Exploration of Location-Aware You-Are-Here Maps on a Pin-Matrix Display

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***Abstract*—Supporting blind and visually impaired people with digital maps that can enhance spatial awareness and learning about the surrounding environment is a challenge. This study introduces an audio-tactile you-are-here map system that presents map elements and users' updated location on a mobile pin-matrix display for blind and visually impaired people. In addition to panning and zooming a map, in the system, a set of tactile map symbols consisting of raised and lowered pins have been proposed to present varying map elements. A field test with eight visually impaired subjects and eight blindfolded subjects who did not have experience with tactile maps and Braille was conducted. Subjects would locate surrounding streets easily after a short-time training, as well as nearby point-of-interests (POIs). The results of the evaluation indicated that the mean relative distance error was significantly lower with nearby POIs, which do not require panning while exploring, than far away POIs. Furthermore, it is important to improve the portability of the proposed prototype and develop a one-hand map exploration method.**

***Index Terms*—Audio-tactile user interface, location-based services, tactile maps, tactile symbols, you-are-here (YAH) maps.**

I. Introduction

VARIOUS maps (e.g., street maps, tourist maps, and floor plans) help blind and visually impaired people to acquire spatial information, prepare journey routes, or learn about related geographic information. In addition to printed maps, map applications on different electronic devices have been used widely. The colorful visualization of such interactive maps and dynamic routes enhance user experience for sighted people. However, for blind and visually impaired people, visual-based maps and map applications are inaccessible.

To support blind and visually impaired people to access map data, tactile maps on different materials (e.g., microcapsule paper maps and thermoform plastic maps) have been developed [1]. Newer tactile map systems incorporate geographic information systems (GIS) [2], [3]. Most existing tactile maps are desktop-based although some global positioning system (GPS)-based navigation applications on mobile phones or special assistive tools (e.g., the BrailleNote GPS and the Kapten mobility device) can guide the visually impaired to their destinations via Braille and/or audible turn-by-turn instructions. Despite this, these navigation applications do not support exploring the surrounding environments and learning detailed spatial layouts of nearby geographic features, such as the shape of a street and its spatial relationship to nearby points of interest (POIs).

You-are-here (YAH) maps, installed on walls or wooden boards, help people to locate where they are within their surroundings and to learn about their surroundings [4]. In general, a YAH symbol indicates the users' current location. Unfortunately, these visual-based YAH maps are not accessible to blind and visually impaired individuals, and few mobile map applications provide accessible YAH maps.

Unlike the concepts which resemble an audible torch [5], which presents POIs in the front and with limited field of view via pure audio feedback, we are interested in allowing blind and visually impaired people, while walking, to locate themselves on maps in a panoramic view and to learn spatial relationships to nearby map elements through independent audio-tactile explorations. We introduce an audio-tactile YAH system to enhance the experience by the visually impaired in exploring real-world environments. The audio-tactile YAH map system is implemented on a touch-sensitive pin-matrix display with a matrix of 30×32 pins. Tactile map symbols and tactile YAH symbols have been designed for representation of different map elements (e.g., streets, bus stations, and buildings) and users' updated location and heading direction. We conducted a proof-of-concept field test using the proposed system where blind and visually impaired subjects, including those without traditional tactile map and Braille experience, can interact with the location-aware maps using functions such as panning and zooming and discover the surroundings in unknown regions.

The remaining parts of this paper are organized as follows. Section II surveys a number of existing accessible maps. In Section III, the proposed audio-tactile YAH map system is presented, and an evaluation with end users is in Sections IV and V. This paper ends with a discussion in Section VI.

II. Related Work

A. Pin-Matrix Displays and Related Applications

Generally, blind people read information on computers through single-line Braille displays or audio feedback. It is difficult to access graphical content, like geometrical curves, photos, and maps. In order to render graphic contents, tactile pin-matrix displays have been developed [6]. Pin-matrix displays can be classified into two categories. One is based on electromechanical actuators, such as piezoelectric refreshable actuators [7], voice-coil motors [8], [9], and shape memory alloys [10]. The second utilizes chemical polymer-based materials that can be

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reshaped [11]. At present, pin-matrix displays with piezoelectric actuators are available in commercial tactile graphic-enabled displays, like the HyperBraille display and the DOTVIEW 2 display.

As emerging assistive devices, pin-matrix displays are employed in many applications to support blind and visually impaired individuals reading graphic content, drawing and accessing tactile animation [12], and playing tactile games (e.g., Sudoku [13] and Ping-Pong Game [14]). Users can read web pages on a tactile web browser [15]. For interactive in-car menu design, Blattner *el al.* presented the advantages of pin-arrayed displays compared with common touchpads, in terms of menu interaction time and gaze behavior [16]. Prescher *et al.* investigated a tactile windowing system on the HyperBraille display [17].

B. Interactive Tactile Maps

To make tactile maps interactive and to render more map data, computer-based audio-tactile maps have been developed. In addition to GIS, audible feedback verbalizes geographic-related information (e.g., street and bus stop name) by text-to-speech (TTS) or human voice. Some map systems play semantic sounds to indicate the categories of geographic features [18].

Compared with previous audio-based map systems that do not show spatial layout of POIs [19], [20], tactile maps are able to present an explicit tactile layout of maps on different kinds of substrates. In terms of map representation and interaction, interactive tactile maps mainly consist of four types: enhanced paper-based tactile maps, virtual tactile maps, touchscreen-based maps, and pin-arrayed tactile maps.

Enhanced paper-based tactile maps (e.g., [21]–[24]) improve the performance of traditional paper-based tactile maps (e.g., microcapsule paper maps and embossing paper maps) by placing such maps on a touchpad and playing auditory information about the contacted map elements. The paper-based substrate can be used to produce street maps for different cities, but interactive map operations (e.g., panning and zooming) cannot be supported.

Virtual tactile maps (e.g., [25]–[27]) render maps via cyberspace and are explored via peripheral equipment (e.g., mouse, gamepad, and force-feedback device). The single point of contact of the virtual maps does not support exploration using fingers or hands, common for reading tactile paper maps.

Touchscreen-based devices are used widely by blind and visually impaired people. Many map systems on touchscreen displays have been developed, like the TouchOver Map [28], the Access Overlays system [29], and the Timbremap system [30]. However, due to a lack of explicit tactile feedback, those touchscreen-based maps cannot help users acquire correct spatial layout information in complex areas, such as the direction of roads and whether the roads closed [28].

Pin-arrayed tactile maps in [31] and [32] are able to support tactile perception via raised pins. Shimada *et al.* presented an overview European map on a desktop pin-matrix display having a matrix of 32×96 pins, without street map data with varying POIs [32]. Although the tactile street map system in [31] can support panning and zooming, it is not suitable for location-aware applications.

C. Location-Based Accessible Maps

The GPS enables location-based applications on mobile devices for sighted and visually impaired people, in particular, various navigation applications. Although there are a number of wayfinding systems that guide visually impaired pedestrians by audible feedback (e.g., [33]–[35] and [36]) or haptic turn-by-turn instructions (e.g., [37], [38]), few systems support users to explore and learn about their surrounding environments.

Accessible location-aware map systems with an exploration function can be categorized into two types: virtual exploration maps and real exploration maps. The virtual exploration maps have no real map representation, but only auditory description of surrounding geographic features. For example, Talking Points [5] allows a user to point her/his mobile phone in a required direction in order to acquire information (e.g., name, distance) about nearby POIs up to 100 ft, and with the SWAN system [39], users can find the categories of close POIs via auditory icons.

The real exploration maps render the surrounding geographic features according to the user's updated location. The touchscreen-based maps enable users to get the street names by touching, like the Ariadne GPS. Due to the lack of tactile feedback from the smooth screens, it is difficult to learn the spatial layout of streets and POIs, direction of streets, as well as the shape of intersections [28]. Although pin-matrix displays support a better tactile sensation for fingers compared with common touchscreen devices, there is no location-based map system to allow an exploration of surrounding geographic features, except for rendering nearby obstacles [40], [41].

III. Audio-Tactile You-Are-Here Map Explorer

To present city maps and updated location for blind and visually impaired people, we introduced an audio-tactile YAH map explorer on a mobile touch-sensitive pin-matrix display, namely TacYAH Map.

A. System Architecture

The TacYAH Map consists of three main modules, *Input Module*, *Processing Module*, and *Output Module* (see Fig. 1). Using the *Input Module*, users can enter their map operation commands (e.g., panning and zooming) on their mobile devices, such as the mobile pin-matrix display and the mobile phone. When receiving users' commands, the *Processing Module* processes the commands and then generates related output responses, including required map data. In the *Output Module*, the tactile maps are presented on pin-matrix displays via tactile map symbols consisting of raised and lowered pins, and audible information (e.g., street/POI names are played). In case of unintended commands input by touch gestures, the prototype employs two controllers on a mobile phone and on a cane. Users are able to input map operations commands (e.g., panning, zooming) on demand via either the mobile phone or the electronic cane.

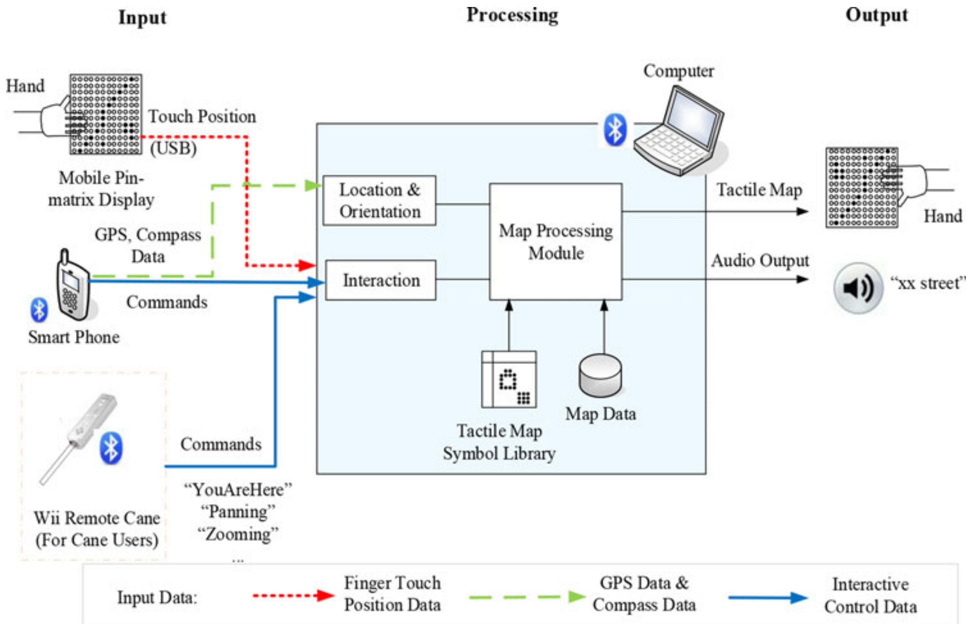


Fig. 1. System architecture of the proposed TacYAH Map system.

(a) (b)

Fig. 2. (a) Touch-sensitive pin-matrix display. (b) Vertical Braille cell.

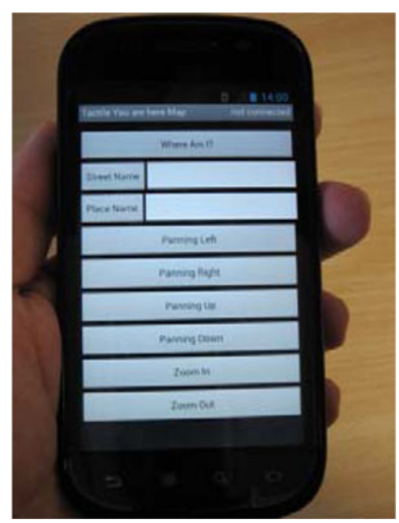


Fig. 3. Accessible mobile phone client of the TacYAH Map system for exploring YAH maps.

B. System Component

1) Touch-Sensitive Pin-Matrix Display [see Fig. 2(a)]: The tactile display consists of a matrix of 30 × 32 refreshable pins with no function keys, and its weight is about 0.6 kg. Benefiting from its novel vertical cells [each cell has 2 × 5 pins; see Fig. 2(b)], the assembled size of the pin-matrix area is 7.0 × 8.1 cm with the height of one cell being about 5.2 cm. The piezoelectric pins can be raised or nonraised. Since each pin can be raised to 0.7 mm and the pins are spaced 2.5 mm apart, the raised pins can be easily distinguished by users' fingertips. The resolution of the display is about 10 pins per inch. The tactile force of each raised pin is more than 30 cN which ensures that the raised pins can stand up even when being touched. Most importantly, since there is a capacitive sensor layer placed on the top of the pin-matrix area, users can make touch gestures on the display [42]. The display can refresh the whole screen typically at 5 Hz and is connected to a host computer via a common USB cable that supplies power and data. Each cell requires 0.08 mA with 5-V power input by a USB cable, and in addition to other electronic components, the maximum power consumption of the display is approximately 1 W.

2) Mobile Phone: An Android touchscreen phone is employed, which runs the TalkBack screen reader and allows blind and visually impaired people to interact with the phone by touch and speech. In addition, it offers updated GPS location and orientation for the system. The phone also has an accessible interface to support exploring the YAH maps: panning, zooming, and acquiring auditory street/POI names (see Fig. 3). With the help of the TalkBack screen reader, it is possible for blind and visually impaired users to explore the menu and control the tactile

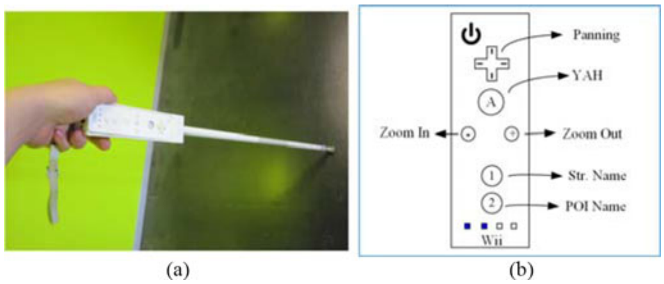


Fig. 4. (a) Wiimote Cane and (b) the functional keys for exploring maps.

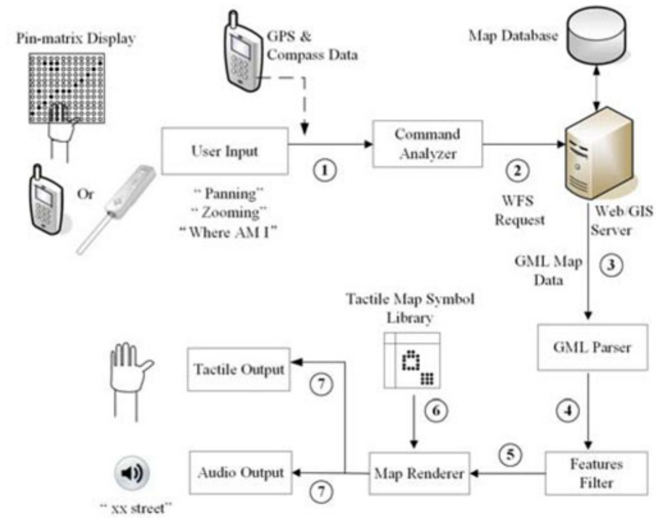


Fig. 5. System data flow of map data processing.

maps using one hand. This allows users to hold and control the phone with one hand while simultaneously exploring the tactile display with the other.

3) Wiimote Cane: It is an especially designed white cane whose handle has been replaced with a regular Wii controller [41] and [43] [see Fig. 4(a)]. The cane's built-in keys are used for controlling the maps (e.g., panning and zooming) while walking, as illustrated in Fig. 4(b). When the cane is used, the mobile phone should be mounted on the body, such as on the shoulder. Thus, the Wiimote Cane is very helpful for white cane users.

4) Computer: A lightweight laptop computer (2.4-GHz CPU, 4-G RAM) runs the main application and the software and connects the other peripheral devices (i.e., pin-matrix display, mobile phone, and Wiimote Cane) via USB or Bluetooth. The computer can be put in a backpack.

Other hardware components include a bone conduction earphone to avoid shielding environmental noises.

C. Typical Scenario of Usage

The TacYAH Map prototype is designed for exploring the surroundings when standing on streets where GPS signals are available. The Wiimote Cane is designed for cane users. The mobile phone as a controller can be used by noncane users and cane users. When cane users use the mobile phone to explore maps, she/he has to put the cane aside.

1) Scenario of Usage of Mobile Phone: If users want to know the names of POIs or streets, they need one hand to touch the screen for triggering commands, and one finger of the other hand to contact corresponding POIs or streets. For panning and zooming, users only need one hand to touch the buttons on the mobile phone. The application supports TalkBack screen reader to offer TTS services.

2) Scenario of Usage of Wiimote Cane: The Wiimote Cane can be used as a normal white cane for detecting obstacles, and also as a map controller. Users can pan and zoom maps with one hand; however, for acquiring the names of POIs or streets, one finger of the other hand needs to touch the corresponding POIs or streets.

The unintended commands is due to users pressing an incorrect key via the controllers, for example, a user plans to zoom in but she/he presses one key for panning. In order to avoid unintended commands, the TacYAH map system plays the commands (e.g., panning left, zoom in) via TTS when triggering via either of the two controllers. The system will not allow the input of a new command until the previous command is processed. Once users trigger an unintended command, they are able to try the opposite command to return to the previous status.

D. Software Components

1) Map Data and Database: The map data are downloaded from the OpenStreetMap (OSM) [44], a crowd-sourcing and free map provider. To store and access the geographic data, a spatial database (PostgreSQL and PostGIS software) and a GIS server (Geoserver software), have been adopted.

2) Main Program: This is run on the host computer. In addition to map data processing and representation, the main program handles users' interactive map explorations.

Other software components include the WiimoteLib library used to connect the Wiimote cane and the host computer via Bluetooth.

E. Map Data Processing

It is challenging to abstract various map elements (POIs) from colorful image maps, even though several available systems are able to abstract street networks, without POIs [23]. However, vector-based maps already contain detailed and structured attributes of map elements, such as the XML-based geography markup language (GML). Compared with image processing-based methods, the study makes use of the GML data while transferring and representing map data, which not only reduces calculation overload, but also contains detailed data of POIs (e.g., name, category, and location).

From the aspect of system data flow, the map data processing has seven key steps (see Fig. 5).

1) Users touch maps on the pin-matrix display and input commands (e.g., getting street name, panning, or zooming) through the mobile phone client or the Wiimote cane; meanwhile, the current mobile phone statuses (i.e., GPS and compass data) are required.

2) The Command Analyzer generates a relevant Web Feature Service (WFS) request and sends the request to the GIS server.
3) The Command Analyzer generates a relevant WFS request, and sends the request to the GIS server.
4) Using spatial analyses on the GIS server, the received WFS requests are processed and the related GML map data are sent to the clients.
5) The GML parser parses the received GML map data.
6) A geographic feature filter removes irrelevant features. This step is essential to tactually present the map layout and map elements for blind and visually impaired people. In order to simplify and adapt the map presentation, a series of methods were employed. A specific filter filters out nontargeted categories (e.g., rivers, lakes) and POIs without names, when extracting map data from OSM. In addition, to prevent the overlapping of map elements, an algorithm maintains space (at least two lines) between map elements presented, either shifting or removing the conflicted map elements. The current prototype only rendered pedestrian paths (e.g., streets) and several types of POIs.
7) Looking up tactile map symbols for the targeted geographic features and the corresponding tactile YAH symbol according users' current heading direction.
8) Rendering of the targeted geographic features and users' location on the pin-matrix display using the predefined symbols one by one.

F. Map Data Representation

1) Tactile Map Symbol Library: The tactile map symbol library consists of two types of tactile symbols: map symbols and YAH symbols. Most of the existing tactile map symbols are designed for maps presented on microcapsule paper, thermoform substrates, and embossing paper, such as the Nottingham Map Making Kit [45] and the Euro-Town-Kit [46]. Compared with those substrates, our tactile display has a lower resolution (ca. ten pins per inch) and its pins have only two statuses, which makes the task of designing map symbols challenging. Additionally, there have been limited studies that focus on designing tactile map symbols on such pin-matrix displays.

Taking into account a large number of categories of geographic features existing on city maps and the limitation of the pin-matrix display to render tactile information, in this study, we focused on those POIs most relevant to the visually impaired. For investigating the importance of geographic features in everyday life, we recruited 12 blind people to complete a questionnaire. The subjects rated the importance of each kind of POI (with 1 being the most positive and 5 the most negative) from a list of 40 common POIs. The 11 most important categories of POIs appear in Table I.

In this system, we proposed to design map symbols by specific patterns of raised and lowered pins, rather than by abbreviations of map elements in Braille, because not all legally blind people have Braille skills and only a few choose Braille as their primary reading medium; for example, in the USA, only about 9% of legally blind children aged 0–21 prefer Braille [47]. Based on the 11 categories, a set of tactile map symbols has been designed, and Fig. 6 illustrates the tactile map symbols.

To inform blind users about their current location and heading orientation on a map, three sets of tactile YAH symbols were initially designed for the TacYAH Map system (see Fig. 7), where the arrow-based symbols not only express the user's heading orientation while walking, but also her/his updated position indicated by the central points of the symbols. To evaluate the three sets, seven legally blind individuals (three females and four males) were invited for a pilot test. The participants' ages ranged from 20 years old to 50 years old, with a mean age of

TABLE I
TOP 11 MOST IMPORTANT CATEGORIES OF POIs

Rank	Category	Mean Rating (STD)
1	Railway Station	1.33 (0.49)
2	Bus/Tram Station	1.42 (0.51)
3	Pedestrian Path	1.58 (0.67)
4	Traffic Lights	1.67 (0.78)
5	Intersection	1.75 (0.87)
6	Supermarket	1.83 (0.72)
7	Hospital	2.00 (0.74)
7	Drug Store	2.00 (1.13)
9	Taxi	2.08 (0.90)
10	Clinic	2.17 (0.58)
10	Bank	2.17 (0.83)

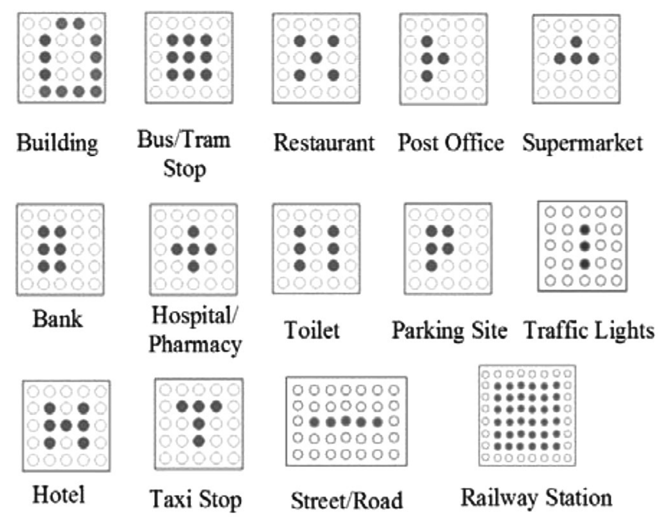


Fig. 6. Tactile map symbols (black dots are raised pins).

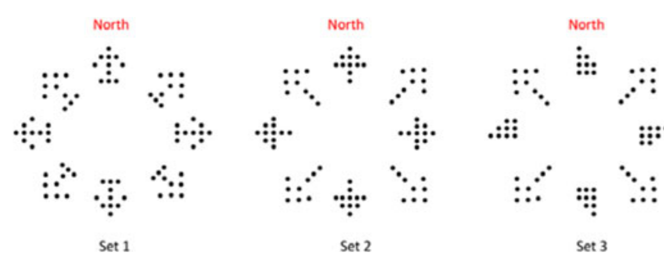


Fig. 7. Three sets of tactile YAH symbols.

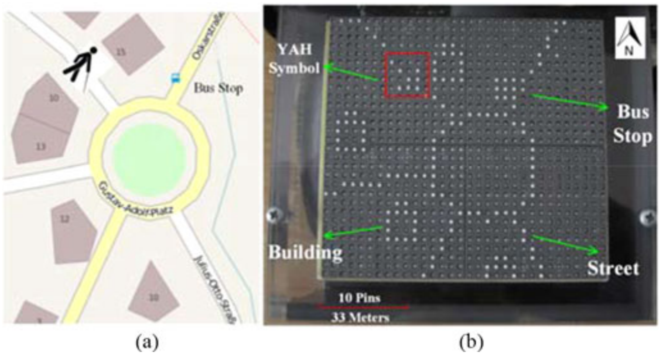


Fig. 8. Map representation of the TacYAH Map system. (a) Screenshot of visual digital maps. (b) Map on the TacYAH Map system.

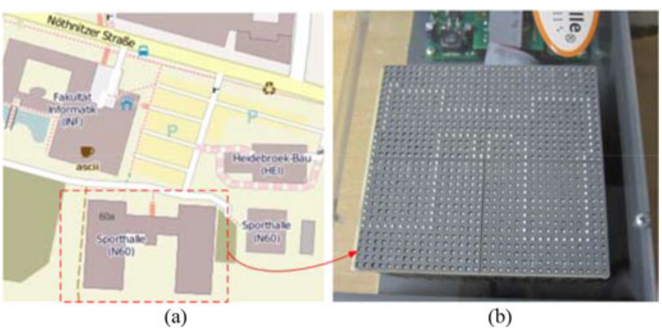


Fig. 9. Example of building shape view. (a) Screenshot from OpenStreetMap. (b) Building shape of "Sporthalle" in TacYAH Map system).

30). The three candidate sets were printed by a commercial embosser printer. Five subjects chose Set 2, and the remaining two chose Set 3. Thus, Set 2 has been adopted for developing the TacYAH map system.

With the help of the predesigned tactile map symbols and YAH symbols, the TacYAH Map system can render a YAH city map by patterned raised pins. Fig. 8 illustrates the tactile map representation when a blind user walks to a complex crossing. Additionally, the proposed system uses "north-up" maps, where the orientation of the presented map was not changed, but the direction of the corresponding YAH symbol rendered could be changed according to users' heading orientation.

2) Default Map Scale: The map can present three views with different map scales: a street view in which only streets are rendered, a POI view where streets and POIs are presented, and a specific building shape view (see Fig. 9). The street view has a smaller pin resolution (about 5 m/pin) than the POI view (about 3.3 m/pin). For rendering the shapes of buildings with varying size, the map scale in this view is flexible, and users can change the setting by zooming. In other words, the whole screen represents an area of 150 × 160 m in the street view, and an area of 100 m × 106 m in the POI view.

G. Interactive User Interface

The TacYAH Map system has several interactive user interfaces, via the mobile client or the Wiimote Cane.

1) Auditory Output: TacYAH Map speaks verbal information such as the name of a street or a bus station in response to map symbols on the display being touched by one finger, through TTS.

2) "Where Am I?": This function renders a corresponding YAH symbol, depending on a user's current orientation, in the center of the map, so that users are able to locate themselves on maps quickly and explore the surrounding environment flexibly. It will not modify the regular display settings, such as the "north-up" setting, map scales, and map symbols. For example, if after several times of panning maps users cannot find the YAH symbol, they are able to use this function to render the YAH symbol (their current position) in the center of the display.

3) Panning: When pressing the panning buttons on the mobile phone or the cross keys (i.e., left, right, up, and down) on the Wiimote Cane, the map is moved for a fixed distance in the intended direction. The fixed distance is about one-third of the length or width of the display (it is not suitable to replace the whole screen while panning, as this might let users lose their previous focus and prevent them from maintaining their orientation).

4) Zooming: Users can zoom in and out on the tactile maps with the function buttons/keys. There are three zoom levels implemented in the TacYAH Map system: for street view, POI view, and building shape view.

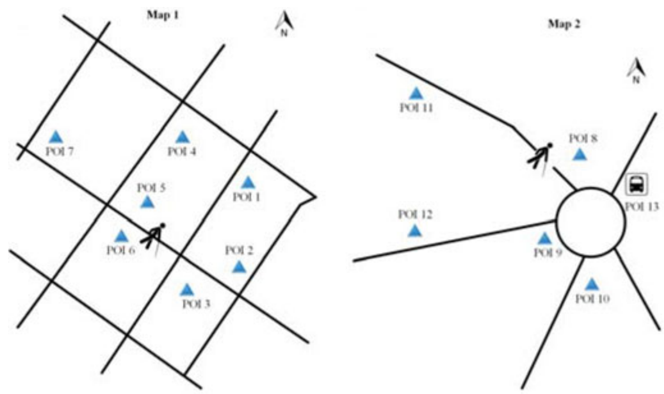
IV. Evaluation Methods

The study was conducted under the framework of the Ethical Guidelines for Educational Research [48]. In this section, an evaluation with 16 subjects in outdoor environments is presented.

As a map application for blind and visually impaired people, it is important to allow users to query their location and surrounding environments, while on the go, especially when getting lost or while in unfamiliar areas. Therefore, our hypotheses is that with limited training, users whether with or without tactile map and Braille experience will be able to locate themselves and discover the spatial relationship (i.e., distance and direction) between themselves and the nearby streets and POIs.

A. Participants

Eight legally blind and eight blindfolded participants took part in the evaluation. In the blind user group (four females and four males), two had severely low vision and the mean age was 32.7 years. All subjects in the blind user group were cane users and had vast experience using Braille and the traditional tactile maps (e.g., microcapsule paper maps and thermoform plastic maps). Six had experience using GPS-based turn-by-turn navigation systems. In the blindfolded group (four females and four males), the mean age was 30 years, and none had used Braille and tactile maps. It was the first time any had used the TacYAH Map system, although several of the blind participants had taken part in experiments testing other desktop pin-matrix display-based systems [17].



(a) (b)

Fig. 10. Maps of two selected test sites. (a) Map 1 with seven streets and seven landmarks. (b) Map 2 with five streets, one roundabout, and six landmarks).

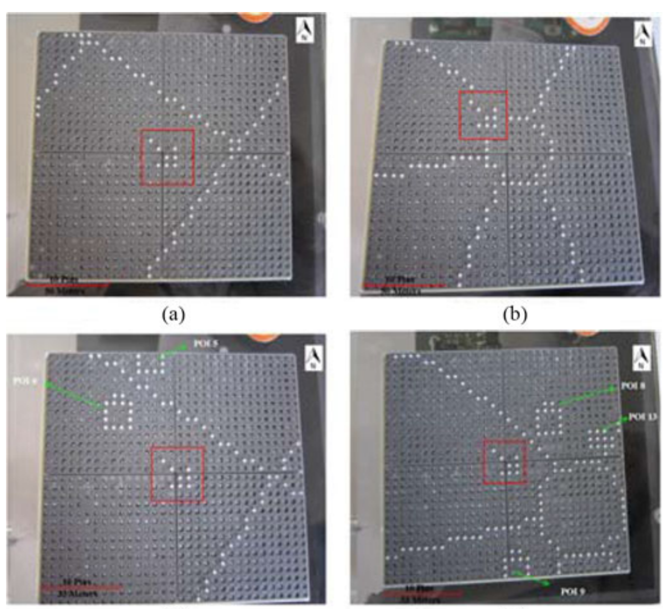


Fig. 11. Subject's initial position on the two maps (the YAH symbol in a red square) (a) Street View of Map1 (b) Street View of Map2 (c) POI View of Map1 (d) POI view of Map2 .

B. Test Environment

Two outdoor test sites with different layouts were chosen. Both sites were located far away from the city center and all subjects confirmed that they had never previously visited the two places. The first site consisted of seven streets and seven preselected POIs. The streets within the first test site were structured in a regular shape [see Fig. 10(a)]. The second site was located in an irregular area, containing five streets, one large roundabout, and six preselected POIs (including a bus stop), as shown in Fig. 10(b). The various landmarks selected included: a kindergarten, a police station, and residential buildings. Their names are numerically (e.g., POI2, POI8) in the paper, but during the evaluation, the real names were used.

In order to compare the participants' performance, subjects were asked to stand at a fixed point with a preselected heading

TABLE II
SPATIAL RELATIONSHIP BETWEEN THE SUBJECTS' STANDING POINTS AND THE 13 SELECTED POIS

POIs in in Map1	Distance (m)	Ori. (clock)	POIs in Map2	Distance (m)	Ori. (clock)
POI1	190	10	POI8	15	10
POI2	145	11:30	POI9	30	1:30
POI3	81	1	POI10	75	1
POI4	170	8:30	POI11	105	5:30
POI5	35	7:30	POI12	110	3:30
POI6	15	5	POI13	33	11
POI7	202	6:30			

Fig. 12. Overview of the proposed TacYAH Map system (the Wiimote Cane as the input device).

orientation (see Fig. 11). Table II lists the spatial relationships (i.e., distance and orientation) between the two fixed points and the POIs represented on the maps. The distance is calculated by the Google Earth rule tool, and the orientation is measured by their locations on maps. The preselected directions and any information associated with the two test sites were not divulged to the participants.

C. Test Settings of the TacYAH Map System

To reduce the impact of the unstable heading orientation while holding the mobile phone, the mobile phone was fixed on the shoulder. Since all blind subjects were white cane users, for the evaluation, all participants were asked to use the Wiimote Cane to explore the maps. The pin-matrix display was placed in a shoulder bag, as shown in Fig. 12. The system was evaluated with the first two zoom levels, i.e., the street view and the POI view. To reduce the load of learning so many tactile map symbols, in the POI view, only the bus/tram station symbol, the building symbol, and the YAH symbols were used. The digital compass was calibrated before each trial.

D. Procedure and Tasks

All subjects were taught the map symbols and the YAH symbols and how to use the system, with a posttraining test. The training task was conducted in a lab, away from the two test sites, and the training map was a well-known area for most of the participants. All questions raised by the subjects were answered. After the subjects acquired related skills, they were guided to the two test sites by bus and by foot, before being asked to begin the evaluation. At the end of the evaluation, they were asked to provide feedback in a brief post-questionnaire.

The two user groups were asked to complete the following five subtasks in order, and the first two were finished in a lab.

1) The training task used a training map from another city which was unfamiliar to all subjects. In addition to learning the eight YAH symbols, building symbol, and bus stop symbol on the mobile pin-matrix display, they were taught how to interact with the maps via the Wiimote Cane. Specifically, how to calculate distances by using their fingers was taught, as well as the map resolution in the street view and the POI view. Several short training tests were completed, which were similar to the tasks in the main evaluation, such as exploring the training map, pointing out the surrounding streets and POIs, panning, and calculating relative distance and orientation to POIs.
2) For investigating users' performance with the YAH symbols, we selected four of eight YAH symbols (i.e., southwest, east, northwest, and south), and participants were asked to identify their heading direction as quickly as they could when various heading directions were rendered on the display.
3) The participants needed to locate their location and the nearest streets in four directions. They had to report their approximate heading direction (e.g., east, southwest), the street names and the corresponding direction to them (e.g., left, right, front, and back). Note that only streets were presented for this task.
4) This task was to find out about nearby POIs within 100 m and report their relative spatial relationship (i.e., distance and orientation) in POI view. Participants had to pan. Since users were familiar with analog clocks, they were asked to give their orientation of nearby POIs using headings such as 3 o'clock. For this task, as in the POI view, the panning distance is about 33 m (one-third of 100 m), and the subjects had to pan at least two times in the same direction to search for the POIs within 100 m, These skills had not been described previously.
5) Each participant was asked to complete a questionnaire. There were six questions, in which Q1–Q5 were five-point scale questions (1– strongly negative and 5– strongly positive). Q6 and Q7 were open ended questions.

Q1: How easy was it for you to locate yourself on the map?
Q2: How easy was it for you to find out about your current heading orientation on the map?

TABLE III
DEPENDENT MEASURE FORMULATIONS IN TASK 4

Measure of POI	Actual Value	Judgment Value	Error-Dependent Measure
Relative Distance	D_a	D_j	$D_e = D_a - D_j$
Relative Orientation	O_a	O_j	$O_e = O_a - O_j$

Q3: How easy was it to explore the surroundings and find spatial relationships (i.e., distance and orientation) to nearby POIs, when the YAH symbols were presented?
Q4: How easy was it to explore the surroundings and find spatial relationships (i.e., distance and orientation) to nearby POIs, when the YAH symbols have disappeared after panning?
Q5: How satisfied were you with the whole system?
Q6: What is good about the system?
Q7: What is bad about the system?

The participants were informed of the test plans and their tasks before the evaluation started, as well as their right to quit at any time. No time limitation was set for each test.

E. Independent Variables and Dependent Measures

1) Within-Subject Variables: The three within-subject variables were test environment (test maps), subtasks, and POI groups. There were two different test maps (Map 1 and Map 2) with two different layouts of streets and three groups of POIs. Map 1 had common structured blocks, but Map 2 consisted of an irregular street layout. The POI group was to classify all POIs into three groups according to how many times panning operations were required to render them on the tactile display: Nonpanning Zone ($D_{\mathrm{poi}} \leq 50$ m), one-time Panning Zone (50 m $< D_{\mathrm{poi}} < 83.3$ m), and nultitime Panning Zone ($D_{\mathrm{poi}} > 83.3$ m) required panning at least two times in the same direction, where D_{poi} is the relative distance to participants. The subtask consisted of five tasks: training, distinguishing the YAH symbols, discovering nearby streets, exploring POIs, and feedback in post-questionnaire.

2) Between-Subject Variables: There was one between-subject variable: demographics. The blind group had vast experience with using tactile maps, while the blindfolded group had no tactile maps-related experiences.

3) Dependent Measures: The dependent measures varied by tasks, including the total training time spent in the training period, the time spent, and the accuracy for discovering surrounded streets and POIs. In particular, for Task 4, in addition to noting the estimated relative distance and orientation to the POIs, the errors were also calculated and analyzed, according to the formulas in Table III.

4) Data Analysis: To study how factors impact subjects' performance on:

Total training time: As the study recorded the total time spent in the training period by each subject, a t-test was used to analyze the difference between the two user groups.

Time spent for discovering the surrounding streets: To investigate the effects of demographics and maps on required time, a two-factor mixed ANOVA test has been conducted.

Accuracy for discovering the surrounding streets: There were four surrounding streets in each map, thus accuracy was measured using a five-level scale. We counted the number of streets correctly identified by a participant. A Mann–Whitney U Test was applied to investigate whether demographics had a significant effect on the accuracy for Map 1 and Map 2, respectively.

Time spent for exploring POIs in 100 m: That is, the total time spent for finding all POIs in one test map. User groups and maps are the two main factors, and a two-factor mixed ANOVA test has been conducted.

Accuracy for discovering the POIs in 100 m: To investigate the effects of maps and demographics on the precision of discovering POIs in 100 m, a two-factor mixed ANOVA test has been conducted.

Mean distance error and the mean orientation error: A three-factor mixed ANOVA test (demographics as the between-subject factors, and maps and POI groups as the two within-subject factors) has been conducted, in order to investigate how subjects' mean distance error and orientation error were impacted.

V. Evaluation Results

Significant results are reported using $\alpha = 0.05$ and trends are indicated at $\alpha = 0.1$.

A. Training

The blind user group spent 27.7 min on average (SD: 5.16) and the blindfolded group took 29.4 min (SD: 4.07) to complete the training task. There was no significant difference in the total training time between the two groups.

B. Distinguishing the You-Are-Here Symbols

Both groups learned the eight YAH symbols in a short amount of time: an average of 128.4 s (SD: 26.1) per blindfolded subject and 126.0 s (SD: 74.5) per blind subject. In the test with the four selected YAH symbols, the blindfolded group took 7.3 s (SD: 3.7) to distinguish each symbol and the mean accuracy reached 93.8%, while the blind group spent 4.2 s per symbol (SD: 2.5) and the mean accuracy was 96.9%.

C. Discovering the Surrounding Streets

1) Time Spent: On average, the blind user group spent 276.8 s (SD: 99.3) in Map 1 and 280.6 s (SD: 136.7) in Map 2, and the blindfolded user group spent 181.6 s (SD: 40.6) in Map 1 and 234.9 s (SD: 127.6) in Map 2, to find the surrounding streets. There were no significant main effects for maps or for demographics, and there was no significant interaction effect.

2) Accuracy: In all, the blindfolded subjects made four errors in Map 2, but the blind participants made three errors and four errors in Map 1 and Map 2, respectively. Therefore, the average accuracy of finding streets by the blindfolded user group was 100% in Map 1 and 87.5% in Map 2. The average accuracy by the blind users was 93.8% in Map 1 and 87.5% in Map 2. In Map 1 and Map 2, the user group factor had no significant main effect on the accuracy of finding streets.

D. Exploring Points of Interests Within 100 m

1) Time Spent: On average, the blindfolded user group took 595.5 s (SD: 162.9) in Map 1 and 640.6 s (SD: 185.1) in Map 2, whereas the blind users spent 540.9 s (SD: 281.7) in Map 1 and 556.9 s (SD: 288.9) in Map 2. There were no significant main effects for maps or for demographics, and there was no significant interaction effect.

2) Accuracy: All participants were able to find the targeted POIs (Recall = 100%), but as the distance of some POIs were estimated imprecisely, the subjects made mistakes while finding POIs within 100 m. The blind subjects performed more precisely (81.3% in Map 1 and 90.8% in Map 2) than the blindfolded ones (75% in Map 1 and 85% in Map 2). The map factor trended to influence the accuracy of finding POIs in 100 m (Wilks' $\lambda = 0.76$, $F(1, 14) = 4.36$, $p = 0.06$). No other effects were significant.

3) Mean Distance Error and Mean Orientation Error: The mean distance error was 1.82 m (SD: 25.4) in Map 1 and –11.84 m (SD: 18.1) in Map 2 for the blind group, and –10.78 m (SD: 25.4) in Map 1 and −4.55 m (SD: 27.2) in Map 2 for the blindfolded group. The map factor and the user group factor had no significant main effects, but the POI group factor did (Wilks' $\lambda = 0.44$, $F(2, 13) = 8.46$), $p = 0.004$). There was a significant interaction effect of maps and demographics (Wilks' $\lambda = 0.74$, $F(1, 14) = 5.03$), $p = 0.04$). A posthoc Tukey test showed that the subjects had significantly larger distance errors for the POIs in the multitime Panning Zone (M: −19.56; SD: 28.00), than for the POIs in the Nonpanning Zone (M: 3.33; SD: 9.24, $p < 0.001$), and for the POIs in one-time Panning Zone (M: −2.78; SD: 26.15, $p = 0.01$), respectively.

The mean orientation error was –5.7° (SD: 3.6) in Map 1 and 13.8° (SD: 6.3) in Map 2 for the blind group, and 3.9° (SD: 3.6) in Map 1 and 2.1° (SD: 6.3) in Map 2 for the blindfolded group. The subjects made different errors while estimating the relative directions to the POIs in the Nonpanning Zone (M: 3°, SD: 2.4), in the one-time Panning Zone (M: −4.2°, SD: 5.1) and in the multitime Panning Zone (M: 10.2°, SD: 4.8). There were no significant main effects for POI groups, maps, and demographics on the relative orientation errors. There was a significant interaction effect of maps and demographics (Wilks' $\lambda = 0.62$, $F(1, 14) = 5.17$), $p = 0.04$, $\eta^2 = 0.27$), and of maps and POI groups (Wilks' $\lambda = 0.73$, $F(2, 13) = 5.17$), $p = 0.05$, $\eta^2 = 0.38$).

Fig. 13 illustrates the interaction plots of the subjects' mean distance error for the map factor and the user group factor. Fig. 14 shows the mean orientation error for the map factor and the user group factor. Fig. 15 shows mean orientation errors for the maps and the POI groups.

E. Post-Questionnaire

Table IV indicates that the subjects felt it was easy to locate themselves (*Q1*) and find their current orientation (*Q2*) on the map. They found it was more difficult to estimate the distance

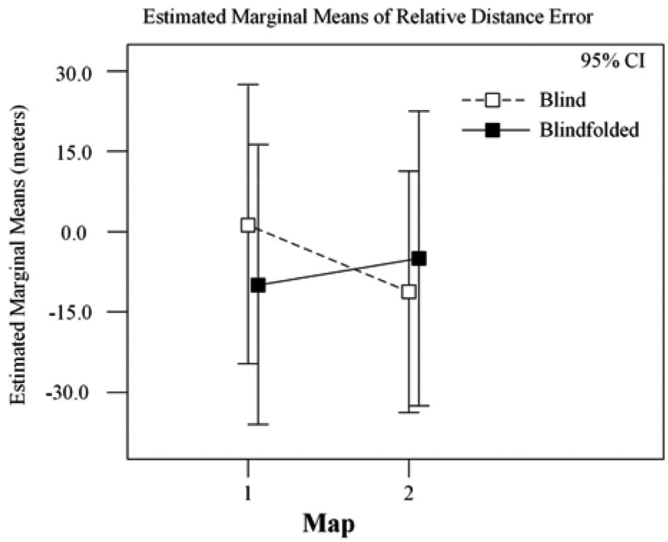


Fig. 13. Interaction plots of the subjects' mean relative distance error for the maps and the user groups.

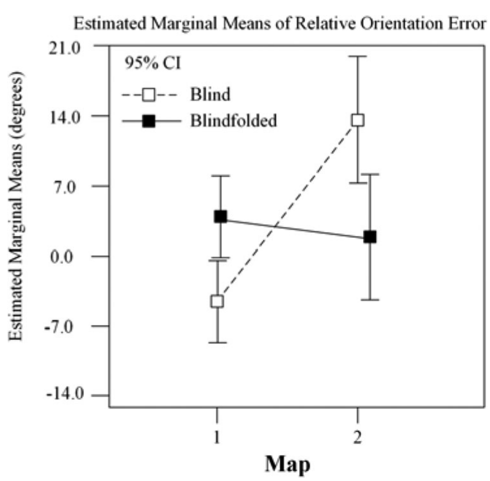


Fig. 14. Interaction plots of the subjects' mean orientation error for the maps and the user groups.

TABLE IV
SUBJECTS' MEDIAN RATINGS ON THE Q1–Q5 (1 STRONGLY NEGATIVE—5 STRONGLY POSITIVE)

	Q1	Q2	Q3	Q4	Q5
Blind	5	5	5	3	4
Blindfolded	4	4	4	2	4

and orientation to the nearby POIs when the YAH symbols had disappeared (in *Q4*, Blind: Median $= 3$; Blindfolded: Median $= 2$) than when the YAH symbols were presented (in *Q3*, Blind: Median $= 5$; Blindfolded: Median $= 4$). The Wilcoxon Signed Ranks Test found a significant difference on the rating of Q3 and Q4 ($p < 0.01$), by pairing all subjects' ratings on Q3 and Q4. Regarding their satisfaction with the whole system (*Q5*), the median rating was 4 for blind subjects and blindfolded

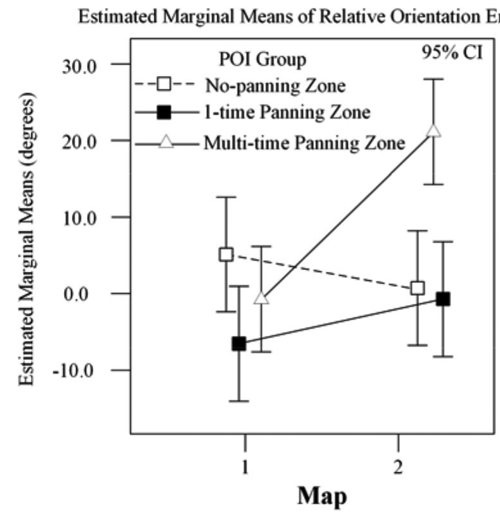


Fig. 15. Interaction plots of the subjects' mean orientation error for the maps and the POI groups.

subjects. For *Q6* and *Q7*, many blind people said it was their greatest experience to be able to explore such location-based tactile maps, by explicitly touching rather than purely listening. They provided their positive feedback on the features: map symbols, YAH symbols, portable display, and interactive functions; however, they hoped the system would be improved from the aspects of the system response time, vibrating YAH symbols after panning, as well as integrating into a navigation system. Most of the blind subjects did not complain about the two-hand operation, as they were used to this way for exploring traditional maps, like swell-paper maps. However, they pointed out the that whole system was still not easy for portability, due to the large tactile display and the heavy computer.

VI. DISCUSSION

Different to wayfinding systems focusing on turn-by-turn instructions, map exploration systems should offer abstract or detailed information about surrounding geographic features. For blind and visually impaired pedestrians, the auditory modality and tactile/haptic modality have become the most important modalities with which to explore surrounded environments. Table V summarizes the differences in terms of functionality and usability between the available audio-feedback-based systems and the proposed TacYAH Map system.

Although all three systems acquire updated location information from GPS and other sensors, only the TacYAH Map system presents a real street map consisting of raised streets and POIs, which allow users to learn the spatial layout of the surroundings. Specifically, the representation of the shapes of streets and roundabouts by the TacYAH Map system might make users more confident in unknown regions.

The three systems employ different methods to present the categories of geographic features: TTS, semantic sounds, and tactile map symbols. The TTS solution requires the least training compared with the two others where users have to spend time to learn the semantic sound patterns and the tactile map

TABLE V
DIFFERENCES IN TERMS OF FUNCTIONALITY AND USABILITY BETWEEN AUDITORY MAPS AND THE TACYAH MAP SYSTEM

		Auditory Feedback based		Audio-tactile Feedback based
		ISAS System [35]	*NAVIG System* [33]	*TacYAH Map System*
Functionality	Updated location data	GPS, Compass	GPS, Inertial sensors	GPS, Compass
	Presentation of a real map	No	No	Yes
	Geographic features	POIs	Obstacles, POIs	POIs, Streets, Roundabout
	Rendering map elements	TTS	Semantic sounds, TTS	Tactile map symbols, TTS
	Input channels	Motion gestures, Touch	Voice input	Touch, Button pressed
	Output map information	Attributes, Distance, Rough direction	Attributes, Distance, Rough direction	Spatial layout, Street shape, Attributes, Distance, Direction
	Panning & Zooming	No (but different ranges enabled)	No	Yes
Usability	How easy to learn	Easy	Medium	Easy
	How easy to discover surroundings	Medium	Easy	Medium
	Portability	Easy	Medium	Medium
	Cognitive loads	One-hand operation, Hearing concentration	Hand-free, Hearing concentration	Two-hand operation, direction and distance estimated by users

symbols. Thus, it is important to classify the output and design distinguishing semantic sounds or tactile map symbols.

Due to the limited screen size of the portable pin-matrix display, it is a challenging task to render large areas on city maps containing various map elements. This is similar to the issues faced by mobile devices for sighted people. The map elements for sighted people can be presented in different styles (e.g., color, width, icon, etc.) and even with overlapped elements. However, such a vision-based map rendering style does not fit the pin-matrix display, which only consists of raised or lowered pins. In this study, we found it is important to keep enough space between each map element to ensure each symbol can be distinguishable, and it is not appropriate to overlap the tactile map symbols.

Apart from designing with various pin patterns, the size of the tactile map symbols should also be considered. The tactile symbols for POIs should be no bigger than the width of one finger (ca. 1.5 cm, which equals the width of six pins); otherwise, users have to pan the contacted finger many times in order to identify their categories. Taking this into consideration, we designed the largest tactile symbol with 6×6 pins for the railway station. Note that, when zooming in or out of the maps, it is important not to change the size of tactile map symbols that have already become familiar to users.

Since there is no real map rendered in the ISAS system [35] and NAVIG system [33], it is hard to implement the traditional map panning and zooming. However, the feature to enable POIs within short or large distance ranges in such a system helps users explore within a wide range, just like the function of panning maps.

Regarding the usability features for learning the systems, in addition to the effort required to learn the semantic sounds or tactile map symbols, users have to learn how to use and control the systems. Users found it easy to learn how to use the ISAS system, although several users had problems in using the gestures [35]. Due to the specific voice commands supported, however, users in the NAVIG system need to learn these commands in advance. Additionally, we found users would learn the TacYAH MAP system during the evaluations, which required about 30 min on average, even for the blindfolded subjects who had no tactile map experience.

It seems that the wearable NAVIG system lets users easily discover the surroundings by voice input and the fusion of various sensor. However, it is challenging to make use of voice input in noisy places. In [35], the blind subjects' difficulty in performing the required precise motion gestures impacted the performance of the ISAS system for discovering. Even if it was easy to discover the nearby POIs when the YAH symbols were presented (in *Q3*, Blind: Median = 5; Blindfolded: Median = 4), the subjects felt it was difficult to estimate the distance and orientation of the far away POIs (more than 100 m).

In this study, we focused on investigating how blind and visually impaired users can discover spatial relationships to surrounding POIs independently, giving up a built-in automatic distance and orientation calculator. The evaluation indicates that the YAH symbols can be useful as reference points for estimating the relative distance and orientation to other POIs. In general, they counted the number of fingers placed between the YAH symbols and targeted POIs and used them as their indicator for the relative distance. When the YAH symbols had disappeared after panning, they took the times of panning into account. From the results of the evaluation, the subjects would estimate more precise distance to the nearby POIs within 50 m than to the far away POIs beyond 100 m (i.e., POI 12 and POI 3). It may be difficult to calculate the relative distance by counting the time of panning.

As a significant feature of mobility aids for blind and visually impaired people, the portability feature cannot be ignored. Since the ISAS system only requires a touchscreen phone and a headphone, it is very convenient for outdoor journeys. Due to the NAVIG system and the TacYAH Map system both being at the phase of concept verification, many separate components (e.g., heavy laptops, sensors, and pin-matrix displays) have to be worn that make the whole system difficult for travelling. With the development of embedded system technologies, there is the potential to improve the portability by adopting functional embedded boards and sensors and therefore becoming wearable and integrated mobility aids.

It is convenient to explore the surroundings with one hand or with no hands, specifically for blind people who have to hold white canes in one hand, as with the ISAS system and the NAVIG system. Nevertheless, the two auditory feedback-based systems both require concentrated listening, specifically to recognize the different semantic sounds, that may be dangerous as blind and visually impaired pedestrians may not pay attention to environmental sounds (e.g., moving cars). Regarding the cognitive loads for the TacYAH Map users, on the one hand, indeed the current version requires both hands, but on the other hand, touching tactile map symbols does not interfere with hearing environmental sounds. Moreover, the Wiimote Cane can still help users detect obstacles with one hand. Vibrotactile feedback might be an interesting method to reach hand-free exploration [37], but there are no available map systems which can offer functional map exploration services.

Additionally, in the TacYAH Map system, the true north of the map is fixed (always north-up); thus users have cognitive load to find out what is in front by reading the YAH symbols. A few participants preferred this solution, but most of them expected a feature that orientated the map depending on the walking direction (always head-up).

Limitations: During the evaluation even if the subjects were standing at the same two spots, marked on the ground, the accuracy of their acquired location based on the GPS technology might be different, depending on several factors (e.g., weather). This study only evaluated four categories of tactile map symbols. If all symbols are tested, it will be more difficult for subjects. Due to the limited number of participants, the power values of some statistical results (like the time spent for finding streets and POIs) were low.

VII. Conclusion

In this paper, we have addressed an audio-tactile YAH map explorer on a pin-matrix display with a matrix of 30×32 pins for blind and visually impaired people. In addition to rendering map elements via tactile map symbols in a panoramic view, the system presents users' updated location and heading orientation. The accessible user interfaces on smartphones or a specific electronic cane allow users to interact with audio-tactile maps (e.g., panning and zooming) independently and to discover unknown environments.

The field tests conducted with 16 participants indicated that users can locate themselves and discover the surrounding environment independently in unfamiliar areas, even for those who do not have experience with tactile maps and Braille. The user study found users would better estimate the spatial relationship (i.e., distance and orientation) to nearby POIs than far away ones, with the help of the tactile YAH symbols.

The proposed prototype system can be improved and extended in the future in different aspects. In addition to speeding up the system and using vibrated pins, it is important to improve the portability of the prototype system by employing embedded systems. One-hand operation should be considered, via, for example, speech input on mobile phones, or specific touch gestures on the tactile display. Furthermore, the system will have the potential to improve the current turn-by-turn instruction-based navigation systems by importing the navigation features and online maps.

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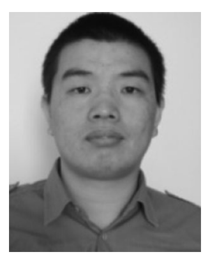

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