Advancing Accessible 3D Design for the Blind and Visually-Impaired via Tactile Shape Displays

Alexa F. Siu
Stanford University, Stanford, CA
afsiu@stanford.edu

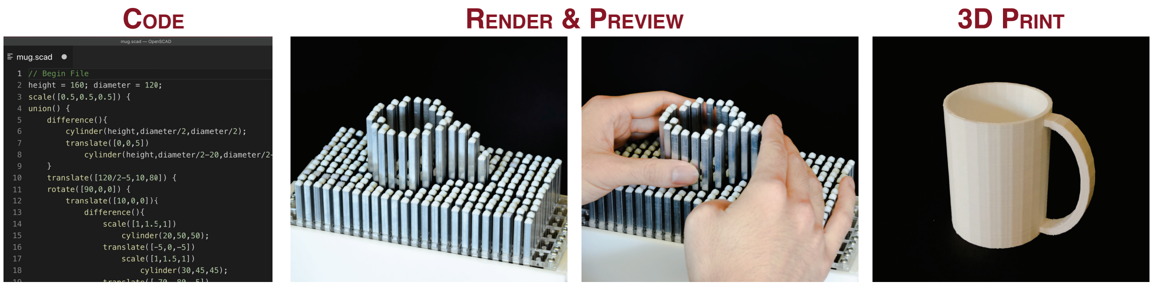

Figure 1. We investigate an accessible 3D modelling workflow where 3D models are generated through OpenSCAD, a declarative programming language for 3D modeling, and rendered at interactive speeds in shapeShift, a 2.5D shape display consisting of a grid of 12×24 actuated pins.

ABSTRACT
Affordable rapid 3D printing technologies have become key enablers of the *Maker Movement* by giving individuals the ability to create physical finished products. However, existing computer-aided design (CAD) tools that allow authoring and editing of 3D models are mostly visually reliant and limit access to people with blindness and visual impairment (BVI). In this paper I address three areas of research that I will conduct as part of my PhD dissertation towards bridging a gap between blind and sighted *makers*. My dissertation aims to create an accessible 3D design and printing workflow for BVI people through the use of 2.5D tactile displays, and to rigorously understand how BVI people use the workflow in the context of perception, interaction, and learning.

ACM Classification Keywords
Human-centered computing Accessibility systems and tools; Human-centered computing Haptic devices

Author Keywords
Accessible Authoring Tools; Accessible 3D Printing; Tactile Graphics; Tactile Displays; 2.5D Shape Displays

INTRODUCTION
People with blindness and visual impairments (BVI) are experienced *makers* having to be adept at using the technology at hand to solve accessibility problems they face in their daily lives. This spirit of creative problem solving and tinkering of the BVI community has existed in parallel to the mainstream *Maker Movement*. The rise in less expensive and distributed fabrication tools, such as 3D printers and easy-to-use micro-controllers, have made it easier for a wide range of groups to engage in making. Yet accessibility remains a challenge and the BVI community, which may benefit immensely from such tools remains marginalized [8]. Accessibility in making can not only provide access points for contextualized learning of many concepts considered critical for STEM but can also give BVI people the tools to participate in the vibrant maker culture as designers themselves [2, 4, 7].

ACM ISBN 978-1-4503-6817-9/19/10 ...$15.00.
http://dx.doi.org/10.1145/3332167.3356875

My dissertation seeks to bridge a gap between blind and sighted makers by identifying and addressing accessibility challenges in the areas of 3D modelling and 3D printing for the BVI. I aim to create an accessible 3D design and printing workflow for BVI people through the use of 2.5D tactile displays, and to rigorously understand how BVI people use the workflow in the context of perception, interaction, and learning. The broad research questions I seek to answer are:

- How can complex 3D information be effectively encoded through tactile representations?
- What are the interaction techniques necessary to create and manipulate 3D models on tactile displays with limited resolution?
- How does access to 3D design and printing in the wild for BVI people change their self efficacy of making and their attitudes towards STEM?

BACKGROUND & RELATED WORK
BVI people face several barriers in the use of digital tools for producing 3D models. The sections below describe current methods that allow BVI people to access graphical content and efforts to overcome barriers in content creation.

Audio & Tactile Graphics
BVI people most often rely on labels and alternative text. Several works have looked at automatic labeling of images,

spatial data such as maps and even complex engineering drawings [18]. However, text-based descriptions of graphics are less precise, and require more cognitive load than a perceptual interface that directly renders the same information through touch or vision [25, 23]. 2D tactile graphics methods while accessible, are most successful at describing outlines and texture but fall short when communicating 3D spatial information. 3D printed objects are a promising possibility since a lot of the haptic multidimensional cues are preserved but these can take a long time to fabricate [24] and accessible tools for the blind to express through this medium don't exist [6]. In my work, I seek to understand what are effective methods for encoding and communicating spatial 3D geometry information in accessible ways for BVI people. I am particularly interested in multimodal methods using both audio and haptics.

Haptic Encoding & Perception

Humans are remarkably good in identifying objects through haptics employing a combination of various exploratory procedures [13, 10]. Object identification is more efficient when more depth cues are available [12]. A limitation in most of these perceptual studies however, is that these have focused on 3D object identification; it is important to highlight that identification is inherently different from understanding in that object identification can happen without having an accurate mental model of the 3D object in question. In the context of this work, I am interested in 3D object understanding rather than identification since modifying an existing 3D model or even authoring one from scratch, requires the user understand all spatial elements of the model. Through my dissertation, I hope to investigate interactions and perceptual cues that help users form an accurate mental model of a 3D object representation.

Dynamic Tactile Arrays & Shape Displays

Tactile arrays and shape displays, which typically consist of a grid of pins that can translate up and down, can provide dynamic rendering of graphical content and have been shown to be as effective as static tactile graphics in conveying the same information [14, 16]. These systems can provide functionality similar to a computer-based system and provide many benefits for gross shape perception. However, tactile arrays and shape displays vary in their resolution and number of haptic cues they are capable of conveying. 2.5D shape displays, such as shapeShift [20] typically sacrifice resolution at the cost of restoring depth cues. Tactile arrays will most likely always have resolution and workspace limitations such that the content being explored will exceed the rendering region of the display. To overcome these limitations, several researchers have explored various interaction techniques that allow BVI people to access large-format graphics through tactile arrays [19, 17]. In this work, I seek to design interactions with 2.5D shape displays that enable BVI to explore, understand, and author 3D models.

Multimodal CAD & 3D printing

Several tools have been created to allow automatic translation from 2D to 3D format compatible for 3D printing [26, 11, 3]. However, these do not allow BVI people to preview the models or add customizations before printing and are limited to flat geometry. Declarative programming 3D modelling tools, such as OpenSCAD and CraftML[27], have more accessible input methods and are compatible with current screen reading technologies [15, 9]. However, several challenges still remain. Methods to interactively visualize the code don't exist, other than audio from the screen reader. The lack of feedback is challenge that prevents debugging and fast iteration. In this work, I plan to investigate ways to overcome some of the programming challenges by using tactile feedback through a 2.5D shape display.

RESEARCH GOALS & METHODS

The proposed research seeks to make contributions across three thrust areas. Thrust 1 will focus on understanding methods for encoding 3D spatial information on tactile arrays for BVI people. The findings from Thrust 1 will be used in Thrust 2 to co-design a workflow for CAD that is accessible for BVI people. Thrust 2 will generate guidelines for multimodal interaction and 3D modeling for BVI people. The workflow co-designed in Thrust 2, will be further validated in Thrust 3 through a long-term field deployment that will assess how knowledge in this domain empowers BVI people in Making activities, affects their attitudes towards STEM, and personal self-efficacy.

Thrust 1: Representing Spatial 3D Information

Towards this aim, I plan to conduct a controlled study to evaluate tactile methods for encoding spatial 3D information. The objectives are twofold: 1) to elucidate on the benefits of the different *encoding representations* for 3D spatial information; compare contours versus reliefs and 2) to understand the interplay of *tactile array resolution* (low, medium, high). The study goal is to assess the strengths and weaknesses of different tactile representations in enabling users to accurately form a mental image of the real object. Understanding perceptual strengths of BVI people is crucial to properly communicating information. Similar to previous work on 2D tactile graphics, a 1:1 visual to tactile translation will likely not be sufficient. Making this type of information more accessible, has implications not only for 3D design but also more generally for access to graphical information; a challenge BVI people already constantly face.

Thrust 2: Co-Design of an Accessible 3D Modelling System Supported by Tactile Displays

Current 3D modelling tools that support viewing, authoring and editing of 3D models are mostly visually reliant and limit access for BVI people. Leveraging recent advancements in 2D tactile arrays [5] and 2.5D shape displays [20], I am developing an accessible multimodal 3D modelling tool for BVI people. To uncover and formulate design guidelines on interactions with tactile displays that support understanding and creation of 3D geometry, I am using a participatory design approach to position participants as co-designers. Zooming and panning operations are common interactions with visually-rendered material that help scaffold layers of information and enable exploration of large-format graphics. I hypothesize similar interactions can improve usability when interacting with a tactile display.

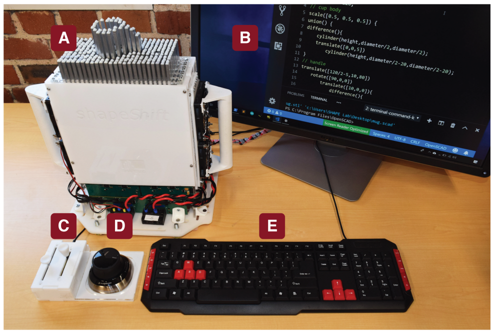

Figure 2. Overall setup of the 3D modelling system comprised of A) a 2.5D shape display, B) OpenSCAD programming language, C) slider inputs for control of zoom and object views, D) 3D mouse for translation and rotation, E) and computer keyboard.

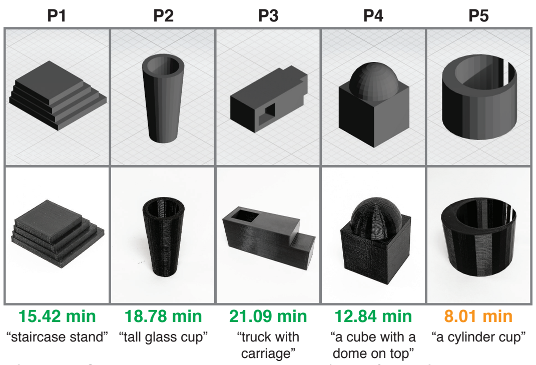

Figure 3. The first row shows the rendering of the 3D models created by four blind and one visually impaired user of the 3D modelling system. The second row shows the model 3D printed using a MakerBot Replicator. All participants reported being satisfied with the final results except P5.

In past work, I have developed the hardware for a 2.5D dynamic shape display and investigated panning interactions for haptically exploring maps larger than the rendering region [20]. An initial study and design imperatives in the context of a 3D modelling application have been published in [22, 21]. In this workflow, participants authored 3D models through program scripts and could obtain feedback by compiling and rendering to the shape display (Figure 1). In a controlled study with the workflow and an additional group of 5 blind users, novices were introduced to the system and asked to both complete a series of controlled tasks and open-ended tasks. Figure 3 shows a sample of models that users created when given time to ideate new models from scratch. The results demonstrate a set of interactions that allow us to use 2.5D shape displays to provide near-immediate feedback for BVI people when authoring and editing 3D models. In a short period of time, novices were able to ideate a range of objects.

Thrust 3: Long-Term Deployment To Assess Learning and Self-Efficacy

After developing and testing for usability of the 3D modelling workflow, I plan to conduct field investigations through a series of workshops and long-term deployment of the prototype. The design workshops will invite a cohort of *makers* to learn about the workflow and 3D modelling. Feedback gathered will allow me to frame insights for future educators and researchers on: 1) guiding tenets and continuing challenges for accessibility in Makerspaces, 2) necessary software and hardware support, 3) a repository of 3D models to inspire future domain specific design tools, and 4) recommendations for course design and integrated classroom dynamics. Participation and collaboration in the Bay Area Blind Arduino Project [1] has enabled me to forge relationships with a community of blind *makers* and enthusiasts in the Bay Area and has provided a platform for the design workshops and deployment.

DISSERTATION STATUS

In the fall of 2019, I will be starting my 5th year of PhD in the Mechanical Engineering Department at Stanford University. I expect feedback from the consortium to help me refine the research methodology in the last milestones of developing and assessing the proposed system. I anticipate the remaining work to take 1-2 years.

EXPECTED CONTRIBUTIONS & POTENTIAL IMPACT

This work makes fundamental contributions to perceptual science, information encoding, and the design of 3D user interfaces for BVI people through the development of an accessible 3D modelling interface and deployment in the wild. At a broader level, it seeks to increase access to STEM concepts and give BVI people, a new medium for creative expression that others across the world already engage in.

ACKNOWLEDGMENTS

I thank my PhD advisor Sean Follmer for his guidance and my collaborators whose efforts have largely contributed to this work. This work was supported by the NSF GRFP (#DGE-114747).

REFERENCES

[1] 2015. Blind Arduino Project. `https://www.ski.org/project/blind-arduino-project`. (2015). Accessed: 2019-07-07.

[2] Paulo Blikstein. 2013. Digital fabrication and 'making'in education: The democratization of invention. *FabLabs: Of machines, makers and inventors* 4 (2013), 1–21.

[3] Craig Brown and Amy Hurst. 2012. VizTouch: automatically generated tactile visualizations of coordinate spaces. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*. ACM, 131–138.

[4] Jonathan Cohen, Jonathan Cohen, W. Monty Jones, Shaunna Smith, and Brendan Calandra. 2017. Makification: Towards a Framework for Leveraging the Maker Movement in Formal... *Journal of Educational Multimedia and Hypermedia* 26, 3 (2017), 217–229.

[5] American Printing House for the Blind. 2018. Introducing Graphiti - A Revolution in Accessing Digital Tactile Graphics. (2018). `https://www.aph.org/graphiti/`

[6] Timo Götzelmann, Lisa Branz, Claudia Heidenreich, and Markus Otto. 2017. A Personal Computer-based

Approach for 3D Printing Accessible to Blind People. In *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments*. ACM, 1–4.

[7] Erica Rosenfeld Halverson and Kimberly Sheridan. 2014. The Maker Movement in Education. *Harvard Educational Review* 84, 4 (Dec 2014), 495–504. DOI: http://dx.doi.org/10.17763/haer.84.4.34j1g68140382063

[8] Amy Hurst and Shaun Kane. 2013. Making making accessible. In *Proceedings of the 12th international conference on interaction design and children*. ACM, 635–638.

[9] Shaun K Kane and Jeffrey P Bigham. 2014. Tracking@ stemxcomet: teaching programming to blind students via 3D printing, crisis management, and twitter. In *Proceedings of the 45th ACM technical symposium on Computer science education*. ACM, 247–252.

[10] Roberta L. Klatzky, Susan J. Lederman, and Victoria A. Metzger. 1985. Identifying objects by touch: An expert system. *Perception & Psychophysics* 37, 4 (01 Jul 1985), 299–302. DOI:http://dx.doi.org/10.3758/BF03211351

[11] Richard E Ladner, Melody Y Ivory, Rajesh Rao, Sheryl Burgstahler, Dan Comden, Sangyun Hahn, Matthew Renzelmann, Satria Krisnandi, Mahalakshmi Ramasamy, Beverly Slabosky, and others. 2005. Automating tactile graphics translation. In *Proceedings of the 7th international ACM SIGACCESS conference on Computers and accessibility*. ACM, 150–157.

[12] Rebecca Lawson and Sarah Bracken. 2011. Haptic Object Recognition: How Important are Depth Cues and Plane Orientation? *Perception* 40, 5 (2011), 576–597. DOI:http://dx.doi.org/10.1068/p6786 PMID: 21882721.

[13] Susan J Lederman and Roberta L Klatzky. 1987. Hand movements: A window into haptic object recognition. *Cognitive Psychology* 19, 3 (1987), 342 – 368. DOI: http://dx.doi.org/https: //doi.org/10.1016/0010-0285(87)90008-9

[14] Fabrizio Leo, Elena Cocchi, and Luca Brayda. 2017. The effect of programmable tactile displays on spatial learning skills in children and adolescents of different visual disability. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 25, 7 (2017), 861–872.

[15] Kazunori Minatani. 2017. Finding 3D CAD Data Production Methods that Work for People with Visual Impairments. In *HCI International 2017 – Posters' Extended Abstracts*, Constantine Stephanidis (Ed.). Springer International Publishing, Cham, 548–554.

[16] Thomas Pietrzak, Andrew Crossan, Stephen A Brewster, Benoît Martin, and Isabelle Pecci. 2009. Exploring geometric shapes with touch. In *IFIP Conference on Human-Computer Interaction*. Springer, 145–148.

[17] Denise Prescher and Gerhard Weber. 2017. Comparing Two Approaches of Tactile Zooming on a Large Pin-Matrix Device. In *IFIP Conference on Human-Computer Interaction*. Springer, 173–186.

[18] Deepak Ramteke, Gayatri Kansal, and Benu Madhab. 2014. Accessible Engineering Drawings for Visually Impaired Machine Operators. *Assistive Technology* 26, 4 (2014), 196–201.

[19] Ravi Rastogi, TV Dianne Pawluk, and Jessica Ketchum. 2013. Intuitive tactile zooming for graphics accessed by individuals who are blind and visually impaired. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 21, 4 (2013), 655–663.

[20] Alexa F Siu, Eric J Gonzalez, Shenli Yuan, Jason B Ginsberg, and Sean Follmer. 2018. shapeShift: 2D Spatial Manipulation and Self-Actuation of Tabletop Shape Displays for Tangible and Haptic Interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 291.

[21] Alexa F. Siu, Son Kim, Joshua Miele, and Sean Follmer. 2019. shapeCAD: An Accessible 3D Modelling Workflow for the Blind and Visually-Impaired Via 2.5D Shape Displays. *Proceedings of the 21st International ACM SIGACCESS Conference on Computers & Accessibility - ASSETS '19* (2019). DOI: http://dx.doi.org/10.1145/3308561.3353782

[22] Alexa F. Siu, Joshua Miele, and Sean Follmer. 2018. An Accessible CAD Workflow Using Programming of 3D Models and Preview Rendering in A 2.5D Shape Display. In *Proceedings of the 20th International ACM SIGACCESS Conference on Computers & Accessibility (ASSETS '18)*. ACM, New York, NY, USA, 343–345. DOI:http://dx.doi.org/10.1145/3234695.3240996

[23] Nancy Staggers and David Kobus. 2000. Comparing Response Time, Errors, and Satisfaction Between Text-based and Graphical User Interfaces During Nursing Order Tasks. *Journal of the American Medical Informatics Association* 7, 2 (2000), 164–176. DOI: http://dx.doi.org/10.1136/jamia.2000.0070164

[24] Saiganesh Swaminathan, Thijs Roumen, Robert Kovacs, David Stangl, Stefanie Mueller, and Patrick Baudisch. 2016. Linespace: A Sensemaking Platform for the Blind. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 2175–2185. DOI: http://dx.doi.org/10.1145/2858036.2858245

[25] Barker Temple. 1990. The benefits of the graphical user interface: A report on new primary research. The benefits of the graphical user interface: A report on new primary research. The benefits of the graphical user interface: A report on new primary research. (1990).

[26] Thomas P Way and Kenneth E Barner. 1997. Automatic visual to tactile translation. II. Evaluation of the TACTile image creation system. *IEEE Transactions on Rehabilitation Engineering* 5, 1 (1997), 95–105.

[27] Tom Yeh and Jeeeun Kim. 2018. CraftML: 3D Modeling is Web Programming. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 527.