3D Printing on Paper for Tactile Graphics

Automated, low cost tactile graphics generation using additive manufacturing techniques, a preliminary investigation of a novel approach and the introduction of an open source software solution.

ANONYMOUS

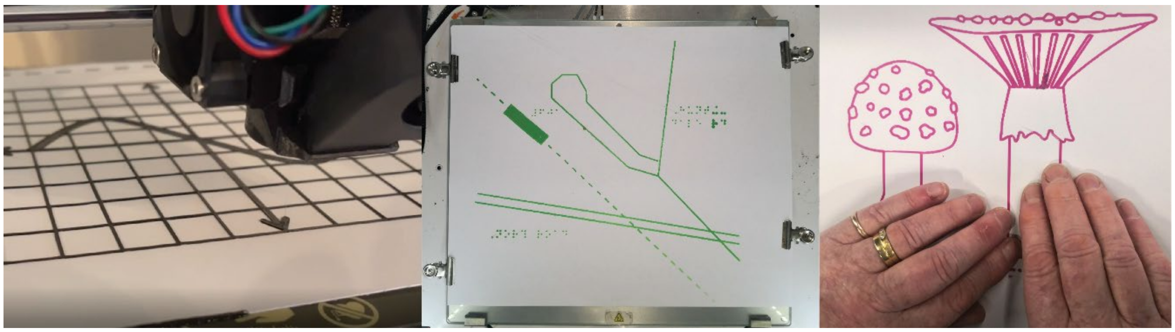

Figure 1: Using a FDM 3D printer to create tactile lines and braille with a single layer of filament on paper; a 3D printed tactile diagram on paper fixed to the printer bed with clips; and touch reading a 3D printed tactile diagram.

Over the past decade, as additive manufacturing techniques have become more commercially available and widespread, there has been much exploration into 3D printing for tactile access to information by people who are blind and vision impaired (BVI). This paper seeks to explore the novel method of using single layer 3D printing on paper. By testing different printer filaments, paper substrates, extruder nozzle sizes, and custom slicing settings, we have developed a method by which robust tactile graphics can be produced at a cost of less than a cent and within minutes. This process is documented in a wiki and supported by an open source, accessible software solution that automates the conversion from visual bit map graphics to 3D print files for single layer tactile graphics. A small user study with five blind touch readers confirmed that 3D printed tactile graphics on paper are legible and can provide value to the BVI community, for example by enabling people to generate their own tactile study materials and maps.

CCS CONCEPTS • Human-centered computing • Accessibility • Accessibility technologies

Additional Keywords and Phrases: 3D printing, Open Source Software, Tactile Graphics, Blind

ACM Reference Format:

1 INTRODUCTION

Tactile graphics, also known as raised line drawings, are an invaluable format providing people who are blind or vision impaired (BVI) with direct spatial access to diagrams, particularly for use in the classroom and to support orientation and mobility training [1, 15]. However, provision of tactile graphics is currently limited by practical considerations. For example, creation of tactile graphics from electronic images relies on expensive specialist machinery. We seek to utilize 3D printers to create a cost and time effective process by which tactile graphics can be produced.

While there has been a huge interest in new technologies for the creation of tactile graphics and haptic devices over the last decade [3], none have yet had a significant impact on real-world production of tactile graphics [9] beyond the adoption of 3D printing for tactile models. Since the 1980s, there have been two main methods for creating tactile graphics from digital images: swell paper and embossing [1, 11, 16]. Vacuum forming (thermoforming) is also common, but relies on a physical master, most often produced through handcrafting techniques. While each method has a set of unique advantages and disadvantages, they all have two things in common - they are costly and specialized. Swell paper, also known as microcapsule paper, costs a minimum of USD$1.50 per sheet and requires a specialized machine costing around USD$1,500. Embossed tactile diagrams have a lower cost per sheet but braille embossers begin at a cost of around USD$4,000 and specialized graphics embosser with finer resolution and ink printing cost around USD$10,000. Clearly, there is a need for solutions that are more affordable and can be used by organisations that do not specialize in accessibility.

By comparison, a 3D printer can be purchased for less than USD$250. In addition, 3D printers are a mainstream technology already available in modern schools and many professional environments. As 3D printers have become cheaper and more widespread, it makes sense to begin exploring them as a viable alternative to costly embossers and swell paper heating equipment. Using a paper substrate and single layer printing technique, we cut the cost to less than 5 cents and time to less than 10 minutes. Using filament in a contrasting color, 3D printing also supports low vision users who have some use of their vision. Preliminary testing has demonstrated that 3D printed tactile graphics can have equivalent longevity to swell paper and embossed graphics. This paper describes an efficient and affordable method for producing tactile graphics using 3D printing on paper with strong adherence that withstands repeated use and flexing of the page.

1.1 Contributions

1. Using a collaborative design process, we determined an efficient and user-friendly process to generate tactile graphics for 3D printing. This process is shared online at [ANONYMOUS].
2. Creation of a free, accessible online tool to convert print graphics to 3D printing files at https://cowlicks.github.io/.
3. Confirming the value of 3D printing on paper through a small user study.

2 RELATED WORK

3D printing has commonly been used to create tactile diagrams for touch readers with a 3D printed base plate, e.g. [5, 6, 12, 13]. This technique offers a new method of digitally creating and distributing tactile graphics with a mainstream technology. However, the majority of the printing time and material consumption is dedicated to printing of the base plate. A much more efficient process could be achieved through elimination of the base plate by printing directly onto paper or a similar ready-made substrate.

3D printing low-relief line diagrams on paper has been explored by several independent groups as means of creating tactile graphics more cheaply or without the need for vision-specialist equipment. The National Braille Press conducted preliminary research exploring 3D printing on paper as an option for saving tactile graphics production time [7]. Barros and colleagues 3D printed with conductive filament to add tactile touch points to print diagrams for audio feedback using an electronic circuit [2, 14]. Willemsen experimented with 3D printing on clear plastic sheets to use as tactile overlays on a touchscreen with visual and audio feedback [16]. These projects provide a range of use-cases in which 3D printing tactile graphics on paper or a similar substrate may be useful.

This prior work has commonly reported problems with adherence of the 3D print to the page and suggested that more thorough work is required to test different filaments and substrates [2, 7, 14, 16]. Moreover, to date, the exact details of how to design and convert a print diagram to a 3D printed tactile graphic have not been publicly shared, and Willemsen called for the development of a software application to create g-code directly from line drawings because “there are too many labor-intensive steps required to get from a two dimensional line drawing to a 3D printed raised line drawing” [16]. Of course, consideration must also be given to the experience of touch reading the resultant 3D printed tactile graphics.

The current project aims to address these problems of adhesion, workflow and legibility to advance 3D printing on paper as a practical solution for non-experts to cheaply produce durable tactile graphics.

3 METHOD

3.1 3D Printers

Processes were tested using several different 3D printers, including the Creality Ender 3 Pro, Ultimaker 2+ and S5, and Prusa MK3s. A majority of prints were completed using the Prusa MK3s, which was favored due to its open source design, consistency, and time effective heating/ start up sequence.

3.2 Designs

A variety of designs were tested to determine effective printing settings and design considerations. Designs for emerging tactile readers designed in Microsoft Word by braille transcribers in collaboration with vision teachers (TVIs) as well as graphics converted from the Desmos graphing app [4] were chosen to test line widths and printer settings. Words in different braille fonts and sizes were used to determine settings for consistently printed legible braille with an appropriately smooth surface finish.

3.3 Input from Tactile Readers

Throughout the development process, informal feedback was gathered from tactile readers of varying skill levels. Visual and tactile inspection of generated tactile graphics was also conducted by sighted researchers with an understanding of tactile graphics standards [1, 10].

4 RESULTS

A process was developed to address the three key challenges to 3D printing on paper identified by past researchers: converting from an image file to a 3D printable file, adherence to the page, and legibility for touch reading. The technical aspects of this process are documented in Appendices A1 to A3.

4.1 Conversion

To convert bitmap image files to 3D printable files with minimal artifacts, we created a free online converter at https://cowlicks.github.io/. Many other converters are not able to adequately convert braille or other small features of tactile graphics, leading to legibility issues and incorrect graphics. Our conversion process minimizes stair stepping which can lead to rough surface finishes, while maximizing resolution so all aspects of a design are properly converted. Furthermore, our online converter runs locally in the user’s browser, therefore sensitive and confidential documents and designs can be converted without uploading to an external server for processing.

4.2 Adherence

Many previous attempts at 3D printing tactile graphics note that3D prints may fail to adequately adhere to the substrates they are printed on. We were able to mitigate this issue and produce graphics with adherence of PLA on par with swell paper graphics by adjusting z-offset slicer settings, using a porous substrate (embosser paper), and fine tuning retraction slicing settings to minimize stringing (plastic "strings" that result from the nozzle oozing filament in between print strokes). PET-G and TPU filaments achieved even greater adherence. That said, TPU prints typically had more stringing, which could be used to pull printed features off the paper substrate. Thus, while adherence with TPU was greatest, the stringing issue lead to greater likelihood of prints becoming detached.

4.3 Legibility

By using our online converter, adjusting our slicer settings, and determining appropriate sizes for braille and other graphic elements we were able to achieve legible results on par with some swell paper designs. Sizing issues were largely determined by the 3D printer extruder nozzle diameter, with finer resolution graphics achieved with smaller nozzle sizes. In general, with a .4mm diameter nozzle sizing up braille size standards [8] around 50% resulted in graphics that minimized print artifacts such as stringing, inconsistent surface finish, and flattened lines. Unfortunately, this up-sizing affected legibility, therefore more exploration with finer nozzles and different braille fonts (square and diamond braille) is warranted.

5 EVALUATION

Tactile diagrams produced using the proposed workflow were evaluated by five totally blind touch readers from 29 to 69 years of age ($\bar{x}$=51; sd=17.4). They rated their experience with tactile diagrams from low (n=2) to medium (n=2) and high (n=1). Five different diagrams were provided, printed using PLA, TPU 95 and nylon filaments on 80gsm copy paper, 120gsm standard and glossy cardstock, and transparent overhead sheets.

All five of the touch testers agreed that 3D printing on paper can produce a diagram that is tactually sufficient to be read by touch. There was no agreement on which filament was preferred from a tactile perspective. For example, some said that PLA was harsh or sticky, whereas others thought PLA was the most distinct. All of the substrates were considered acceptable, including the cheap copy paper.

All five touch testers also agreed that 3D printing is a useful technique for the creation of tactile graphics.

> "This is a great option."

They were most excited about the possibilities of using 3D printing on paper in schools (n=4), its low cost (n=2), for quick access (n=2) and when a 3D printer is available but other specialized equipment is not (n=1).

> "A teacher could print a diagram on mainstream equipment. There's a real advantage in that."

6 DISCUSSION

6.1 Potential Applications

While developing and testing the process of 3D printing on paper, several everyday applications emerged, particularly for independent creation of tactile graphics by BVI users. In the [ANONYMOUS] School, 3D printed tactile graphics were generated from Desmos [4] to provide BVI students with tactile access to mathematical graphing. As the required conversion tool is accessible, students should be able to create their own tactile graphics from their chosen equations. Three of the five adult touch testers requested maps of specific interest to them, and two discussed the possibility of purchasing a cheap 3D printer to use in combination with online tactile mapping tools to cheaply create their own maps to support orientation and mobility and independence.

"I'd like to be able to do it at home. Get me a map of such-and-such."

6.2 Limitations and Future Work

This represents preliminary work. More thorough user testing is required with both BVI individuals and TVIs to ensure that the method is replicable and practical for implementation. Our conversion software is constantly under development as we improve its robustness, accessibility, output quality, and add new features such as .SVG to .STL conversion. Furthermore, a further investigation into the longevity of prints in an academic environment and the adherence of different filament and substrate types is warranted.

Future work could explore extending this process to 3D print tactile graphics using two or three layers to enable multiple heights. The drawback of this approach is that it would take longer to produce and print.

6.3 Conclusion

This works presents a replicable process of 3D printing on paper to quickly and cheaply produce tactile graphics with strong adherence that withstands repeated use and flexing of the page. The conversion software is available for free online use. It is hoped that this work will assist in the creation and use of tactile graphics for access to information by touch readers where access to specialized equipment has previously caused barriers.

ACKNOWLEDGMENTS

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A APPENDICES

A.1 Slicer Settings

Note: These slicer settings are found in the Prusa Slicer software. Other slicing software such as Cura should have analogous settings but may require some exploration. When fine tuning settings, adjust speeds in increments/decrements of 5 mm/s and distances/lengths in increments/decrements of 10% of the original value.

Table 1: Slicer Settings

Slicer Setting	Setting Description	Recommended Ranges	Notes
Layer Height	Extrusion height	.2 mm - .25 mm	Limited to 25% - 80% of your extruder nozzle diameter
First Layer Speed	Speed that the first layer prints at	20 mm/s	This can change depending on your filament. The first layer speed will override your global print speed for the first layer.
Z Offset	Distance printer ahead defaults to above build plate	.10mm-.15mm (.12mm for embosser paper)	Helps with adherence and stringing. Measure thickness of paper substrate and use value. Cura needs 3rd party plugin or GCODE modified to change.
Extrusion Width	The width of each extrusion.	.4 mm	Limited theoretically to your nozzle diameter. In practice, pushed to 60%-200% of nozzle diameter. Contributes to tactile finish
Bed Temperature	Temperature of heated Print bed	Will be determined by filament type	Helps with adherence. Setting to 0 minimizes some paper warp due to heat but can lead to poor adherence.
First Layer Temperature	Temperature of extruder	Will be determined by filament type	Lower temperatures will help with stringing. The first layer speed will override your global temperature for the first layer.

Slicer Setting	Setting Description	Recommended Ranges	Notes
Retraction Speed	Speed filament retracts during printer head movements in between extrusions	35 mm/s – 45 mm/s	Helps with stringing issues
Retraction Length	Length that the filament retracts during printer head movements in between extrusions	2 mm	Helps with stringing issues
Lift Z	Amount printer head is lifted off bed during movements in between extrusions	.1 mm - .25 mm	Helps with stringing issues
Perimeters	Number of extrusions in objects outlines	1-100	Having a large number will limit or negate infill for large areas. Contributes to tactile finish
Infill (various settings)	Relevant infill settings include: density, fill pattern (bottom), infill extrusion width	(various settings)	Allow for different tactile finishes without having to change the design
Skirt and Brim (various settings)	Pre extrusion on first layer helpful for priming	(various settings)	Skirt or brim will require manual removal but can help when beginning extrusions are weak or not adhering

A.2 Printer Filaments

Table 2: Tested FDM 3D printer filaments

Filament Type	Filament Characteristics	Filament Notes
PLA	Relatively low printing temperature. More flexible than PET-G, but still rather brittle surface finish ~.6% shrinkage	Widely used. Acceptable adherence achieved
PET-G	Stronger than PLA but still somewhat brittle and less flexible. Higher printing temperatures ~.3% shrinkage	Better adherence achieved then PLA to paper substrates.
TPU 95	Flexible, smooth and soft surface finish. Different hardness. Attracts moisture, which can affect print quality. Higher printing temperatures.	Susceptible to stringing which can greatly affect legibility and adherence. Difficult to print with Bowden extruders (direct drive extruders recommended)
Nylon	Flexible with a soft finish.	Difficult to print with Bowden extruders (direct drive extruders recommended)

A.3 Substrates

Table 3: Tested Substrates

Substrate	Substrate Characteristics	Substrate Notes
Standard copy paper (80gsm)	Thin paper. May buckle due to shrinkage of the 3D printed graphic.	Sufficient for short-term use.
Cardstock	More durable and with better adherence than 80gsm paper. Weights 120 – 150 gsm	The texture of regular paper/cardstock is generally preferred over glossy paper. Embosser paper works well
Thermoform paper	Textured surface. Low melting temperature.	Not recommended as heat from the printing head can deform and melt the paper.
Plastic sheet protector	Very thin transparent plastic.	Not recommended as heat from the printing head can melt holes in the sheet, and it is unstable and scrunches up under the fingers.
Overhead transparency sheet	Stable, clear plastic sheet.	Not recommended due to poor adherence. The slippery texture is also unpopular with touch readers.