Customizable 3D Printed Tactile Maps as Interactive Overlays

Brandon Taylor
Carnegie Mellon University
5000 Forbes Ave
Pittsburgh, PA 15213
+1 412 268 2000
bttaylor@cs.cmu.edu

Anind Dey
Carnegie Mellon University
5000 Forbes Ave
Pittsburgh, PA 15213
+1 412 268 2000
anind@cs.cmu.edu

Dan Siewiorek
Carnegie Mellon University
5000 Forbes Ave
Pittsburgh, PA 15213
+1 412 268 2000
dps@cs.cmu.edu

Asim Smailagic
Carnegie Mellon University
5000 Forbes Ave
Pittsburgh, PA 15213
+1 412 268 2000
asim@cs.cmu.edu

ABSTRACT
Though tactile maps have been shown to be useful tools for visually impaired individuals, their availability has been limited by manufacturing and design costs. In this paper, we present a system that uses 3D printing to (1) make tactile maps more affordable to produce, (2) allow visually impaired individuals to independently design and customize maps, and (3) provide interactivity using widely available mobile devices. Our system consists of three parts: a web interface, a modeling algorithm, and an interactive touchscreen application. Our web interface, hosted at www.tactilemaps.net, allows visually impaired individuals to create maps of any location on the globe while specifying (1) what features to map, (2) how the features should be represented by textures, and (3) where to place markers and labels. Our modeling algorithm accommodates user specifications to create map models with (1) multiple layers of continuously varying textures and (2) markers of various geometric shapes or braille characters. Our interactive application uses a novel approach to 3D printing tactile maps using conductive filament to provide touchscreen overlays that allow users to dynamically interact with the maps on a wide range of mobile devices. This paper details the implementation of our system. We also present findings from a user study validating the usability of our mapping interface and the utility of the maps produced. Finally, we discuss the limitations of our current implementation and the plans we have to improve our system based on feedback from our user study and additional interviews.

Categories and Subject Descriptors
• **Human-centered computing~Accessibility technologies** • *Human-centered computing~Haptic devices*

General Terms
Algorithms, Design, Experimentation, Human Factors.

Keywords
3D Printing; Tactile Maps

1. INTRODUCTION
Tactile maps are a well-established tool for providing visually impaired individuals with a spatial understanding of their environment [10]. Unfortunately, the availability and utility of tactile maps are limited [27]. Whereas sighted individuals, thanks to online map repositories and modern graphical rendering techniques, can instantaneously produce virtually any map they may desire, visually impaired individuals are much more restricted in their access to customized maps. However, as the commercialization of 3D printers has driven down the cost of producing personalized physical artifacts [5], the opportunity to provide visually impaired individuals with tools for independently creating their own personal tactile maps, has arisen.

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In this paper, we will introduce a set of tools and techniques that allow visually impaired individuals to create customized tactile map models. This work consists of three related parts. The first part is a website, designed with screen-reader compatibility in mind, which allows users to choose locations to map *and* specify a wide range of map features. The second part is a back end-algorithm which takes user-specified parameters from the website, downloads relevant data and generates 3D printable models of the specified region. Finally, we present an Android application that uses physical maps generated by our system and printed using a secondary conductive filament as a touchscreen overlay to provide dynamic touch interactivity to the maps.

This paper will provide an overview of previous literature related to creating customized tactile maps, highlighting the advantages that 3D printing can provide. It will then provide a detailed overview of each of the three parts of our system. Next, we will present the findings from our evaluation to verify that our system can be used independently and that our map models appropriately convey information. We will then discuss the limitations of our work, how it can be improved in the future and what the implications of such a system are.

2. BACKGROUND
There is a wide range of literature demonstrating the utility of tactile maps and specifying best-practice guidelines for the creation of tactile graphics [4,6,10,17,18]. Here we will focus on research most relevant to the various parts of our system.

2.1 3D Printed Maps
Tactile maps have a long history that predates 3D printing as a commercially available technology. Embossers and microcapsule paper can be used to automatically create maps from computer-generated images [23]. However, these techniques provide only two layers of depth and require expensive equipment. Braille embossers start at $1800 and can range up to $80,000 for high-speed machines [2]. Microcapsule, or swell paper, printers can be had for $1350 and also require specialized paper that costs more than a $1 per sheet [3]. Another production method, vacuum forming, offers a wider range of possible tactile features.

However, this comes with the cost of needing a master mold of the desired form, which does not readily lend itself to an automated process [25]. With the arrival of commercially available 3D printers, the possibility of obtaining the best of both approaches (automated modeling with a wider range of tactile surfaces) at a reduced cost has become a reality. 3D printers are already available for as little as a few hundred dollars [1] and unlike embossers or swell paper, the market for 3D printers is expected to continue expanding [5].

Unsurprisingly, a number of researchers began exploring the benefits 3D printing could provide to tactile map production. The HaptoRender project produced a 3D printed tactile map using OpenStreetMap data in 2009 [16]. Gotzelman and Pavkovic presented a more rigorous approach to automatically mapping OpenStreetMap data to flat, layered 2.1D models with braille annotations explicitly for use with 3D printers [14]. Ensuring that blind individuals could independently use their method was left to future work and their methodology is not publicly available at this time. Touch Mapper is a similarly motivated project, with a web interface that allows users to query addresses and download 3D map models of the surrounding area [20]. While Touch Mapper will generate maps that distinguish roads and rails, waterways, and buildings, it offers no labels (braille or otherwise) beyond a direction indicator and customization is restricted to a limited number of size and scale options.

In contrast to these efforts, we have explicitly focused on providing visually impaired individuals with the ability to create fully customizable maps. In doing so, we have developed a 3D modeling algorithm that moves beyond 2.1D layered maps to produce maps that can currently include: different textures for up to 5 different map features, topographical data, braille annotations, and the labeling of points designated by a set of geometric shapes or braille labels. Our system is designed to move beyond a one-size-fits all solution to automated map production and allow users to add, remove, and adjust how map features are represented tactilely.

2.2 Independently Customizable Tactile Maps

While designing algorithms that can produce 3D printable tactile maps from online repositories of geospatial data is certainly a necessary step in allowing visually impaired individuals to create customized maps, the algorithms themselves are not sufficient to solve the problem. An accessible interface that allows visually impaired individuals to independently produce the maps is also needed. Here we will examine the limits of projects that have explicitly focused on providing accessible interfaces.

The Smith-Kettlewell Eye Research Institute's Tactile Maps Automated Production (TMAP) project was an earlier effort with an explicit focus on allowing totally blind individuals to independently produce customized tactile street maps [23]. The TMAP project provided visually impaired users with an accessible web interface for specifying maps that would then generate digital files that could be printed using a braille embosser. The TMAP project was restricted to use within the United States as it relied on the US Census Bureau's Topologically Integrated Geographic Encoding and Referencing (TIGER) data. As of 2014, after an 11 year run, the TMAP project was decommissioned "due to aging digital infrastructure and is no longer available" [28]. A similar project was undertaken to provide independent tactile map creation within Japan [24]. The Japanese Tactile Maps Automated Creation System (TMACS) was later adapted to use OpenStreetMap [15] data allowing it to generate maps of locations across the globe [30]. To our knowledge, there are no other currently available services that have been demonstrated to allow visually impaired individuals to produce customized tactile maps.

Unlike these approaches, our system allows users to specify not only the locations they want to map, but also how and what geographic features should be represented on the tactile map. In this way, we have both a tool to help visually impaired individuals explore their environment and a platform by which we, as researchers, can examine user preferences and improve the design of 3D printed tactile maps.

2.3 Interactive Tactile Maps

One consistent difficulty in the generation of tactile maps lies in the problem of annotating features. While braille labeling, either directly on the map [14] or as a legend [23] is the most common solution, it is not without its own problems. Braille is understandable to only a small subset of the visually impaired population [11] and braille size requirements create real constraints on the density and size of maps that can be produced [6]. As a result of this and the constraints of the embossing machines commonly used, most tactile maps produced are printed on paper sizes A4 or larger [26]. It is perhaps unsurprising then, that most users indicate that they prefer to use tactile maps at home rather than while out and about [27].

Faced with these limitations, a number of researchers have explored methods for producing more interactive tactile maps. The TMAP project mentioned earlier, later incorporated Touch Graphics' Talking Tactile Tablet technology [22] to create the Talking TMAP [23]. The Talking TMAP used unique map numbers that users could manually enter into a tablet so that it could access a digital representation of the specified map. By aligning the embossed map with the tablet, touch interaction could then be registered with appropriate regions of the map. Unfortunately, this approach required both a specialized tablet and software that is no longer available.

By making use of commercially available multi-touch touchscreen devices along with raised line prints on paper, Brock et al. explored how various gestures could be used to enhance interactive tactile maps [7]. When evaluating their system, they reported a high level of user satisfaction; the fact that braille was not needed was the most frequently cited positive aspect [8]. Like the talking TMAP before it, this approach relies on a touchscreen that detects touches through a thin sheet of paper, precluding additional depth information that can be produced by 3D printing.

Efforts to provide interactivity to 3D printed tactile maps have been explored using computer vision. Linespace differs from other systems by using a much larger interactive surface (more than a square meter), which can allow for the persistence of more spatial information than other systems [29]. Users can also interact with the system by drawing or touching the surface with computer vision-based approaches detecting user actions. While Linespace is certainly a promising interface, the need for specialized hardware raises issues of availability while the scale clearly prohibits portability.

An explicitly portable approach that makes use of 3D printed maps has been explored by Gotzelmann [13]. By embedding visually detectable barcodes along the edges of 3D printable map models, a smartphone app can use the phone's camera to register uniquely produced maps. Additional computer vision can then be used to detect finger positions on top of the map and provide dynamic feedback. While the potential of such an approach is exciting, the need to hold the smartphone camera so that the map is in frame while pointing at features and tapping the phone leave an open question as to how usable such an approach may be for a visually impaired user.

Our approach to providing interactivity resembles the touchscreen overlay systems that relied on thin raised line maps. By using conductive filament for parts of our 3D prints, we are able to extend the touchscreen's sensitivity up to the surface of our maps. This allows for a wider range of depth information than earlier overlay approaches. It also eliminates the need to orient the maps to any camera, allowing for additional portability and ease of use. Also, by developing our maps so that they work with interactive applications that run on common touchscreen devices, our system does not face the barrier to entry that systems with custom hardware face.

3. SYSTEM DEVELOPMENT

Our system began as an exploration of how to make online mapping tools available to visually impaired individuals via 3D printing. While at the time, examples of 3D printed maps existed, the tools necessary for visually impaired individuals to independently create them were lacking. Thus began a development process of alternately adding features to our modeling algorithm and modifying the web interface to give users control of these features. Later, when we learned of conductive filaments, we began exploring the possibility of incorporating interactivity into our system as well. In this section, we will describe the system as it exists now, with an emphasis on reasons behind the design choices we made.

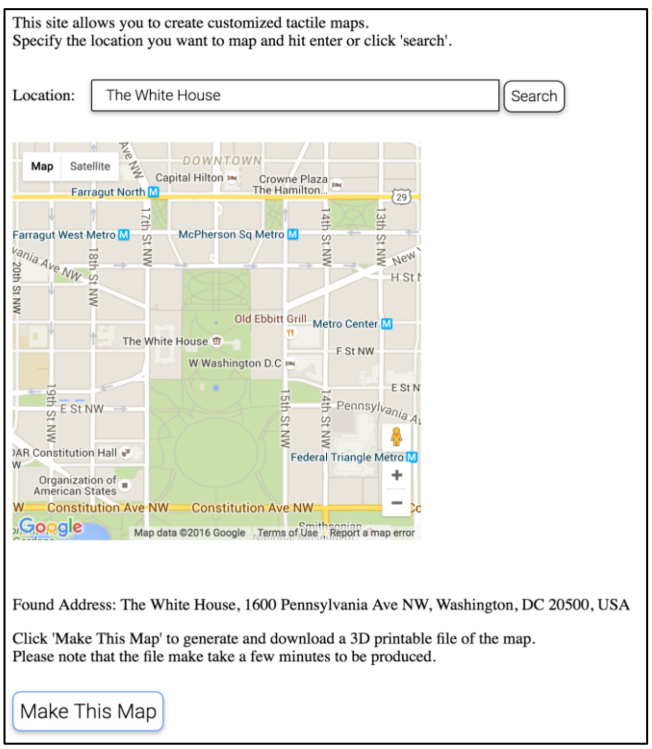

Figure 1. The simple web interface

3.1 Focus Groups

Throughout the development of this project, but prior to the evaluations described below, eight visually impaired individuals were interviewed either individually or as part of a focus group. The purpose of these interviews was to both explore potential use cases for customized maps and to receive feedback on models and web interfaces produced at various stages. While these discussions were informal, they did inform many aspects of our design.

3.2 Web Interface

Our web interface has evolved significantly throughout the development of our project. As we sought to balance intuitive interfaces and full customization, we created a series of interfaces exploring different levels of control.

3.2.1 Simple Interface

The simple interface is designed to generate a usable map with the absolute minimum amount of effort on the user's part. Users only have to search for an address and click 'Make a Map'. No customization options are available. The map is generated using a default set of parameters designed to provide an area of about .5 km^2. The web page, shown in Figure 1, does include a map image that displays the area centered on the location returned by the Google geocoding API. A text field labeled 'Found Address' conveys the resultant address or an appropriate error message in the case that no address can be found.

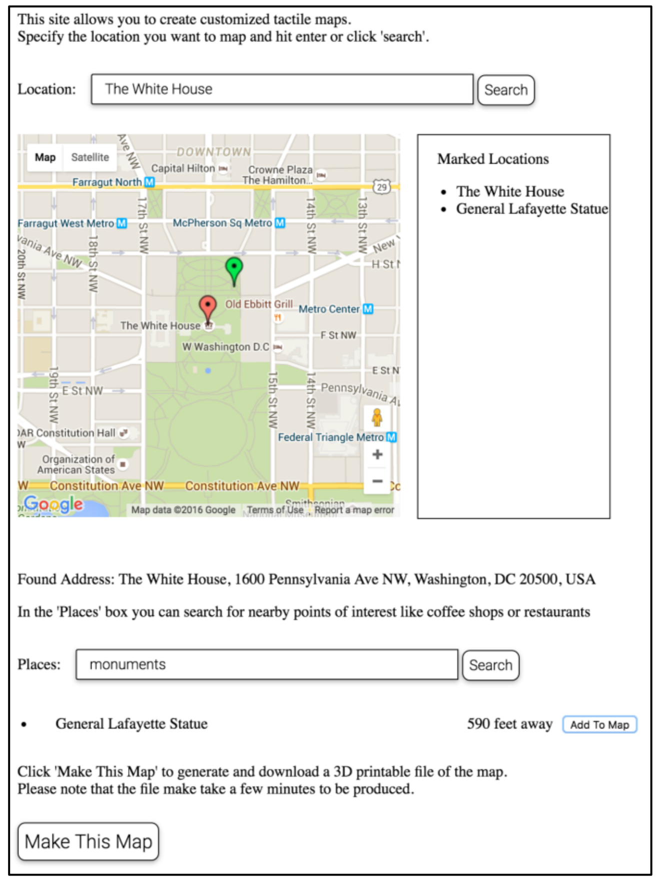

Figure 2. The places web interface

3.2.2 Places Interface

The places interface works much like the simple interface to create a map of a region using default parameters. However, users can then search for locations nearby using a second 'Places' text entry box (see Figure 2). The second box uses the Google Places API [12] to generate lists of relevant locations found within the map boundaries. Users can then select the locations they wish to tag and markers will be placed on the map models accordingly. Again, the 'Found Address' text field provides an indication of the map area and a separate 'Marked Locations' list provides a list of points that have been added to the map.

3.2.3 *Advanced Interface*

The advanced interface, shown in Figure 3, opens up a wide range of parameters to the user. Instead of merely specifying locations, users can adjust whether the locations are marked by geometric shapes or braille labels. Different map features can also be selected or removed from the maps and the textures and heights that will be used to represent the different features are also adjustable. Lastly, print sizes and coverage areas can be adjusted.

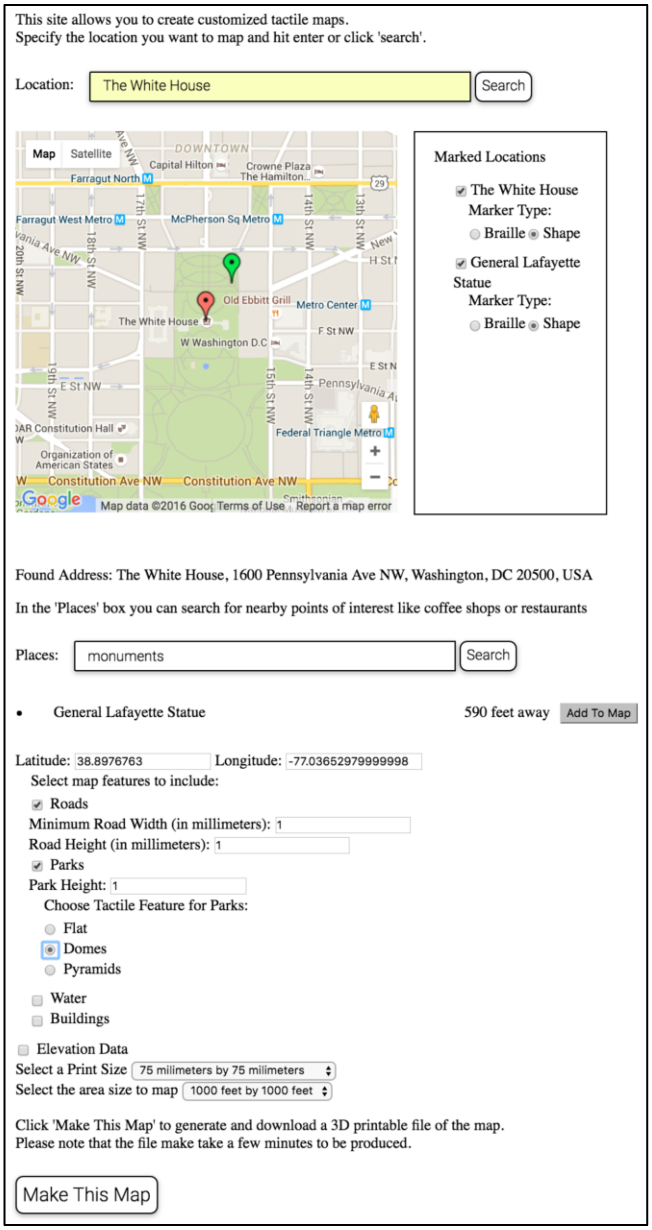

Figure 3. The advanced interface

3.3 Map Model Generation

Map models are generated by a set of Python modules that take various user-specified parameters. In this section we will describe the process by which our model-generating algorithm accesses data and generates 3D models to be printed.

3.3.1 *Map Data*

A majority of the data used to generate our map models is accessed via OpenStreetMap APIs [15]. Google APIs are also used to acquire elevation data and to geocode user-specified locations for both the maps and labels. Features designated in the OpenStreetMap corpus can then be represented as distinct tactile elements in our map models. Our current implementation can distinguish roads, walkways, buildings, waterways and parks. Additional features designated in the data corpus, such as pedestrian crossings or public transportation access, could be added to our models using a similar approach.

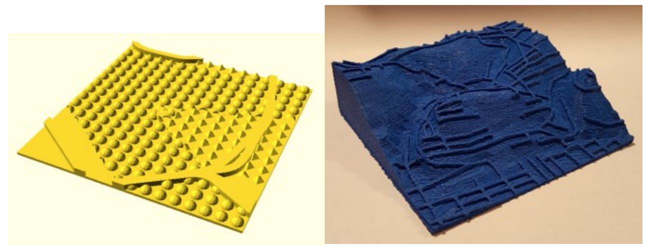

Figure 4. Tactile maps generated by our system. On the left, a rendering of a map model demonstrating different textures for different map regions. On the right, a printed example of a map including roadways overlaid on topographical elevation data.

3.3.2 *Generating the Models*

OpenStreetMap provides xml data containing the geographic coordinates of points, lines, and boundaries that define a number of map features (e.g., roads). Our code parses the xml data, grouping the relevant features into sets of polygons. Additional polygons are created for specified map labels and annotations. The polygons are trimmed to the specified boundaries and overlapping areas are hierarchically removed to leave a set of non-overlapping polygons that completely cover the specified region. Tactile features, specified by a layer height and a textured surface pattern, are then applied to each of the unique regions. Triangle meshes are then generated along all the surfaces, walls between adjacent features, and along the edges and bottoms of the mapped region. These meshes are then written out to an .stl file. Figure 4 (Left) shows an example of a generated model with four distinct tactile features. Water is represented by a pattern of domes, pyramids specify a park region, roads and non-defined regions both have flat surface textures, but roads are raised above the other features.

3.3.3 *Feature Validation*

Throughout the design process, we explored many variations in how different features could be represented. While we ultimately wanted to provide as much flexibility and customization to the end user as possible, we needed to establish usable default settings. To inform the default parameters, we created a set of example prints that demonstrated variations in how information could be represented. Some were designed to explore tactile perceptual preferences (e.g., what density of road patterns did users prefer) while others were more focused on the utility of potential representations of information. As an example, a print including direct representation of elevation data (Figure 4, Right) tended to draw more interest than flat maps, though most participants were skeptical of the utility of such a feature.

These example prints were shown to all focus group members as well as study participants to maximize feedback. The default settings for the maps generated with the simple interface (see

Section 3.2.1) are informed by this feedback. For the most part, user responses were consistent. Users preferred variations in width rather than height to distinguish different road types and, while they were often interested in additional map regions (e.g., waterways, parks), they expressed strong concerns over map complexity. However, one feature that received a decidedly mixed reaction was the approach to annotating roads by collocating braille labels on the back of the print. Figure 5 shows the two sides of such a map (the map was printed in two parts and later glued together). While some participants were intrigued by this approach, an equal number strongly disliked the idea of braille that was not horizontally aligned.

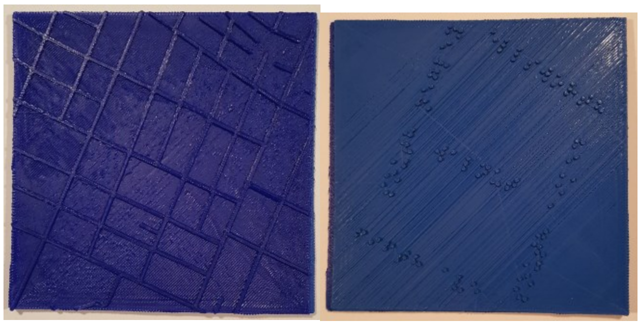

Figure 5. A neighborhood map (left) with the braille labels of major street names collocated on the back of the map (right). The image of the streets has been horizontally reversed to visually highlight the alignment between roads and labels.

3.4 Interactive App

Using tactile maps as overlays for touchscreen devices has been demonstrated as an effective way to provide interactivity and reduce the necessity of braille annotations [23]. Previous approaches, though, relied on the relatively low impedance of thin materials used to create raised line maps (typically either embossed or microcapsule papers). In contrast, our approach uses multi-material 3D printing that embeds isolated conductive regions in the passive plastic that forms the map. Through this process, we can extend our tactile maps into the 3rd dimension in ways that were not possible with other production methods without sacrificing interactivity.

3.4.1 Printed Components

In order to use custom printed maps with our interactive application, a customized case must be used. The case is designed to hold the maps in place against the touchscreen so that conductive touch points are properly aligned with the application's GUI interface. We designed a prototype phone case in which different maps can be slid in and out (see Figure 6). The phone case also has six static buttons that can be used to trigger specific application functions.

In addition to the custom cases, maps must be printed using a combination of passive plastic and conductive filaments. When placed on top of a touchscreen, the conductive filament will engage the touchscreen below when touched. In other areas, the plastic is thick enough to impede the user's touches so the touchscreen does not detect them. The maps are also given a Near Field Communication (NFC) tag to uniquely identify them.

3.4.2 Android Application

A custom application running on a phone or tablet identifies the particular map by its NFC tag and accesses the web interface's server to register the map. The conductive touchpoints, which can be user defined (see section 3.2.2) or automatically generated according to map features (e.g., major intersections) prior to printing, will have corresponding touchscreen buttons to register responses. When users then touch a printed touchpoint, the application uses text to speech to inform the user of the location they pressed. For example, the map shown in Figure 6 has touch points that were automatically generated at the intersections of the region's primary roads. When users touch one of the points, the names of the two intersecting roads are spoken.

The fixed buttons on the case can also be used to trigger specific functions such as providing the user's current location via GPS or instructing the user to orient the map to their surroundings using the magnetometer. Since the touchpoints are 3D printed like the rest of the map, the regions can vary in size and shape to make specific points or whole regions interactive.

Figure 6. An interactive map with 6 black conductive touchpoints. The map is held in a case with 6 conductive buttons that houses a Samsung Note 2 with a 5.5-inch screen.

4. VALIDATION

While we are not the first to use OpenStreetMap data to 3D print tactile maps [14,16], our modeling algorithm does offer depth information and tactile features not previously explored. However, additional features are not necessarily better if the underlying models are incomprehensible or the interfaces to create them are unusable.

To verify our system's utility, we conducted three related studies. The first study focuses on the web-interface and demonstrates that visually impaired users are able to use our tool to generate map models without assistance. The second study verifies that maps printed from models generated by our tool are understandable and usable. Finally, a small qualitative study explores users' experiences using the interactive overlays.

4.1 Web Site Validation Approach

As described in the Section 3.2, we have developed a small set of interfaces for our web tool, each offering slightly different controls for map generation. We recruited seven severely visually impaired participants with prior experience with screen readers to test the various web interfaces. Participants were allowed to use their preferred screen reader, with six choosing to use JAWS and the seventh using NVDA.

Each participant was given an explanation about the www.tactilemaps.net web tool and then presented with a set of printed map examples that highlighted different map features and options. We explained that we were seeking to evaluate the interface for our tool and were interested in seeing if the web tool was designed appropriately so that an individual could independently use it. We explained that there were three different interfaces, and that we would provide specific tasks for each interface.

Each participant was first presented with the simple interface and then asked to generate a map of any location they wished. During the trial period, the investigators did not answer questions, though any issues or concerns were noted for later explanation. After each trial, users were asked to provide qualitative feedback about the interface.

After successfully completing the first trial, participants were then presented with the two more complex interfaces. For the places interface, users were asked to generate a map of a specific location, search for restaurants, and add one of their choosing to the map. For the advanced interface users were asked to adjust the area of the map to 2 km^2 and to include elevation data.

We do not have a consistent evaluation across participants as we made improvements to the interface in response to issues that arose in earlier trials. Even so, all but one participant was able to generate a map using the simple interface. That participant said they rarely used the internet and their difficulty came with navigating the browser more than the web interface itself. Success was decidedly more mixed for the more complex interfaces. Early on, there was a lack of feedback if a searched address returned no results. Some participants would continue, assuming the search had worked, but ultimately be unable to create a map. Another issue arose with an autocomplete menu that would pop-up when searching for places. Participants were given no warning about the menu, but it would change the effects of navigating in the text edit box. These issues and others were addressed following the trials in which they were observed. The result is a much improved interface which at least one participant has continued to use to generate maps for their own personal use.

4.2 Model Validation Approach

To demonstrate that maps generated by our modeling approach appropriately conveyed geographic information we conducted a study using two example maps generated by our web-tool. The maps, shown in Figure 7, represent actual regions in Nevada, MO and Austin, TX. The maps varied slightly in the information they contained and both were produced as 2.1D road maps to provide a more direct comparison with prior work. The Nevada, MO map was the simpler of the two with three levels (markers, raised roads, and undefined areas) and four marked locations designated by different geometric shapes (a square, a circle, a triangle, and a pentagon). The Austin, TX map has five layers (markers with braille above them, roads raised, waterways lowered, and undefined areas between) and included 4 locations designated by raised regions with braille labels reading 1, 2, 3, and 4.

Five participants with severe visual impairments or blindness were recruited to evaluate the maps. For each map, we first asked participants to explore as long as they wished and to describe their impressions as they did. We did not specify whether these should focus on descriptions of perceived tactile features or their symbolic representations, though most users did both. Users were instructed that the rounded or notched corner on the map represented the Northeast direction on the Nevada, MO map and the Southwest direction on the Austin Map. We asked users to orient the map so that the North edge was farthest away from them and recorded whether the orientation was correct.

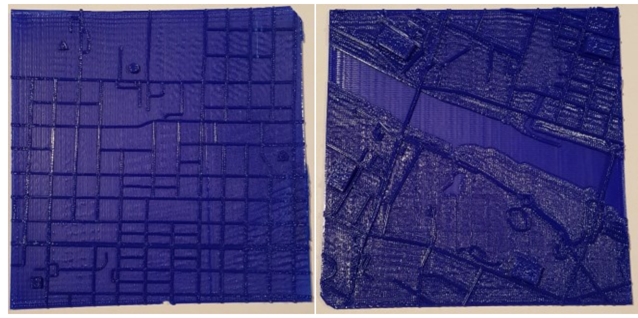

Figure 7. Test Maps. On the left, a map of Nevada, MO with 4 locations designated by geometric shapes. On the right, a map of Austin, TX, with 4 points designated by braille labels.

During their free exploration of the maps, every participant independently recognized the designated points on each map. For the Nevada, MO map, users were asked to (1) describe the shapes they felt, (2) specify which two marked points were closest to each other, and (3) provide directions from the triangle to the square, assuming the raised lines indicated roadways. On the Austin, TX map, users were additionally asked to identify the braille on the marked points. If they mentioned bodies of water in their description, participants were asked to indicate where the water was, if not, they were informed that the map did have a representation of water and asked to identify it. Due to a limited number of braille fluent participants and an issue with braille dots breaking off of the labels we did not collect proximity or direction information for the Austin, TX map. Table 1 lists the percentage of users able to accomplish the various tasks.

	Orientation	Labels Recognized	Nearest Points Identified	Water Feature Recognized
Nevada	5/5	5/5	5/5	N/A
Austin	5/5	5/5	N/A	3/5

Table 1. Map recognition tasks

As can be seen in Table 1, all users were able to orient the maps and located all marked points. Users easily identified the triangle, circle and square. The pentagon was easily distinguished as another, different marker, but slight warping during the printing process impacted users' ability to identify the shape. One participant described it as "a roundish shape with a point". Another participant thought that the triangle marker was an indicator of North rather than a marker like the others. Several participants did not notice the river in the Austin, TX map. However, all but one participant was able to correctly identify the lower region as a waterway when informed that one was present. That participant felt another area was water due to an unintended printing effect that created a surface texture that reminded them of how water was indicated on another map they had encountered prior to our study.

In additional to exploring and describing the features of the maps, we also asked the participants to provide directions from the triangle marker to the square marker on the Nevada, MO map while staying on roads marked on the map. The directions provided were unambiguous across four participants (e.g., "Go South on the road to the right of the triangle for 6 blocks then turn right…"). The fifth participant did not seem to understand the procedure and provided no directions. The paths described by the participants are marked in Figure 8 by the thicker lines with an

'X' indicating the final location after following the directions.

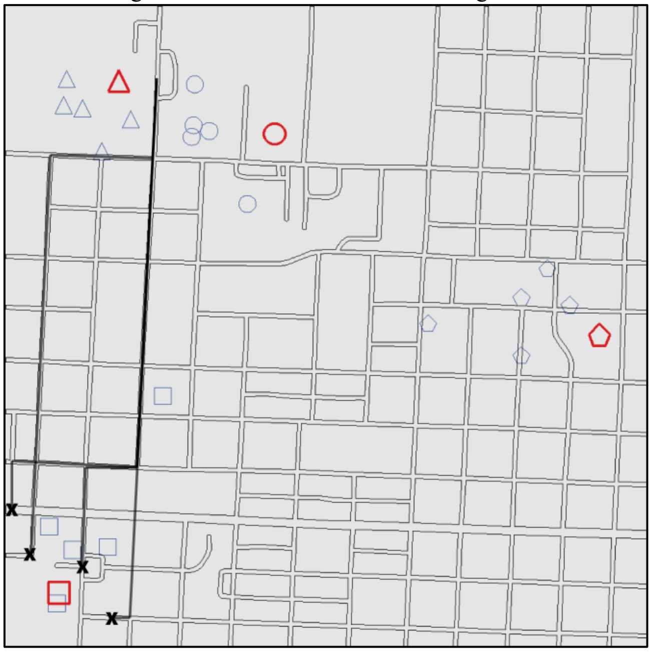

Figure 8. A map of Nevada, MO showing the same features represented on the tactile map presented to participants (see Figure 7). The larger red shapes show the actual locations of the marked points. The smaller corresponding shapes represent the locations marked when the participants recreated the maps. The shaded lines with X's at the end represented the path described by participants when asked to provide directions from the triangle to the square.

Finally, we employed a spatial cued response, as described by Kitchin, asking the participants to recreate the maps by drawing the locations of the marked points on a square piece of paper without tactile features [21]. The locations marked by each participant were then measured and transcribed (as the smaller geometric shapes) onto the map shown in Figure 8.

As we can see, users were able to provide generally correct, though often not exact, directions from the triangle to the square. Similarly, users were able to roughly recreate the maps. While we do not claim that our maps are better at conveying spatial information than previously tested approaches, we do feel that these results demonstrate a basic level of utility.

4.3 Interactive Overlay Exploration

Participants were provided with two prototype interactive maps. One was designed for an phone running our application (see Figure 6) the other was printed for use with an tablet (see Figure 9) . The participants were asked to freely explore the maps and describe their experiences. Feedback from their explorations will be discussed in the Future Work and Discussion sections.

5. DISCUSSION

In addition to the previously described tests, we also interviewed participants about their experiences with maps and navigation. Here we will focus on the most salient issues that will provide guidance to others interested in developing tactile maps.

Use Cases. From the beginning, we largely focused on developing maps for providing an understanding of an area covering a few blocks within an urban setting. While participants agreed that such a use case is reasonable, many other ideas were brought up that we had not considered. P1 was interested in a small scale, shopping area map and had actually commissioned a custom made map of such an area near their home. P7 was interested in how city neighborhoods were arranged relative to each other. In the same way that visual maps use different zoom levels to let users see different types of information, tactile maps need to be able to provide different amounts of detail depending on the user's intent. Systems that optimize for a particular use case (such as our simple interface) inherently limit the utility of the maps they create. Flexible, customizable controls (such as our advanced interface) need to be explored to satisfy different user needs.

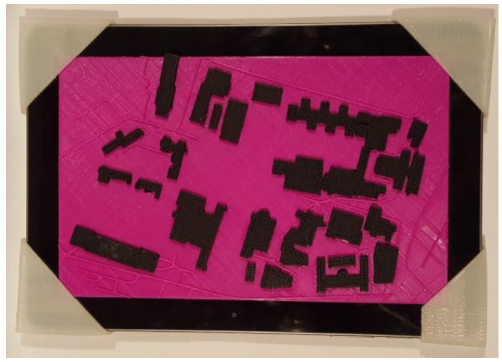

Figure 9. An interactive map of a college campus on a Samsung Galaxy Tab 10.1 tablet. The black buildings act as touchpoints and announce the building name when touched.

Holistic Explanations. Participants had a range of familiarity and interest with tactile maps, generally. However, none of them had particular experience with the 3D printed maps as we generated them. When introduced to the exemplar maps, many focus group members and study participants asked questions about features that were not present on a given map. For example, multiple users asked how big of a map we could create and others asked about labeling street names. For potential web users who have not been handed a physical map, the terse description, 'This site allows you to create customized tactile maps' almost certainly raises more questions than it answers. How to convey a sense of the tactile artifact that will result from learning to use our interface is a challenge that needs to be addressed.

Printing Limitations. An issue that we repeatedly encountered was that of the limitations of the 3D printer resolutions. When printing braille labels, the results, while usually legible, were suboptimal. P4 described it as "weird braille," saying, "It just doesn't feel good to me at all." Unintended print artifacts, such as a seam in a wider road or an area of the print that just happened to print more smoothly than others, also occurred. Participants noted several artifacts and often attributed meaning to the artifacts. As 3D printer quality continues to improve we expect many of these issues to be resolved, but in the meantime, care must be taken to use surface textures that exhibit clear, intentional differences.

Portability. In designing our interactive tactile overlays, we had imagined that users would find it advantageous to be able to interact with a map in the location. However, feedback about this idea was tepid, which is in line with surveys about tactile map preferences [27]. What remains unclear from our interviews though, is if this idea is biased by previous experiences with maps that are bulky and require considerable mental effort to decipher. Having interactive maps that could take advantage of location technology available in smartphones is not something they had experienced. Whether or not portability and customization would shift users' perception about tactile map technologies is something that we would be interested in exploring. Clearly, though, the first step is to make the underlying technology as available and usable as possible.

6. FUTURE WORK

While the system we have built is available online and is available for anyone to use, it would benefit from improvements. Each part of our system (the web interface, the modeling algorithm, and the interactive application) has a number of aspects that can be improved. Here we have highlighted the most pressing improvements we intend to work on.

6.1 Web Interface

Improve web interface usability. During the studies, there were some specific accessibility issues that were overlooked (e.g., buttons were not tagged in a way that brought them up on the JAWs screen reader's links list). However, most of these had straightforward solutions and have been addressed. A more systematic issue was a lack of properly detailed information about what the different website options would do and what the final result should be. Many users expected the generated map file to be immediately useful in some way. Simply providing a more detailed explanation of the process of generating the maps and providing links to 3D printing services would help.

Incorporate way-finding or path designations. One limitation of our current system is that there is no way to designate a specific path. While our modeling algorithm could easily raise specified road segments above others (or mark them with some tactile feature), users have no way to make such specifications. During our interview with an orientation and mobility specialist, it was brought to our attention that having an option to allow a sighted individual to designate a preferred pathway on a map could be a useful training tool. This idea was reinforced by P4, who mentioned that she often had her sighted husband check maps for audible crosswalks before planning routes. One can easily imagine a modified interface that allows a sighted individual to draw a designated path on a map. Alternatively, routing algorithms could be used to designate pathways.

6.2 Modeling Algorithm

Increasing the number of map features. OpenStreetMap currently recognizes 26 primary features, many of which contain a range of subfeatures. Due to time and resource limitations, we have not been able to incorporate all of these features. While too many different features on any given tactile map may leave it unusably complex, we believe providing the option to incorporate more features is better. In particular, features like public transit stops and audible crosswalks are high priorities for incorporation.

Increasing the number of surface textures. Currently our system only offers three different textures (flat surface or tessellations of domes or pyramids). The spacing and size of the tessellations, though, can be adjusted to create a wide range of textures. To expand upon this set, surface waves or randomized features could be implemented. Further exploration of how tactile perceptual limits and print resolutions interact to define readily distinguishable surfaces is needed.

6.3 Interactive Application

Explore additional touch interactions. Other interactive mapping approaches have explored accessing layers of information from a single region by distinguishing different tapping gestures (e.g., double or triple tapping) [23]. Thus far, we have only explored simple touch responses. In addition to tapping gestures, we intend to explore sequencing effects that could indicate sliding gestures from one point to another or the designation of an intended pathway between multiple points. We also intend to explore adding interactivity to specific map features, such as roads, as suggested by two participants.

Increase interactive element density. Using a dual extruder 3D printer, it is possible to print both the interactive and the static map parts together into a single cohesive object [9]. We hope to soon acquire such a system so that we can more efficiently produce complex interactive maps. Our first exploration will be to produce a map with a grid of as many discrete interactive points as possible. In effect, the tactile surface will be the same as any other non-interactive map, but the touch sensitive regions will resemble a lower resolution touchscreen. We are interested in exploring how a denser array of interactive points can lead to more sophisticated interactions.

Directly incorporate into the web interface and modeling algorithm. As dual extruder printers or multi-material printing services become more readily available, integrating the interactive elements into both the web interface and the modeling algorithms will become a necessary step. While we have taken steps in this direction (e.g., the web interface for designating points creates a file that is accessed by the custom app to map UI elements on the touchscreen), many aspects are still not fully customizable (e.g., no option currently exists to specify the audio response to the designated points).

7. CONCLUSIONS

In this work we have shown a complete end-to-end system which allows visually impaired individuals to independently customize tactile maps, have the maps 3D printed, then interact with the maps as either passive objects or as an overlay for touchscreen phones or tablets. Our system allows visually impaired individuals to independently customize maps with a much greater degree of freedom than any previous mapping system. In addition to selecting particular locations to map, users can specify the scale, the tactile features, and the labels to present on the maps. The usability of the publicly available web interface (www.tactilemaps.net) has been tested by 7 visually impaired individuals and iterated upon to incorporate much of the feedback we received. The 3D printable map models generated by our system offer novel features such as elevation data and adjustable tactile patterns. The modeling algorithm is designed to incorporate users' specifications and a test using example maps confirmed that basic geographical information is conveyed by our models. Finally, we introduced a technique of producing 3D printed tactile maps with conductive regions that allow for dynamic interactions with a wide range of touchscreen devices. We produced an Android application and multiple example maps that demonstrated the proof of concept for how such interactive maps can be generated along with dynamic content to resolve many of the labeling issues that surround tactile maps. This system, taken together, represents a significant step towards making user-specified interactive, 3D printed tactile maps an affordable and accessible way for visually impaired individuals to explore the world around them.

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