LucentMaps: 3D Printed Audiovisual Tactile Maps for Blind and Visually Impaired People

Timo Götzelmann
Nuremberg Institute of Technology
Keßlerplatz 12
D-90489 Nuremberg, Germany
+49 911 5880 1616
Timo.Goetzelmann@ohm-university.eu

ABSTRACT

Tactile maps support blind and visually impaired people in orientation and to familiarize with unfamiliar environments. Interactive approaches complement these maps with auditory feedback. However, commonly these approaches focus on blind people. We present an approach which incorporates visually impaired people by visually augmenting relevant parts of tactile maps. These audiovisual tactile maps can be used in conjunction with common tablet computers and smartphones. By integrating conductive elements into 3D printed tactile maps, they can be recognized by a single touch on the mobile device's display, which eases the handling for blind and visually impaired people. To allow multiple elevation levels in our transparent tactile maps, we conducted a study to reconcile technical and physiological requirements of off-the-shelf 3D printers, capacitive touch inputs and the human tactile sense. We propose an interaction concept for 3D printed audiovisual tactile maps, verify its feasibility and test it with a user study. Our discussion includes economic considerations crucial for a broad dissemination of tactile maps for both blind and visually impaired people.

CCS Concepts

• **Human-centered computing→Accessibility systems and tools** • Human-centered computing→Auditory feedback • Human-centered computing→Ubiquitous and mobile devices • **Hardware→Tactile and hand-based interfaces** • Hardware→Touch screens.

Keywords

Tactile maps; audio-tactile; blind; orientation; global; accessibility; tangible user interfaces; functional; 3D printing; capacitive; touch screen; marker; capacitive sensing.

1. INTRODUCTION

Tactile maps are an essential means to support orientation and navigation of blind and visually impaired persons. These maps can be used to familiarize people with neighborhoods, for journey planning or can be used in situ to improve the spatial understanding of blind users in unfamiliar urban environments [6]. Many of these tactile maps are mainly designed for blind people. According to estimations of World Health Organization (WHO), globally there are about 39 million blind people, but nearly a quarter billion visually impaired persons [38]. A majority of these people live in low-income settings and in some countries, visually impaired persons do not get financial support from the government (such as blind persons do). Ideally, visually impaired people could also benefit from tactile maps, and these should be affordable to this target group.

Since several years electronic versions of the maps can be generated automatically. Their physical representations can be produced by multiple printing technologies (e.g., [33]). Braille *embossers* approximate line drawings of maps by punching series of dots into ordinary paper. *Microcapsule (swell) paper* can be printed with monochrome drawings of maps where the dark parts swell when they are treated with controlled heat from a *fuser*. More recently, tactile maps are being produced by 3D printers which print elevated 3D models generated from map material. This technology has several advantages that can be used for structuring map content as well as the simultaneous use of multiple materials which is leveraged in this paper.

However, printed tactile maps from all these technologies have one characteristic in common – they have to be kept simple. There are multiple reasons for excluding Braille annotations from tactile maps. First, only a smaller proportion of blind people are able to read Braille at all [2]. It can be assumed that an even smaller proportion of visually impaired people can read Braille labeled maps. Another argument to exclude Braille labels is to limit the tactile complexity of maps. As pointed out by Tatham [29], the extensive use of Braille annotations in tactile maps may worsen the overall legibility of the maps. Additionally, similar to visual maps, the alternative of using legends and keys may complicate the interpretation of tactile images due to reduced immediacy [11].

An alternative is the combination of tactile maps with an interactive component. Recent studies [3] have shown evidence that interactive audio support for tactile maps is advantageous in relation to the ISO 9241 usability design goals. There are numerous approaches for audio-tactile maps. In this paper, we present an approach that can be applied to existing approaches using different tactile map designs, but additionally addresses the visual modality of visually impaired persons. Because these tactile maps are interactively supported by both auditory and visual cues, we refer to them as *Audiovisual Tactile Maps*.

2. RELATED WORK

There are numerous approaches for audio-tactile maps which use various techniques to support blind people. We report some of the most relevant approaches from a technological perspective. These

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audio-tactile maps can be differentiated according to *Zeng&Weber's* classification [36]. In our paper we refer to these categorizations, nonetheless we structure the approaches in a more purpose oriented manner in relation to our solution.

2.1 Pure Software Approaches

There are approaches, which mainly rely on communicating cartographic map features and directions using software and standard hardware built in off-the-shelf computers or mobile devices. Some approaches, also called *Virtual Acoustic Maps*, rely on *sonification*, i.e., they encode tactile elements and directions as sound (e.g., *Timbremap* [27]). Other approaches use touch inputs to explore an electronic map by playing sound files when the user enters specific regions of the touch input (e.g., [13]). Experiments show that this strategy may contribute to the spatial understanding of blind and visually impaired people. *TouchOver map* [24] belongs to *Virtual Tactile Maps* and displays street networks on mobile devices and uses a vibration actuator and speech to guide blind users along displayed streets. Since it uses conventional paper maps, it is mainly designed for people with low vision. These approaches simulate tactile sensing, but without a physical representation, which induces the user to cognitively transfer his or her sensation.

2.2 Integrated Approaches

There are several approaches to so called *Braille Tactile Maps* which utilize *Hyperbraille*, a technology mainly for blind people that uses the combination of a tactile display (a matrix of piezo actuators) with a desktop computer. There are multiple approaches from *Zeng et al.* (e.g., [35–37]) for interactive tactile maps that adapt their tactile rendition due to a user's touch interaction. Another approach [25] addresses the tactile exploration of building plans and outdoor maps, which is supported by a text-to-speech (TTS) functionality.

Adaptability is a key strength of this technology. Displayed maps can adapt their tactile renditions dynamically and interactive augmentation techniques (such as blinking encoded by oscillating tactile elements) can be implemented. Another technology is *Linespace* [28], a combination of a camera and a modified 3D printer attached to a whiteboard. Map updates can be initiated by people who are visually impaired whilst preserving parts of the previous map contents. One main advantage compared to *Hyperbraille* is the significantly lower production costs, however its downside is the lack of immediacy. Both, Linespace and tactile displays address a major claim of *Jacobson* [21], that map updates, especially cause a high cognitive load to visually impaired users when no context information is preserved. However, the drawbacks of these technologies are their limited mobility and availability.

2.3 Approaches Augmenting Physical Maps

The following approaches partially belong to the category *Augmented Paper-based Tactile Maps* and use physical representations of tactile maps in conjunction with electronic devices. The aim of these technologies is to provide additional information stored as electronic content to map features the user is interested in. This helps to reduce the tactile complexity of maps and thus, addresses the issue of tactile cluttering particularly caused by textual map annotations. The use of these two independent components makes it possible to solve two main challenges of tangible user interfaces. First, the physical component has to be identified by the electronic system in order to couple both the electronic and physical entities. Second, to allow interaction with particular parts of the map, its position and orientation have to be determined or restricted to specific constraints.

A system of a touch-sensitive surface and a desktop computer linked by a USB interface in combination with tactile overlay sheets was presented by the *Talking Tactile Tablet* (TTT) [20]. When exchanging these sheets, they had a specified size and layout and had to be arranged exactly in the frame of the touch surface according to three calibration points. After justifying the sheets, the user had to touch multiple positions to register the map with the system. A graphical user interface was used to create graphics as source for the tactile sheets that are printable by local Braille embossers. A subsequent approach [22] allowed the automatic production of TTT sheets for US maps optionally by third party companies.

Wang et al. [32] described a system to analyze existing visual maps in order to transform them into a simplified image that can be printed by embossers or on microcapsule paper. These prints could be placed over the displayed image of the original map. During exploration of the tactile map, the automatically extracted metadata of street networks was used for auditory feedback to map features. Another approach, *Touchplates* [16] presented a system of a tabletop computer and acrylic plastic overlays combined with visual markers. It was able to recognize these overlays automatically by a technology called *infrared based diffused illumination*, which is integrated in tabletops such as Microsoft PixelSense. *Brock et al.* [3] used a system of a touch input space and raised-line drawings on microcapsule paper to examine multi-touch exploration of visually impaired people. The approach *Mappie* [5] extended this approach for a study focusing on visually impaired children, that incorporated 3D printed objects which could be placed on the tactile map.

These approaches allowed the exchangeability of tactile maps and, partially, to recognize tactile maps by performing a manual procedure of multiple steps. The necessity to place the map exactly in a certain way on the touch device and the restricted portability of these systems are the limitations of these approaches.

2.4 Mobile Approaches

There are also several approaches which allow the transportation of both the electronic component and the tactile map, which has been shown to be helpful in a study done by *Espinosa et al.* [6]. *McGookin et al.* [21] presented a combination of opaque, raised paper overlays for non-visual interaction with dedicated applications using touch screens. *Sennette et al.* [26] presented a portable approach which allowed the use of tactile microcapsule prints of the popular *OpenStreetMap* database as an overlay for tablets and smartphones. After electronic map contents were loaded manually, the tactile maps were constrained to be placed exactly in line with to the display's borders. Another portable approach [9] relied on a combination of smartphones and 3D printed tactile maps placed on a flat surface. Users were instructed by voice commands to hold the smartphone above the map to recognize it by inscribed barcodes. An optical finger detection allowed users to query information about map features. A user study with blind users verified its feasibility, but this approach was considerably dependent on lighting conditions and constrained users to a one-handed exploration of the tactile map.

Hence, some of these approaches are portable. But even when the system supports interchangeable tactile maps, users have to carry out a defined, multi-step procedure when changing a map. Additionally, there are hard constraints for the arrangement of the maps on the touch displays which could impede independent use for blind people. In the following, we introduce a novel approach to overcome these issues and additionally supports visually impaired persons by augmentation of individual map features.

3. APPROACH

As pointed out in Sec. 1, our aim was to develop a highly mobile solution for audio-tactile maps for both blind and visually impaired persons that uses auditory and visual augmentation. The development of our approach required several initial design considerations to solve general questions of technical LucentMap design to make them usable with capacitive touch displays. Next, the step of changing tactile maps, i.e., especially the effort required to mount the map on the touch display, had to be minimized. Finally, for the realization of user interaction, software related questions had to be addressed.

3.1 Technical Map Design Considerations

There are multiple web services which enable the production of tactile maps for different printing technologies, mostly for raised line drawings. An inherent limitation of creating detailed tactile maps using microcapsule paper is the support of only one elevation (height) level. Even worse, the elevation cannot be reliably controlled. Small features as well as thin lines may suffer from under-elevation whilst extensive elevated areas are prone to heating artifacts when the fuser's temperature is set too high.

In contrast, 3D printers are designed to fabricate spatial structures and thus do not have this limitation when printing tactile maps. This technical feature can be exploited to support the grouping and differentiation of individual map features, and thus the map's readability. Another advantage is that 3D prints can be produced in a single pass whilst integrating multiple printing materials. This fact is leveraged in this paper to permit automatic recognition of maps (see 3.2). However, currently available 3D printed tactile maps cannot be used without modification for the joint use with touch displays. Multiple technical and physiological constraints have to be harmonized to adapt existing 3D printed tactile maps.

Three main factors influence our design considerations: (i) the discriminability of the finger's skin, (ii) the effective resolution of consumer 3D printers, and (iii) the ability of capacitive inputs to recognize touches through multiple elevation levels of a map. The latter raises the requirement to minimize the height differences between elevation levels.

Resolution of Consumer 3D printers

There are 3D printers on the consumer market that work according to different printing techniques. The most common consumer 3D printers work according the *Fused Decomposition Modelling* (FDM) principle. Printers of this type use thermo-plastic polymers, usually in the form of filament wound up on coils. By using stepper-motors for the x- and y-axes, each point on the printing bed can be accessed. The printing head melts the filament and deposits it on points defined by the 3D model. This procedure is repeated layer per layer, whereas the printing bed (z-axis) moves away from the printing head(s) for a defined distance. By using printers with two or more printing heads, multiple printing materials can be used to fabricate (functional) multi-material 3D objects in a single turn.

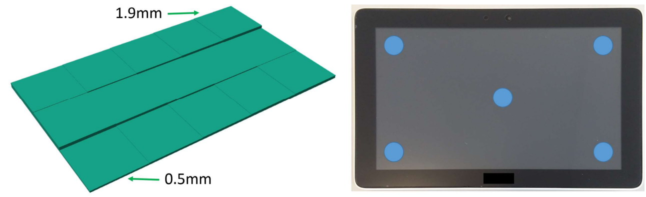

Fig. 1: Ramp of height differences to measure the range of distances for proximity touches of touch displays (at blue dots).

The resolution of these printers is dependent on numerous factors. The most important characteristic for realizing multiple elevation levels for tactile maps is the resolution on the z-axis (layer resolution). Current consumer FDM printers achieve up to 20 microns (20µm) layer resolution. However, printing with high resolutions may drastically increase printing time.

Discriminability of Elevation

Even fractions of a micron can be sensed due to deformations of the papillary ridges of the finger's skin [19]. However, this is only possible in specific settings which are not applicable to 3D printed map features. To ensure that the intended elevation of distinct map features is not confused with 3D printing artifacts, at least the nominal layer resolution should be used.

Smaller elevations require more time for reading [15]. The optimal elevation with regard to scanning time between two elevation levels has been determined to start at 160 microns [14]. According to *Way&Barner* [33], the exploration of tactile images follows two stages. First, the entire image is explored to gather a general overview and second, detailed information of specific parts is obtained. We adapt this strategy to the elevation levels of 3D printed tactile maps. On this basis, we propose that differences in elevation between categories of map features (area-, line-, point-features) should be elevated at least 160 microns. Only if needed, fractions of this value should be used to allow the discrimination of differences between individual map features within these categories.

Sensing Abilities of Capacitive Touch Inputs

Current mobile devices usually integrate capacitive touch displays which enable the registration of at least 10 concurrent touches by the device's software. The user interactions are tracked by frequent determination of the individual fingers' positions, which touch the display's surface. In order to locate the touch positions, a sensitive microcontroller (e.g., *Atmel maXTouch*) senses load changes in a uniform grid of sensor wires attached to the touch display. This grid may be located directly on the surface (surface capacitance) or be placed below an insulating surface, such as robust glass (projected capacitance). The latter type is used for modern mobile devices. An important factor is that load changes in the sensor grid can already be detected when a finger approaches the touch surface. Hardware manufacturers adjust their touch microcontrollers well to maintain an equalized touch sensitiveness over the whole display area. This controlled sensitiveness allows it to sense touches through thin non-conducting materials (e.g., paper, plastics, glass). In this paper, we make use of these technical characteristics and refer in the following discussion to such indirect touches as *proximity touches*.

To design tactile maps using multiple elevation levels, an initial study is necessary to find out the range of distances where proximity touches are detected by touch displays.

Methodology
We evaluated discriminable height differences in current mobile devices. We tested 20 devices to estimate the range of proximity to the display. We tested it through a 3D printed PLA ramp with ascending height differences by utilizing the open-source constructive solid modelling tool *OpenSCAD* [17]. It consisted of multiple adjacent platforms of 1.5cm^2 and height differences of .1mm in the range of .5-1.9mm (see Fig. 1). For each device, five measuring points (center and the display's corners) were evaluated. Each measuring point was touched a total of five times in decreasing distances from 1.9mm. We recorded the maximum distance proximity touches when each of the touches could be correctly recognized.

Results
The range of medium distances between devices[1] was 0.58-1.90mm (Ø: 1.17mm, σ: .40mm). Hence, each of the devices was able to detect proximity touches on average up to 0.58mm distance. However, more than 75% of the tested devices were able to detect proximity touches of ≤ .99mm. According to the results of our preliminary study on touch proximity, 75% of the tested devices were not able to detect proximity touches from a distance above 1.43mm. This information is useful to define the minimum distance of conductive materials which should not cause a proximity touch (i.e., the bridging component of the capacitive codes descried in Sec. 3.2).

Discussion
Based on the results of this study we argue that the elevation levels used for encoding tactile map features should remain below 1.0mm to ensure that map interaction by proximity touches is possible. Combined with the physiological characteristics of tactile perception, this makes it possible to have 4-5 elevation levels. For this additional level of freedom in 3D printed tactile map design, a reasonable strategy has to be identified. Although an in-depth study of multi-elevation-level map design for 3D printed maps is not the focus of this paper: we propose the following strategy for this paper (see Table 1).

Elevation	Map features	Examples
Level 1	Superior areas	Building blocks, campuses
Level 2	Inferior areas	Buildings
Level 3	Walkable streets	Residential roads
Level 4	Footpaths	Pedestrian zones, walkways
Level 5	Points of Interest	Bus stops, shops, accessible crosswalks

Table 1: Elevation levels and their associated map features.

3.2 Map Recognition

Capacitive coupling of human fingers is sensed by touch surfaces. By using conductive materials, this coupling can be passed along the surface (e.g., *Sketch-a-TUI* [34]) or through objects (e.g., *CapWidgets* [18]).

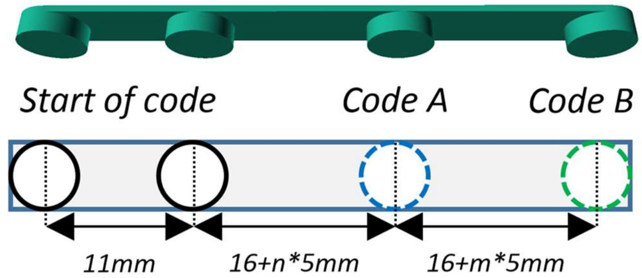

Fig. 2: The ID code which is embedded in the tactile map: varying distances by variables *n* and *m* encode a unique identifier which can be recognized through touch-displays.

When the capacitance of the user's finger is bifurcated to different locations on the touch surface, multiple concurrent touches are registered when the user touches this element [30]. The principle of bridging multiple points on the touch surface by conductive material can even be realized for untouched detection [31]. The concept of capacitive codes is based on the fact that distances between concurrent touch points can be measured. Because of this, these distances can be used to encode information.

We apply this principle to encode an identification of the tactile map[2]. Two touch points have at a minimum distance of more than 10mm to be detected as individual points. Larger distances between two points can be measured with an accuracy of at least 5mm. Our map ID code consists of four points in a row. The first two points are at the minimum distance of 11mm and mark the *start of code* (see Fig. 2). A third point (*Code A*) is placed at least at the minimum distance +5mm, to distinguish it from the beginning of the code. The fourth point (*Code B*) is placed in the same manner relatively to the third point. By varying the distances of Code A and B by multiples of 5mm, numerous combinations can be achieved. This code is integrated into the tactile map's 3D model and printed by conductive filament.

When the interactive application is started on the mobile device, it first requests that the tactile map with such an integrated capacitive code is placed on the touch display and for the user to touch or move it. This causes the registration of four concurrent touch points by the interactive application. The application detects the start of code (which is always two points at the distance of 11mm) and then measures the distances to both of the other touch points to extract the ID code. Besides the ID code, the exact position and orientation of the tactile map is extracted from the registered touch points.

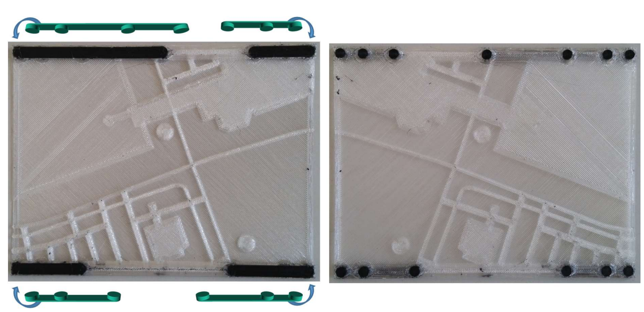

Fig. 3: Capacitive codes at tactile map's corners are printed with conductive filament. View from bottom side (right).

[1] Tested devices (Focus was on current lower cost tablets. Smartphones are marked italic): Acer Iconia One 10; Acer Predator 8; Apple iPad mini 4; Apple iPad Pro 12.9; Apple iPad Pro 9.7; Archos 101 Xenon Lite; Archos 7.0c Xenon; Asus Zenpad 10.1; Huawei MediaPad 10 Link+; Lenovo Yoga Tablet 3; *LG G Flex 2*; Odys Score Plug 3D 10.1; Samsung Galaxy Tab E 3G; Samsung Galaxy Tab E Wifi; Samsung Galaxy Tab 7; Samsung Tab S 10.5; Samsung Tab S2 9.7; Trekstor Surftab Breeze 7.0 Quad 3G; *Wiko Getaway*; Xoro Telepad 7 A3.

[2] Parts of this section have been previously published in Ref. [7].

For each map ID, there is a dataset which includes geographic coordinates of the map's corners, its real size and, optionally, a description of the map. This data as well as the information about the tactile map's position and orientation on the touch display serves to adapt the electronic rendition of the map and its touch interaction with the map to the overlaid physical tactile map. The visual representation on the map is aligned to the map's position on the touch display and its angle (when not parallel to the touch display).

The LucentMaps' cardinal direction north is always on the top side. Since the ID code is located to the upper left of the tactile map this serves as orientation for blind users who can feel the longish shape of the ID code. To make the maps also usable on small mobile devices, we integrated special codes for the remaining corners of the map (see Fig. 3). After the ID code of the map is recognized, these corner codes can be used to explore maps which are larger than the mobile device's display (see Fig. 4). These corner codes only contain the start code and a third point which encodes the corner by its distance to the start code analogous to Code A of the ID code (see Fig. 2).

3.3 Interaction

When a capacitive code is recognized, the actual user interaction starts. The user is able to explore the tactile map which is supported by touch interaction, speech input and output, and the visual augmentation of the map.

General

The integration of capacitive codes into the printed map minimizes the effort required to interchange tactile maps. The software offers a simple way to initiate an exchange of the tactile map.

LucentMaps are also designed to be used in situ to improve orientation. Due to their portability, both allocentric and egocentric exploration strategies [23] are possible. To support egocentric exploration, GPS and magnetic sensors, integrated in many mobile devices, can be used. If these modules can be activated by the software, the mobile application should be able to first communicate to the user whether she or he is currently located within the coordinates of the detected map. Secondly, the user should be able to know at which angle the map on the mobile corresponds to the real world's geographic directions.

Touch interaction

When exploring the map, users should have the opportunity to get immediate feedback about the map features they are interested in (such as its feature type and name). It is technically feasible to support many touch gestures through tactile maps. However, in order not disturb the tactile exploration, we decided to keep the touch interaction simple. For the immediate feedback on specific map features, double tapping on the desired map feature was used. We followed the suggestions of [3] to extend the time interval between the double tap to 700ms.

Since LucentMaps are designed to be used in an interactive context, we deliberately avoided integrating a scale into the tactile map. In contrast, the interactive application allows the determination of arbitrary distance measurements by a multi-touch gesture. One finger has to mark the starting point of the measurement (e.g., a crossing) and a second finger marks the end point of the measurement by simply touching the desired end position (e.g., a corner of a building). The exact real world distance is reported by the TTS. To not confuse blind or visually impaired users taking distance measurement with bimanual tactile

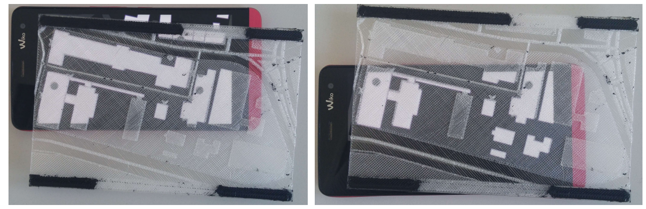

Fig. 4: User touches ID code at the map's top left corner and explores the map using a small device. By touching the code on the bottom left another part of the map can be explored.

exploration, this touch interaction has to be activated by an adequate voice command for each measurement.

Speech interaction

In order to facilitate the tactile exploration of the map, the touch interaction is kept simple. To access additional functionality, speech input is used. In order to ensure acceptable response times and to be independent of internet access during exploration (e.g., when maps are used in situ), the speech detection works offline on the mobile device. The functionality covers (i) showing all map features of a certain class (point-, line-, area features), (ii) showing map features of specific categories (Health, Eating&Drinking, Shops&Services, Culture&Entertainment, Nature&Leisure, Transport&Traveling, Accessibility) and should (iii) allow the user to obtain more detailed information about specific map features. Finally, the functionality mentioned before (measuring distances, locate and help user to be congruent to real world directions, changing maps) should be accessible by speech input. The results of these interactions are also communicated by speech output. In the case of multiple map features, the TTS speaks the number of the augmented map features.

Visual augmentation

The electronic map consists of area (e.g., buildings), line (e.g., streets) and point (e.g., traffic lights) map features. Visually impaired users should be able to augment each of these groups individually. Moreover, many of these map features are equipped with descriptive tags in order to characterize them (e.g., regarding their classification). Users should be able to augment each element of a specific class, (e.g., shops, pharmacies, public transport). Additionally, when selecting an area or line feature by double tap, the shape of this individual map feature should be augmented.

4. FEASIBILITY

To test the feasibility of the requirements defined in Sec. 3, we printed multiple maps and implemented a mobile application for detection of the maps and interactive components.

4.1 Creation of maps

There are several approaches for the automatic creation of 3D printable tactile graphics (e.g., [4]). For this paper we used a specialized web service (http://blindweb.org) to generate 3D models [8] usable for printing tactile maps. Its medium map detail level covers an area of 422x287 meters; the actual map's scale is depending on its printed size (1:1875 for a printed size of 22.5x15cm). By using its Python-API, we developed a plugin for the free open source 3D authoring tool *Blender 3D* [1] to automatically adapt these maps to the constraints of our approach and to substitute them with capacitive codes. The resulting multi-material 3D model was stored in two complementary 3D models (.STL) which share a joint coordinate system. This combination can be used by common 3D printing software for multi-material prints.

For the actual fabrication, we used an off-the-shelf dual-head 3D printer (*FelixPrinters FelixPro 1*), working according to the FDM principle. To print the map prototypes, we used a transparent filament, *FormFutura HDglass^{TM}*, for the tactile map itself and *Proto-pasta Conductive PLA* filament for the integrated capacitive codes. The fewer layers used, the less light scattering occurs. Hence, to both minimize printing time and to maximize translucency of printed maps we chose a layer resolution of 160 microns.

We intentionally omitted the integration of a wind rose or arrows for cardinal directions, because north on the maps is always represented by the upper bar containing the biggest capacitive code. On the one hand, this capacitive code can be used to find the cardinal directions relative to the map contents. On the other hand, the mobile device's compass could be used to obtain the orientation of the map contents relative to their real world entities. Likewise, a fixed scale was not printed in the map since the software allowed exact measurement of each distance the user is interested in by a two finger multi-touch gesture.

4.2 Mobile application

We implemented a mobile application for Android tablets and smartphones which run on at least API level 15 (Android 4.0.3), which is supported by the most current Android devices.

4.2.1 Implementation of functionality

For the recognition of the 3D printed tactile maps, we implemented an algorithm for detecting the capacitive codes embedded in the corners of the tactile map. When started, the application waits until it registers the four concurrent touch points in a line. Next, the detected touch points are classified. First, the start of code is extracted, followed by the classification of *Code A* and *B* based on their distance to the preceding point. When the map's ID is determined, its assigned geographic coordinates and real size are retrieved. Together with the computed coordinates and angle of the tactile map on the display, the electronic map is configured. The user is briefed about the recognized map.

For the map rendering and interaction, we relied on the *Mapsforge SDK*[3], which has also been used for numerous other research works. It uses compressed maps from the *OpenStreetMap* database. Our application determined the geographic coordinates from touch interaction with the map even when the map view was rotated by the angle determined by the capacitive codes. For example, a double-tap on one position in the map queried the map database for features at that position. Then the information about the map feature's type and name was communicated by the TTS. The results of queries (e.g., to highlight all buildings) were visually augmented by adapting the rendering styles of the map.

For the speech interaction, we utilized the *CMU PocketSphinx SDK* [12] developed for offline speech detection mobile devices. It supports multiple detection models, such as context-dependent phonetic search, which allows good recognition results. Because of likely performance issues on some mobile devices, we had to use context-independent search which had to be tailored to our application to achieve reasonable results. To limit the unintentional triggering of voice commands, we defined the keyword "Computer", which is needed to start the actual recognition. We implemented a state machine to navigate through our auditory menu. To increase the detection accuracy, in each level only a small dictionary of recognizable words was used. The auditory menu structure by its detected words is listed below (curly brackets for submenu):

- Overview {Buildings, Streets, Points}
  To show each representative of a feature class.
- Show {Eating, Health, Travel, Shop, …}
  To show representatives of a feature category.
- Which {Name, Type, Else}
  To obtain detailed information about a map feature the user points at.
- Map {Locate, Distance, Change}
  To get information about GPS and orientation to real world directions; to measure distances on the map; to change the tactile with another map (starting with recognition of capacitive code).

For text output, we used the standard Android TTS engine. For this study we only used the normal voice speed. However, the speed can be easily set to user's preferences for optimal use.

4.2.2 Usage scenarios

In the following, we define three intended usage scenarios in order to illustrate possible procedures of usage.

Blind person using tablet

Prior to a trip, the user wants to familiarize himself or herself with the target area. The user starts the application on a tablet computer and places an appropriate tactile map on its display. The user touches the capacitive code and waits for the acknowledgement that it has been recognized. Next, the user simply fixes the map by two strips of adhesive tape. Now, the user queries the map for public transport and street names to the destination, memorizes their shape and measures distances. The user is also interested in descriptions of buildings surrounding these streets. This scenario could also apply to a visually impaired person (e.g., when searching for the way from a bus stop to a building), who is additionally supported by visual augmentation (see Fig. 5).

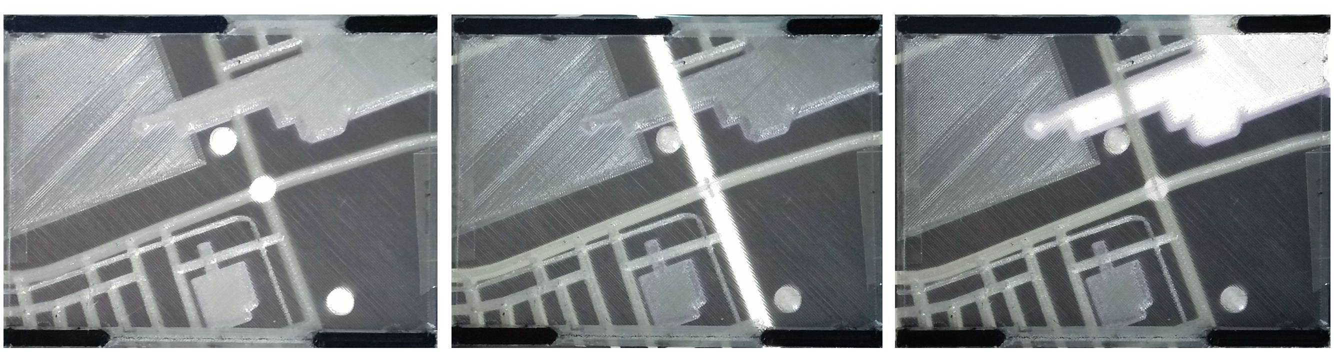

Fig. 5: User queries map for public transport and traffic map features (left), followed by a double-tap on the street (center) and finally on the building (right). For each of these interactions the TTS tells name and type of the corresponding map features.

[3] https://github.com/mapsforge/

Visually impaired person using smartphone

A visually impaired user wants to consult a tactile map on a journey after arriving at the target area by bus. He or she retrieves the smartphone and a map out of their pocket, places the map on the smartphone and touches the capacitive code. Subsequently, the TTS reports the description of the map and the map is fixed by adhesive tape. She or he initiates the location feature in order to orient the map to real world directions and then explores a part of the map. Since the display is smaller than the map, another corner of the map is placed on the display and the corresponding corner code is touched. After the application recognizes the new corner of same map, it adapts and the map exploration continues.

Visually impaired person using tablet

The map is recognized just as in the previous scenarios. This time the user explores the map of a crowded area of a city center. By using voice commands, he or she gradually browses through the map feature categories and requests additional information about augmented map features of special interest.

5. EVALUATION

To assess whether blind and visually impaired people are able to use our approach and to obtain qualitative feedback, we conducted a brief application-driven user study. Because we think the target group for interactive tactile maps are mostly younger people, we cooperated with the regional school for visually impaired and blind persons.

We recruited nine participants (five females) with an average age of 15.67±5.57 years. Six of the participants were visually impaired (5-30% residual vision), one had residual vision of 2% and two were blind. Each of the participants had basic knowledge about tactile maps. For the study, we used an inexpensive off-the-shelf Android tablet (*Huawei MediaPad 10 Link+*) with our implementation of the detection of capacitive and the interaction with the tactile map as described in Section 3. The display was set to maximum brightness, augmented parts of the map were represented by white color, whereas the remaining map features were indicated by a dark grey color.

Procedure

Initially the participants were given a brief description of the tactile maps and that mobile device touch displays are able to detect touches even through thin plastic. It was explained that capacitive markers are attached to the top and bottom sides of the map and that the tactile map can be automatically recognized by the tablet by touching or moving these markers on the tablet's display. Next, they had the chance to explore a trial map and were instructed to find the ID code which is the largest (black) structure located on the upper left side of the map. Subsequently, multiple use-oriented tests were carried out with each of the participants.

1. The participants were asked to grasp the tactile map from the table and to place it on the tablet computer's display. Next, they had to locate and touch or move the ID code until they heard the TTS message that the map had been recognized. Finally, they had to shift and tilt the map to another position at least three times, using the capacitive code each time to reorient the system. After each shifting or tilting action they had to rest for a short while until the TTS finished reporting the changes in coordinates and angle.
2. After that, participants had to explore a tactile map fixed by adhesive tape on the tablet. They had to find each of a point-, line- and area-feature and obtain verbal explanations by double tapping these map features. The visually impaired participants were asked to show the visually highlighted shapes of line- and area-features.
3. Next, voice commands were used to highlight
   a. all restaurants,
   b. all buildings and
   c. all point-features

   on the map. In each case, the visually impaired people were asked to determine the number of highlighted map features.
4. Finally, after activating the distance measuring feature by using the voice command, the participants were asked to measure the distance between two map features on the map by using a multi-touch gesture.

Results and Discussion

All of the participants were able to place the tactile map on the tablet's display and to use the capacitive code for detection of the map. When the users relocated the map, this was detected by the application and the correct angle was reported (1). All of the participants were successful, none of the users needed numerous trials, which resulted in registration timings considerably less than 10s. Multiple users tried to rotate the map more than ±90 degree which resulted in failure to recognize the code. However, this was a technical issue which could be solved by software in future versions.

All of the map users successfully managed the task to obtain additional information on point-, line- and area features (2). Visually impaired users recognized the rough shape of augmented map features and each of them recognized the correct number of augmented point features (3a+3c). Four visually impaired participants recognized the correct number of 11 augmented buildings on the tactile map, one counted only 6 buildings and another was not able to see adjacent buildings (see Fig. 6) as individual buildings. Each of the participants were successful to carry out the multi-touch gesture (4) in order to measure the distance between two map features.

Both groups of people, blind and visually impaired, were curious to use the interactive approach. They obviously liked the fact that the map is automatically recognized when its capacitive code is touched on the tablet's display. Multiple users mentioned that it should be combined with a popular navigation application called *BlindSquare*, in order to be able to "feel" individual map features. One participant proposed to invert the augmentation of the map features, i.e., to augment the whole map except selected map features. Another participant liked the mobility of the map and the fact that small maps usable with smartphones or tablets do not attract attention of sighted people in contrast to large maps. Finally, the users had multiple suggestions on improvements of the map design. Despite map design is not the focus of this paper this information can be used for our future work (see 6.3).

Voice commands had to be repeated in some cases. We expect that outdoor use could be problematic and suggest using a

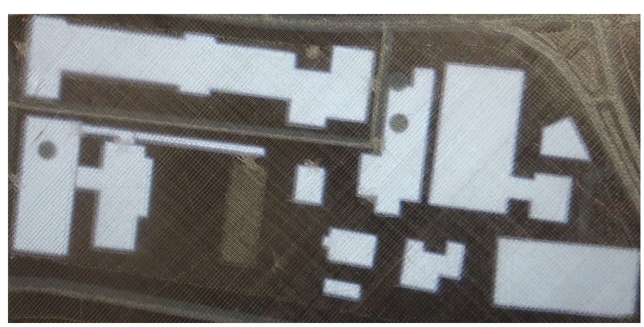

Fig. 6: Augmented tactile map: adjacent buildings on the left weren t recognized as individual buildings by one participant.

Bluetooth headset for future applications. Despite the implemented keyword-search functionality, the voice recognition had to be disabled by the test supervisor between the individual tests, since sometimes unintentional commands were detected. For future versions, we suggest integration of a dedicated button in one of the display's corners which would allow speech-recognition when it is pressed instead of the keyword-search functionality.

6. DISCUSSION AND LESSONS LEARNED

This section discusses outcomes of our research and proposes improvements for future development of 3D printed *Audiovisual Tactile Maps*.

6.1 Costs and Availability

As discussed in the introduction, costs are an important factor for many in the target group. Exemplary 3D printed tactile maps of 10x15cm had an average weight of approximately 10g and consisted of ~90% transparent HDglass filament (750g: ~$40) and ~10% conductive PLA (500g: $48). On average, this means that the material costs of such a map usually is below $0.60. Even cheap 3D printers may be suitable for printing LucentMaps – we successfully tested prints with a dual-head 3D printer with a price point below $1000. Because there is a competitive market for 3D printers and filaments, it can be expected that this will continually drive quality and cost reduction of these mass products. Suitable tablet computers and smartphones can be purchased for less than $50.

6.2 Limitations

Besides the technical issues regarding the voice input, the magnetic sensor used for the compass functionality sometimes delivered skewed orientations. To prevent this behavior, users should always wave the device in an infinity-shaped manner before using the orientation feature. The offline map material used by the *Mapsforge* framework is freely available on the internet. However, it is pre-processed to be stored efficiently in a compressed format, which also incidentally excludes some special tags for accessibility. By using existing tools, specialized map material for blind and visually impaired people could be generated from the *OpenStreetMap* database and provided to the community through the internet.

Consumer 3D printers still lack standardization and their usability is still limited in terms of software and hardware. However, when these components are well adjusted, they can already produce 3D printed tactile maps in a consistently high quality. The main challenge to tackle in the future, however, is to identify how the tactile representation of automatically created maps should be and how this can be technically achieved in general (including multiple zoom levels). Since a similar task has been solved for electronic visual maps decades ago, the authors are confident that this can achieved for tactile maps as well. To realize this, the promising research results of user studies carried out to address these questions (e.g., [2,5,35]) have to be transferred to formal rules for computing functional and usable maps. Likewise, for volumetric tactile material there is an increasing number of publications (e.g., [10]) which could help to optimize the usage of multiple elevation levels (such as sketched in Sec. 3.1) for tactile map design. This has to be done with current and upcoming technologies in mind. Multiple tactile reproduction technologies should be addressed by an integrative approach to reach most of the blind persons.

6.3 Future Work

The visual augmentation of the transparent tactile maps is dependent on lighting conditions. In bright areas (e.g., outdoors) this could impede the recognition of augmented map features. Similar issues could occur for speech interaction. This is also true for standard use of mobile devices for sighted users. However, we plan to carry out a comprehensive user study to assess different augmentation techniques including varying light conditions, the effect of noise on speech interaction, and the benefits of using a Bluetooth headset for in situ orientation (such as Espinosa [6]).

Auditory and visual output should ideally be redundant to support blind and visually impaired people in equal measure. Currently, there is still a bias towards visual augmentation. Especially when the user prompts to highlight categories of map features (e.g., public transport), the application merely verbally reports *how many* of these map features are on the map, but not *where* they are located on the map. The individual map features are only visually highlighted. Hence, verbalization of the position of individual map features and, ideally, a verbal description of their shape as a complement to the tactile exploration of map features by blind people is in the focus of our future work.

Our approach can be applied to diverse tactile maps and thus, this paper did not focus on tactile map design. In our future work we plan to carry out a comprehensive user study about the discriminability of multiple elevation levels and on design considerations for 3D printed tactile maps.

7. CONCLUSION

We presented a novel approach designed for both blind and visually impaired persons. It extends the concept of audio-tactile maps by extending the visual modality. Particular map features are augmented by illumination and groups of map features sharing content-related characteristics are emphasized.

Our approach significantly simplifies the combination of mobile devices with physical tactile maps. By integrating conductive elements into the tactile map, the user is able to register maps by a single touch or movement of the tactile map placed on a touch screen. It does not require the placement of the map in a specific way or aligned to a specific axis. Even completely oblique arrangements of the map can be used immediately. A sufficient fixation of the map is possible by simply attaching two strips of adhesive tape on the borders to the map. No extra attachment system is needed; the strips can be reused and temporarily stored on the mobile device's backside. We carried out a study of capacitive displays in order to obtain characteristics of proximity detection. These results were used to propose usage of multiple elevation levels of tactile maps.

The maps used for our approach can be automatically generated by existing approaches. The conductive elements for the recognition of the maps can also be automatically integrated. This combination can be reproduced in a single turn by off-the-shelf 3D printers. Additionally, this approach does not necessarily need large displays, it also works with displays smaller than the tactile map. When at least one corner is placed on the display the parts overlaying the device's display can be explored by the user's fingers. This makes the maps pocket-portable and they can be used in situ with audio tactile maps on a normal smartphone. We implemented a mobile application to test feasibility and evaluated our approach by an application-driven user study. The authors think this could contribute to the broader dissemination of audio-tactile maps.

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