckbackDelay* Parameter Testing; Suckback delay of 0.15 seconds was found to be close to optimal.

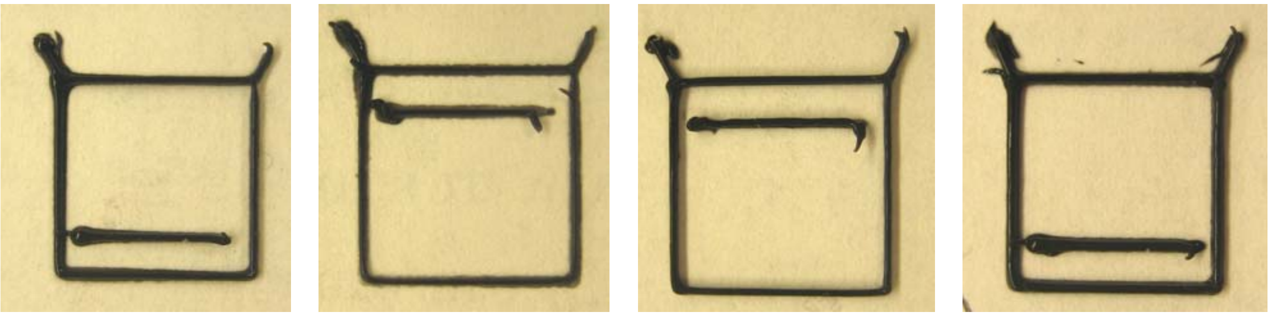
A second parameter *Suckback* determines the volume pulled back at the end of a stroke. The *Suckback* parameter *was* adjusted on a few ELIA letters while *SuckbackDelay* was also further tuned (Figure 6a-f). Additionally, the ELIA letter “h” was printed in three layers but with different path routes (Figure 6g). The first path route was similar to the path routes of trials 1-6. The second route printed the lines in reverse motion from the first. Finally, the last layer was printed identical to the first layer. This alternation of path routes with each run improved the uniformity of the lines; instead of tapering out towards the finishing tips, as seen in trials 1-6, trial 7 produced a more uniform height and width.



(a) Trial 1
Suckback = 0.20
SuckbackDelay = 0.10

(b) Trial 2
Suckback = 0.25
SuckbackDelay = 0.10

(c) Trial 3
Suckback = 0.25
SuckbackDelay = 0.12



(d) Trial 4
Suckback = 0.25
SuckbackDelay = 0.13

(e) Trial 5
Suckback = 0.25
SuckbackDelay = 0.15

(f) Trial 6
Suckback = 0.25
SuckbackDelay = 0.20

(g) Trial 7
Alternating path route
with each layer

Figure 6. *Suckback* and *SuckbackDelay* Testing: (a-f) After many trials, the optimal setting for *Suckback* and *SuckbackDelay* were found to be 0.25 and 0.13 seconds, respectively. **(g)** Alternating path route with each layer improved the ELIA letter h's uniformity.

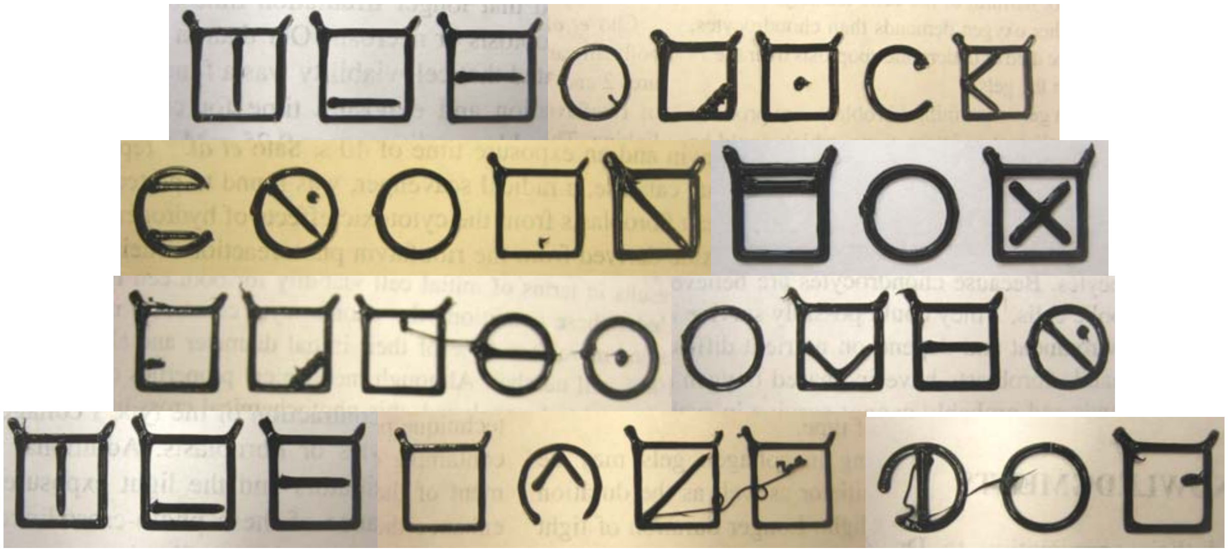


Figure 7. The Quick Brown Fox: The famous pangram is used to test the letters of the ELIA Alphabet.

All the letters of the ELIA Alphabet were printed in black silicone using the 0.10" diameter red-tapered precision tip and were tested by printing the famous pangram "The quick brown fox jumps over the lazy dog" (Figure 7). In order to print all of the ELIA letters, there were some challenges to overcome. First, letters that contain a dot in their designs were not being printed properly because the silicone could not be extruded fast enough for a single point. These letters included *c, i, r, u,* and *s*. This problem was solved by changing the single coordinate to four coordinates in the shape of a diamond. As seen in Figure 8, the word “circus” is written with clearly printed dots.

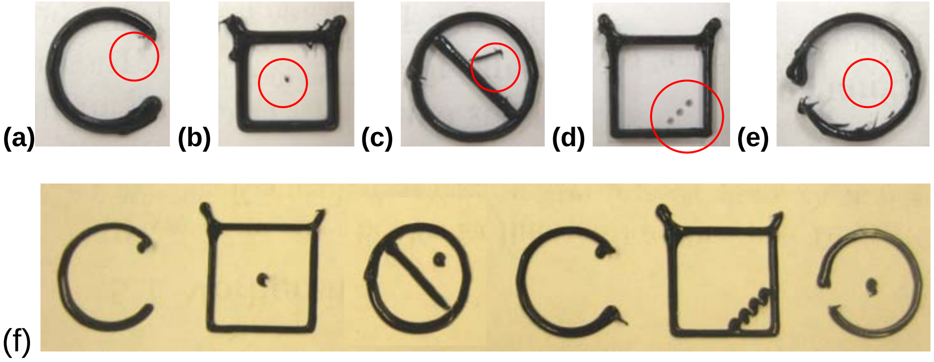


Figure 8. Dot Letters: Letters that contain dots had poorly printed or no dots (a-e). Using diamond-shaped prints in place of single points, we can write “circus” with clear dots (f).

A second challenge was that the letters *d*, *m*, *n*, *q*, *u*, *w* and *y* were being printed with an unusually large amount of material. After multiple trials, it was evident that this problem was not due to the position of the letters or bad timing as these letters were consistently being printed poorly. Attempts to fix this problem were made by changing the path route and path speed. None of these attempts were successful. Another attempt was made by rewriting the code for the printer software. The new printer software code recalculated the *pushout* and *suckback* parameters—two parameters that were suspects for causing the glitch in the system. This solved the problem and the trouble letters now printed normally (Figure 9).

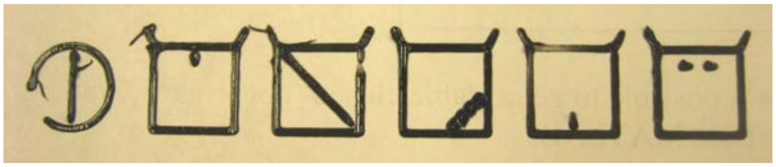


Figure 9. Improved Problem Letters: Letters *d, m, n, q, u, w,* and *y* are improved with the new printer software code. The letters are now printed with a normal amount of material.

Repeatability

To test the repeatability of the letters, an experiment was conducted in which letters *a* through *h* were printed twelve times each (Figure 10). This test proved that each letter – even the previously-mentioned problem letters such as *d* – printed in a very consistent matter.

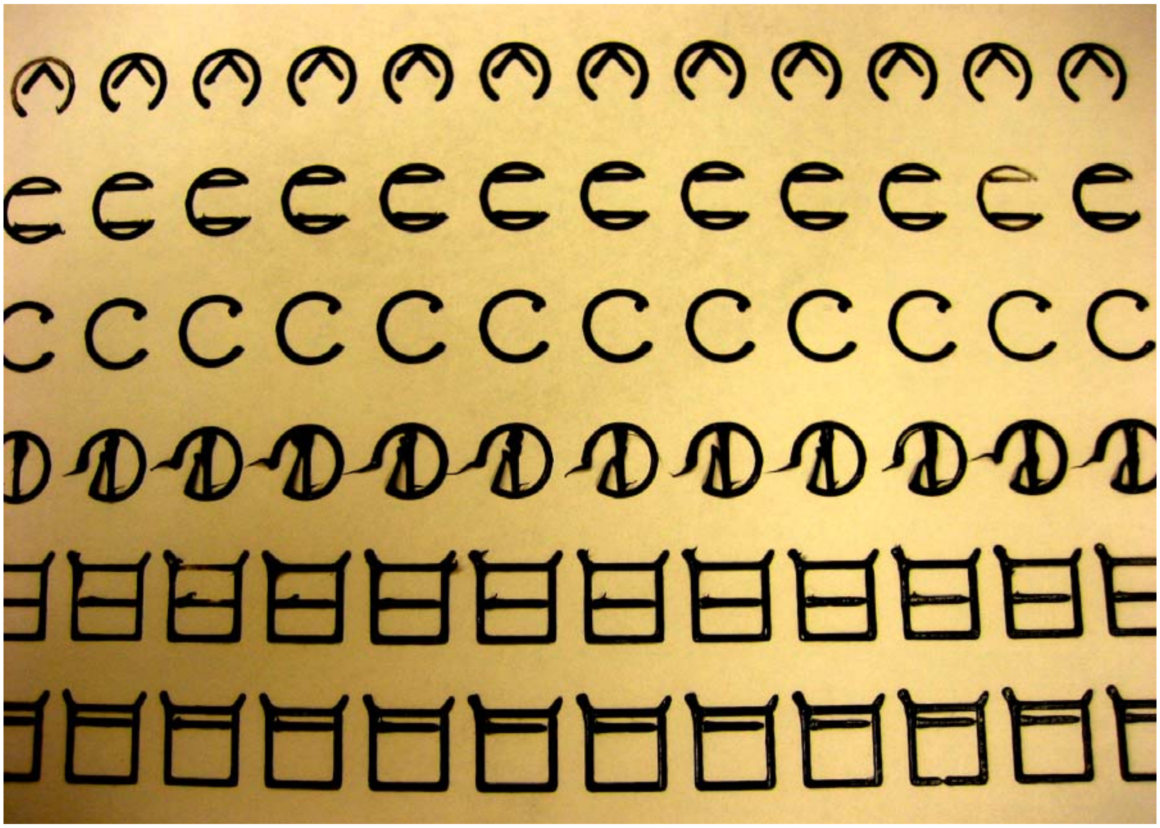


Figure 10. Repeatability of Letters a through h: The Fab@Home was found to print the ELIA letters very consistently.

Print Time and Material Usage

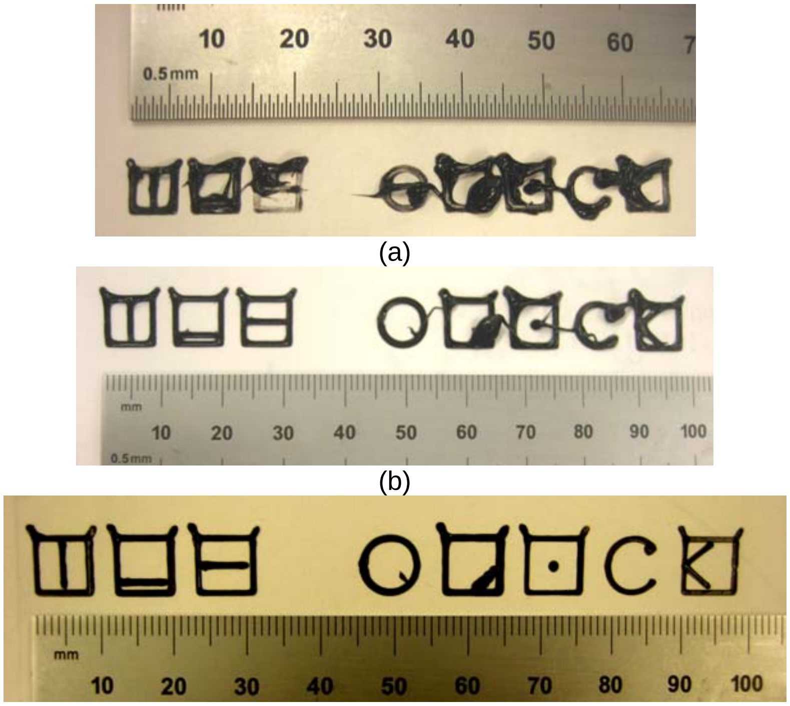
To measure the approximate amount of time each letter takes to print, we timed the printing of each letter in *the quick dog* pangram (Table 3). Additionally, the mass of the deposition tool was measured before and after printing a phrase of 19 3-layered letters. The initial mass was 16.755 g and the final mass was 15.750. Therefore, approximately 1.005 g can print 19 letters, if printing 3 layers, and about 57 letters if printing single layers.

Letter	Time (sec)	Letter	Time (sec)	Letter	Time (sec)	Letter	Time (sec)
a	30	**h**	40	**o**	14	**v**	39
b	27	**i**	36	**p**	22	**w**	38
c	19	**j**	52	**q**	39	**x**	46
d	26	**k**	39	**r**	28	**y**	34
e	36	**l**	30	**s**	22	**z**	34
f	39	**m**	36	**t**	44		
g	34	**n**	37	**u**	50		

Table 3. Printing Times: The time (in seconds) represent the approximate time of printing for each letter using three layers.

Smaller-Sized Font

One of our goals in this project was to print the ELIA letters in different-sized fonts. First, the standard 1 cm by 1 cm letters were scaled down to 0.5 cm by 0.5 cm (Figure 11a), but the red-tapered tip was not sufficiently fine to print such small letters. Hence a smaller font was successfully attempted by scaling down to only 0.75 cm by 0.75 cm (Figure 11b,c). Decreasing the size of the letters also required some of the printing parameters to be adjusted. Therefore, there are two material files: one for the standard-sized letters and another for the ¾-sized letters.



(a)

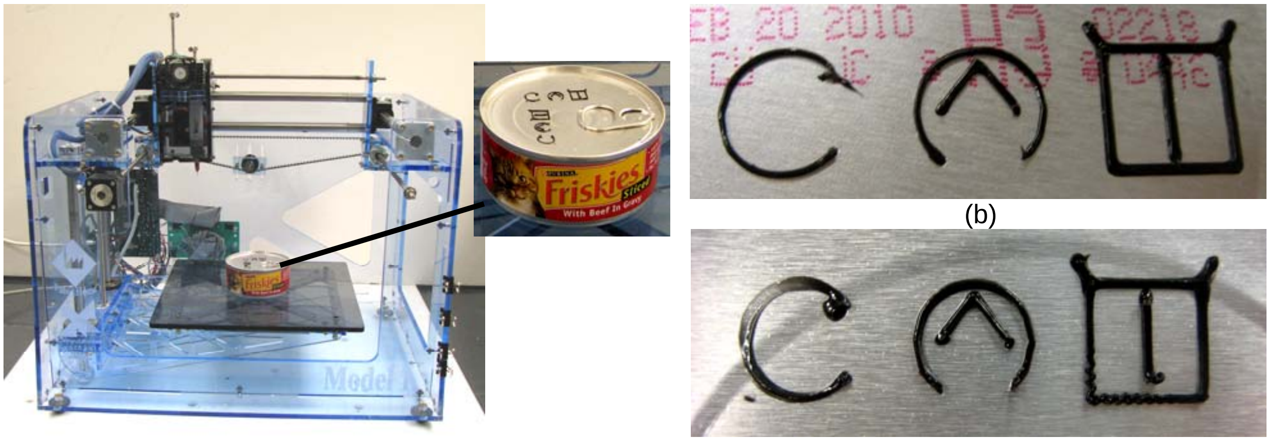
(b)

(c)

Figure 11. First Trials for Smaller Fonts: (a) The ½-size font was too small to print accurately. **(b)** The ¾-size font showed more promise and was pursued further. (**b**) An improved ¾ size font was achieved with some additional parameter tuning.

Printing on a Can

One potential application of printing tactile text with the Fab@Home is to print labels on products to improve their accessibility to the visually impaired. A product of interest for this research project is canned foods. In particular, one might want to easily distinguish pet food from other canned food. To this end, we successfully printed the word “cat” (for cat food) on the lid of a can (Figure 12). The uneven surface of the second can lid (Figure 12b) due to the circular indents made printing with standard size font difficult. In this case the ¾-size font allowed us to avoid this difficulty to some extent, however parts of the word “cat” are printed thinly (e.g. the upper left of the *c*) due to the raised surface. Likewise other parts are printed unsteadily (e.g. the lower left of the *t*) due to the slight dip on the surface of the can. We foresee this problem in future applications with uneven surfaces. In Section 7 we discuss a potential solution to this problem.



(b)

(a)

(c)

Figure 12. Printed Can Lids: (a) The Fab@Home system is used to print the word “cat” a can lid in **(b)** 1 cm and **(c)** ¾ cm size font to help a person with a visual impairment identify the product as cat food.

Printing WindowArt

WindowArt was the second material we tested to print ELIA letters. Using a red-needle syringe tip, we tuned the parameters to print “window art” (Figure 13). in the standard size font. Printing trials were done only on paper surfaces. Due to the comparatively lower viscosity in WindowArt than in black silicone, the lines were not as straight and clear as those printed with black silicone. As seen in Figure 14, the WindowArt print has a “drippy” effect, especially at the ends of lines, due to its low viscosity.

Figure 13. Printing WindowArt with Red Tip: WindowArt is printed with considerable precision using the red flexible tip.

Conclusions

This research project addressed the primary concerns in adapting the Fab@Home system to printing the tactile ELIA alphabet on a variety of surfaces. We identified four promising, non-toxic materials for this purpose: black silicone, white silicone, WindowArt and 3D Squeezable Paint. We discovered that these materials can print and remain adhered to paper, can lids, and plastic bottle caps over a period of months but do not adhere reliably to Styrofoam.

In order to print the ELIA alphabet, we developed an extension to the previously-existing Fab@Home software to allow the parsing of vector graphics files into the Fab@Home internal representation. Using this conversion software, we developed a library of files for printing the ELIA letters as well as a tool to combine these letters into specified sentences.

Using the updated software and text-printing tool, we further investigated the dimensional tolerance and repeatability of printing the ELIA alphabet using the Fab@Home. Experimentation with black silicone revealed that 1 g of black silicone can print up to 57 single-layered letters which each take between 14 and 52 seconds to print, depending on the letter. The letters printed were found to be consistent, a set of printing parameters were identified to reduce the dimensional errors of the printed characters. Successful prints were made of all the 26 ELIA letters. Successful printing has also been demonstrated with a second material: WindowArt. Overall, we have demonstrated that printing tactile text is a feasible application of the Fab@Home printer.

Future plans include more systematic user-testing of the resulting printed text under a broad range of conditions. Beyond the specific results attained here, we believe that these experiments suggest that RP has the potential to be used in a variety of applications that involve custom product adaptation to address a wide range of disabilities.

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