A Prototype Audio-Tactile Map System with an Advanced Auditory Display

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ABSTRACT

Tactile surfaces can display information in a variety of applications for all users, but can be of particular benefit to blind and visually impaired individuals. One example is the use of paper-based tactile maps as navigational aids for interior and exterior spaces; visually impaired individuals may use these to practice and learn a route prior to journeying. The addition of an interactive auditory display can enhance such interfaces by providing additional information. This article presents a prototype system which tracks the actions of a user's hands over a tactile surface and responds with sonic feedback. The initial application is an Audio-Tactile Map (ATM); the auditory display provides verbalised information as well as environmental sounds useful for navigation. Two versions of the interface are presented; a desktop version intended as a large-format information point and a mobile version which uses a tablet computer overlain with tactile paper. Details of these implementations are provided, including observations drawn from the participation of a partially-sighted individual in the design process. A usability test with five visually impaired subjects also gives a favourable assessment of the mobile version.

Keywords: *Audio-Tactile Map, Auditory Display, Binaural, Psychoacoustics, Tactile Interface*

INTRODUCTION

Tactile displays are those which transmit information through features that can be determined by touch and are often used to improve accessibility for blind and visually impaired users. These may take a variety of approaches including electronic devices with actuated pins, but it is possible to produce comparatively inexpensive paper-based versions.

The addition of a sensing capacity to such a static, low-cost display would be beneficial; tracking the touch of the user would enable the delivery of additional information specific to

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a tactile feature. This may be accomplished in a number of ways with off-the-shelf consumer technology and can have benefits for visually impaired users who rely on such displays by facilitating multi-modal information delivery through an additional feedback channel.

This article describes the initial development of a system which adds an interactive auditory display to a paper-based tactile surface. The first implementation is a navigational aid for blind and visually impaired users; an *Audio-Tactile Map* (ATM). The prototype system presents geographical information on tactile paper and provides interactive audio feedback. Two interface versions are described which use different sensing mechanisms; the first uses an affordable camera-based controller and the other a mobile tablet computer.

The next section reviews existing approaches to the provision of navigational aids for blind and visually impaired individuals in order to position the ATM system in context. Previous work is summarised suggesting that tactile displays combined with sophisticated auditory displays may have benefits for navigational applications.

NAVIGATIONAL AIDS FOR THE VISUALLY IMPAIRED

It is common for blind people to explore a new location (such as a work environment) when there is little other traffic present, in an effort to develop a mental map of the location; the spatial model developed from gathering this experiential knowledge is a *cognitive map* (Kuipers, 1978). From the outset, it was the intention of the ATM project to address this type of scenario by providing a virtual reality tool which can help a visually impaired individual to form a cognitive map of a location remotely, before visiting the physical site (Picinali et al., 2014a). Assistive navigational technology for blind and visually impaired individuals takes a number of approaches, but may be broadly classified into *in-navigation* or *pre-navigation tools*, the latter of these being of primary concern here. The reader is directed to literature reviews included in documentation of the background experimental work for the present project (Picinali et al., 2014a) and early-stage documentation of the ATM project (O'Sullivan et al., 2014a, O'Sullivan et al., 2014b).

Mobile devices equipped with Global Positioning System (GPS) technology allow visually impaired travellers to receive direction while in transit via an auditory and/or a tactile display. In the case of the former, Rowell & Ungar (2003) found that synthesised verbal delivery can be distracting at times, but a comprehensive review of the effectiveness of in-navigation systems in outdoor environments was positive (Loomis, 2001). The Blind Maps system is a concept providing an assisting-device with real-time tactile feedback only, i.e. no audio (Spitz et al., 2012). It was designed as a portable clip-on peripheral for the Apple iPhone for use with on-line map applications. The device renders symbols on an actuated pin display to direct the user during a journey, allowing aural focus to be kept on surroundings. An example of a navigational tool that is currently active is Open Street Map for the Blind (OSMB), as described in Rifat et al. (2011) and with information available online[1]. This is an open-source, user-maintained map system which is audio-based and delivered via mobile phones equipped with screen readers. OSMB is a well-considered list of established world features and associated audio tags that aid mapping and system development by the contributors. More generally, design guidelines for assistive devices for blind pedestrians that aim to help spatial cognition have been suggested by Gallay et al. (2013).

In situations where GPS does not function properly, such as inside buildings, alternative methods must locate the user within the space (Loomis et al., 2005). Solutions to the problem of indoor navigation include the use of infrared technology (Gill, 1996) and the Drishti system, which uses GPS when available for outdoor navigation and ultrasonic range-finding sensors when indoors (Ran et al., 2004). Other notable research by Swobodzinkinski and Raubal (2009) identified way-finding principles for interior spaces used by blind and visually impaired individuals which can inform the development of particular routing algorithms. Nevertheless, applications to indoor navigation have received less attention than for outdoors. Several systems have emerged more recently, such as an interface that includes a Geographic Information System (GIS) integrated with visual landmarks to help with user location and to trace a route through the site (Serrão et al., 2012). Another approach uses a magnetic sensing setup in a building to provide location and direction information (Riehle et al., 2012).

Various human-computer interfaces have been developed for use in virtual spaces, often to further the knowledge of how users locate and navigate and/or to improve accessibility for applications such as gaming. These include using inexpensive gaming technology to give auditory and haptic feedback (Evett et al., 2009) and the codification of spatial information (e.g. depth and colour) into musical sounds in a multi-touch interface (Gomez et al., 2012).

In contrast to systems providing navigational information while travelling, research supports the benefits of pre-learning of routes and formation of cognitive maps prior to journeying (Rowell & Ungar, 2003). AmauroMap is an example of a pre-navigation tool which aims to support the formation of a cognitive map of a location before visiting it, being an on-line map project that lets the user navigate by interactively exploring digital city maps (Wasserburger et al., 2011). Experimentation with the interface highlighted the importance of orientation points in way-finding for the visually impaired, but it was noted that the points of interest generally chosen were highly individualistic, particularly in the case of acoustic features. Users accessed textual information that is automatically annotated by the system from spatial description information, which can be presented through a screen reader or a Braille display.

An alternative approach is implemented in a 3D map analysis system which produces force-field maps from using image processing techniques (Moustakas et al., 2007). However, the use of haptic devices for feedback has been found to be unstable and to have significant usability issues in application to cognitive map learning (Brown et al., 2011).

Audio-Tactile Maps

Tactile displays can be described as *static*, *vibratory* or *electro-tactile* (Kaczmarek & Bach-Y-Rita, 1995). A simple example of a static display is stamped or etched Braille; information is encoded through a series of raised dots on an otherwise flat surface. In contrast, more technically sophisticated electronic displays can provide interactivity (e.g. sensing the user's touch) and dynamic haptic feedback (e.g. applying a real or simulated mechanical force on the user). *Tactile Graphics Display* (TGD) devices can use mechanically-actuated pins to generate shapes and textures or apply small electric current to simulate force feedback[2]. A notable project is the Talking Tactile Tablet. This is a specialised touchscreen peripheral over which a hinged tactile overlay may be placed and which responds to user input with audio information (Landau & Gourgey, 2001). Emerging technologies include those which use acoustic interference mechanisms in the ultrasonic frequency range to simulate tactile surfaces (Iwamoto et al., 2008). These are expensive and technologically complex when compared to displays which use 'low-tech' solutions; several technologies exist for the production of low-cost tactile maps, the use of which has matured in recent years (Koch, 2011). *Microcapsule* or *swell paper*, for example, can be used to create raised textures on printed areas produced with a normal photocopier or printer when heated with a fuser oven (Perkins, 2001).

When deployed as navigational aids, tactile displays present geographical information as *tactile maps* (Tatham, 1993) These have been found to be effectively presented on TGD devices by applying suitable styles to aid legibility (Schmitz & Ertl, 2012). The Tactile Map Automated Production (TMAP) system produces Braille-based maps automatically or semi-automatically generated from GIS data for locations in the USA (Miele, 2004). In turn, interactivity may be added to paper maps in numerous ways, such as with specialist touch-screen computer peripherals. This approach is used in the Talking TMap project, which extends the original TMAP project by providing map templates for the Talking Tactile Tablet device previously described.

A comprehensive review of the adoption of tactile maps for blind and/or visually impaired individuals studied the qualitative experiences of their use, providing a ranking list of desirable features and guidelines on their implementations (Rowell & Ungar, 2003). In general, portable tactile maps created using specialised paper were generally well-received by test subjects when used for navigational purposes. The use of a tactile overlay on a multi-touch surface has also been explored with a view to identifying a suitable device that fulfils the requirements of a multimodal map (Brock et al., 2010). The device experimented with in that study was a resistive touchscreen capable of tracking multiple touches and gestures, interfaced with a computer using a specialised hardware driver and data bus mechanism. However, it was found that the sensing mechanism was over-sensitive and caused triggering of multiple sounds concurrently. Performance was particularly poor when subjects explored the map with two hands. Nevertheless, the authors noted the potential of multi-touch devices for the interactive display of geographical information in the tactile and auditory modes.

Although some systems discussed above use audio to deliver information (e.g. Talking TMap, OSMB), this is usually textual information rendered by a text-to-speech (TTS) synthesiser or as pre-recorded audio files of spoken word. AmauroMap is a notable exception as it also includes environmental sounds, but the integration of tactile maps and interactive audio feedback has received less attention in the literature than other navigational tools. Another example is the Blind Audio-Tactile mapping system (BATS), which uses auditory icons and text-to speech synthesis with a keyboard and pointing-device interface (Parente & Bishop, 2003); the user explores a large-scale map by moving a cursor, with feedback including environmental sound effects. The TouchOver map uses a mobile phone to present digital maps with speech-based audio and tactile feedback via the vibration function on the device; a study using 8 sighted subjects found the technique to be useful for learning the basic layout of a map with the phone hidden from view (Poppinga et al., 2011). It is of interest, however, to investigate how a more sophisticated auditory display can help deliver additional useful navigational information by exploiting knowledge of psychoacoustics and spatial cognition.

Advanced Auditory Display

Broadly defined, auditory displays present information through sound and include those that use speech-based audio, audification or sonification techniques with non-speech audio, and/or other methods (Hermann, 2008). The reader is directed to a comprehensive review of the field edited by Hermann et al. (2011). The provision of an audio channel on a computerised information system has obvious benefits for those with visual impairment and the examples of audio-tactile systems reviewed previously take some advantage of this. However, it may be possible to present more sophisticated audio information to aid in navigation.

It is usual in everyday environments to hear sound sources with some level of reflection. Under certain conditions, multiple acoustic reflections from the same source can often provide information regarding the surrounding environment, including space dimensions and material properties. Reviews of the relevant mechanisms of spatial auditory perception and localization previously discussed how the nature of sound reflections in a space can give valuable acoustic cues for orientation (Katz & Picinali, 2011; Picinali et al., 2014a). Although sighted individuals do not generally use hearing to judge the spatial configuration of their environment, this ability is developed in the blind and visually impaired. In addition, this latter group were found to use self-produced sounds such as finger-snaps and footsteps to learn about their surroundings by listening to the reverberant feedback from the space (Picinali et al., 2014a). A number of studies detailed in Katz and Picinali (2011) found that this type of acoustic display of environmental information can affect the formation of cognitive maps when used in a pre-navigation training phase.

As such, the inclusion of non-verbal spatialized audio feedback has the potential to enhance a tactile map and provide relevant guidance information for a space before entering it. However, none of the available systems combine a low-cost tactile interface with an interactive auditory display that emulates the types of acoustic cues found in real spaces.

AIMS AND OBJECTIVES

The development of audio-tactile interfaces for a variety of applications is hereby proposed, with initial focus on the provision of an ATM for navigation and locational information display. The primary target user group are blind and visually impaired individuals, where it is felt the technology could be of significant benefit to accessibility. However, we see applications in other areas such as digital building heritage and social inclusion. The aim of this phase of the project is the development of a low-cost computerised system which more effectively aids the visually impaired in navigating a closed or open environment by addressing the perceived shortcomings of existing systems. The ATM is therefore intended to be used in pre-learning the characteristics of a given area, rather than receiving active guidance during navigation. The approach is to assist spatial learning through provision of suitable acoustic events using a virtual reality device. This is to be achieved by supplementing a paper tactile map with an interactive auditory display of the target environment, featuring verbalised information and simulations of characteristic acoustical features. A prototype system with basic functionality has been realised and the initial development and preliminary evaluation of our prototype are described next.

PROTOTYPE IMPLEMENTATION

A prototype software system has been developed which provides an auditory display for users interacting with a paper tactile map. Two forms of the system interface have been created as *desktop* and *mobile* versions. The first of these is designed as a larger-format information point; the movement of a user's hands are tracked over the tactile paper map with selections being made through large push-buttons. The use of comparatively inexpensive camera technology has kept the cost of this system low while allowing maps to be used up to A3 paper size. In addition, this technology has the potential for tracking interaction with objects other than low-relief paper tactile maps. The mobile interface uses a tactile paper overlay on a multi-touch tablet to sense user interaction. The ubiquity and quality of such devices makes their use in the deployment of the ATM worthy of investigation, despite the smaller sizes of maps that can be produced at reasonable cost. It must be stressed that although touted as a mobile interface, this latter version is still designed to assist in the cognitive map training rather than as an in-navigational tool to be carried and used while in transit. Both interfaces communicate with the system software running on a computer, but a self-contained application which runs on the OSX operating system for Apple mobile devices has also recently been prototyped.

The first map used with the system is a portion of the campus of De Montfort University (DMU) in Leicester, including buildings, streets and the nearby river. As shown in Figure 1, various textures indicate specific features and a key written in Braille is provided at the bottom of the map. A second map of a building within this campus has also been used. The map shown in Figure 2 shows the first floor of the Queen's Building, with portions of the ground floor and main ground floor entrance also visible. Dark blocks are used to indicate interior spaces without any additional use of a texture key. These digital map images are printed on swell paper using a regular office printer and are then passed through the fuser oven. Areas of dark print absorb heat and become raised, generating a textured surface as shown. The fuser has a heat setting which determines the height of the raised elements.

Software

To facilitate rapid-prototyping while maintaining flexibility, the current software was written in the Java programming language and consists of a number of modules, as illustrated in Figure 3. A digitised map and data files are loaded and the map is analysed using an image processing module to automatically extract regions of interest of arbitrary shape. In the DMU campus map example, each of the buildings is segmented and labelled. Labels are combined with meta-data, such as the building name, and any associated audio files for that map location. At run-time, a software zone is specified for each building; tracking data is projected onto the map coordinates and a zone returns its information when selected. The system has a graphical user interface (GUI) that displays information for sighted individuals and provides administrator access to system settings and metadata.

The current software was developed to allow two modes of use by tracking the interactions of the user with the paper tactile map. The first presents the user with information about specific landmarks and can be used to find out about buildings, roads or other key features of the map- this is the *exploration mode* of operation. The second is designed as a *navigation mode*, presenting the user with an interactive, sequential route between two chosen landmarks. Intermediate way-points are provided which describe nearby landmarks and features, helping to create a cognitive map of the route.

Auditory Display

The ATM system delivers spatial audio over headphones (but with mono-compatibility for loudspeaker playback) and uses audio in two ways; text-to-speech synthesis of map meta-data and sounds of characteristic acoustical features of spaces. Interaction with the map produces audio feedback and the nature of sounds produced is context sensitive. When a user selects a map feature, the information contained in the associated map zone is rendered using a basic text-to-speech engine. For example, when a building is selected on the ATM of the DMU campus, its name is synthetically spoken first, followed by any additional stored information.

Audio is also provided in the form of *environmental* and *self-produced* sounds. Examples of the former are the background sounds positioned about the DMU campus map; the sound of the river can be heard at outdoor locations towards the top left of the map, for example. Some interior spaces on the Queen's building map have recordings of self-produced sounds, such as hand-claps, finger-clicks and footsteps, embedded at various locations. All sounds were recorded using binaural microphones at the associated physical locations, as this allows for the reproduction of realistic 3D sound-fields using a pair of headphones (Hammershøi, 2005). This type of auditory display preserves the acoustic cues found to be useful for navigation in physical spaces by blind and visually impaired individuals.

Desktop Interface

The mounted paper tactile map is shown in Figure 4. A Leap Motion device[3] is positioned above the map and is used to track the movements of hands on the tactile paper. The Leap Motion is an inexpensive consumer device and is finding popular use in interactive applications as a free air gesture controller. It comes with a suitable Application Programming Interface (API) to allow rapid prototyping and code integration. The device has a pair of cameras and illumination technology contained within a small form factor enclosure, making it unobtrusive and well-suited to the current application. The coordinates and orientations of hands, fingers and tools in view of the device are sent to a computer over a Universal Serial Bus (USB) cable connection.

Preliminary testing of the interface with a visually impaired user participating in the early

Figure 1. Campus map of DMU used to produce a tactile map. The key at the bottom provides Braille descriptions of the various textures used to signify different features

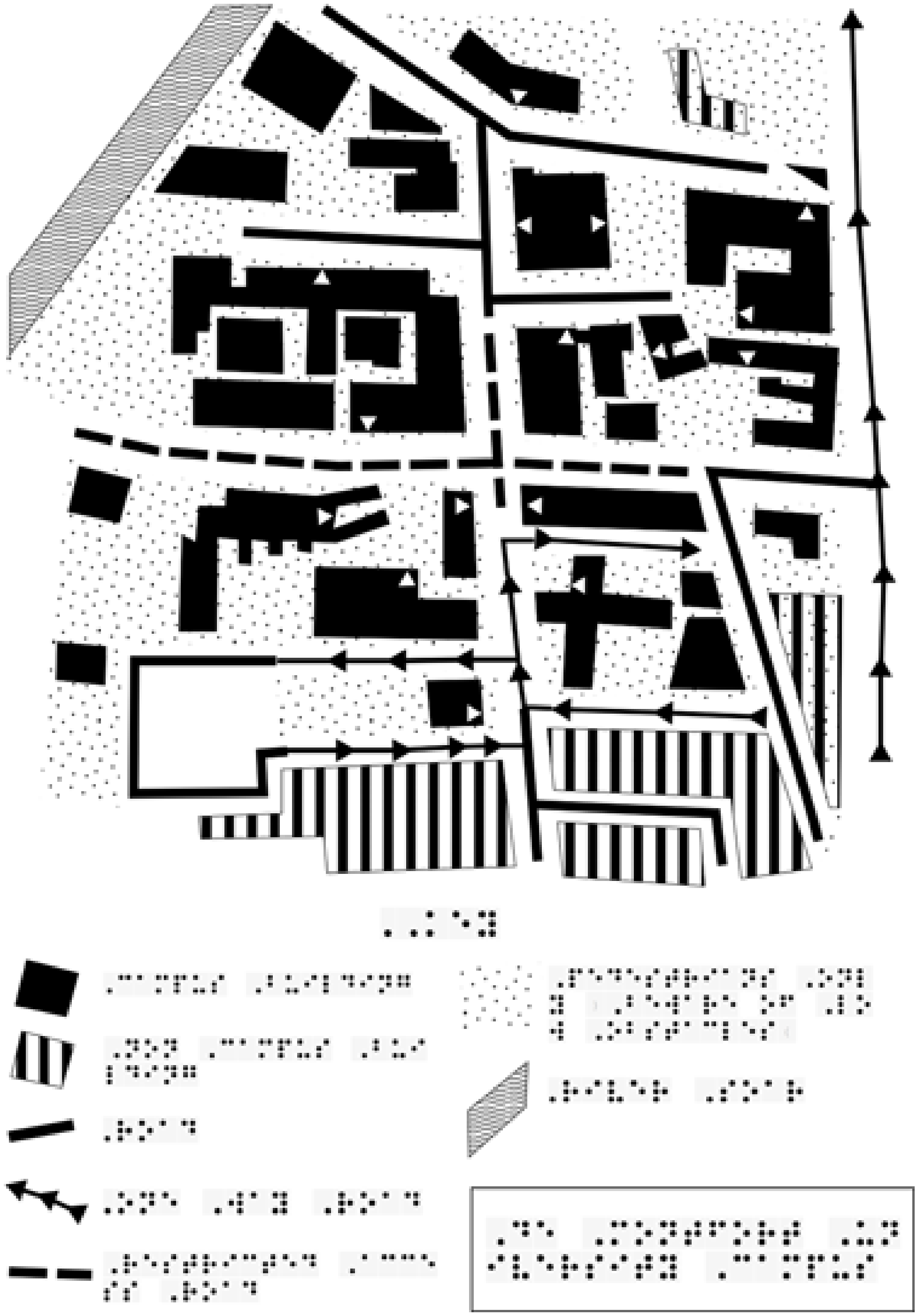
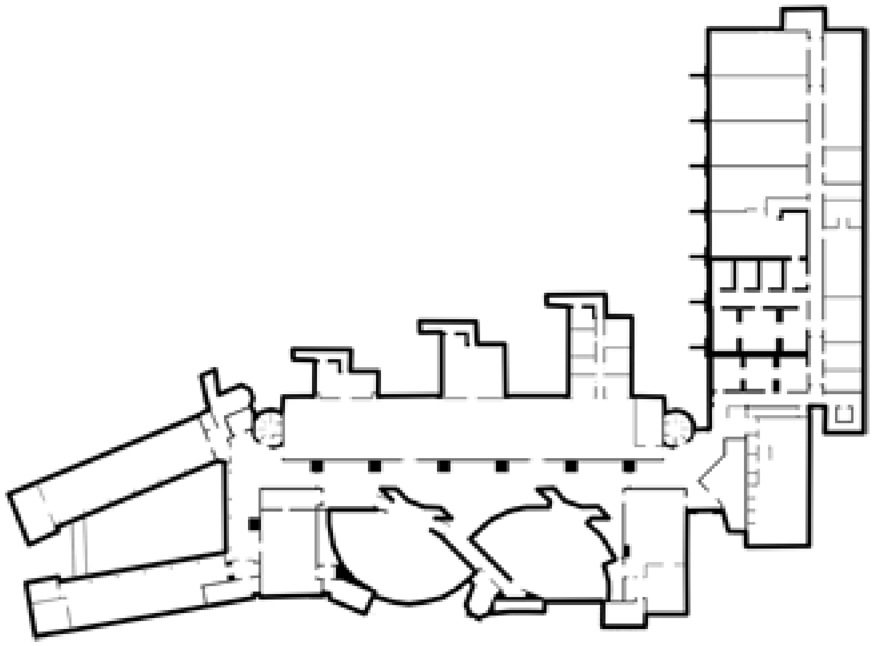


Figure 2. Map of the Queen's Building on DMU campus, used as the second tactile map with the ATM system



stages of the system development has previously been described (O'Sullivan et al., 2014a). The observations made were generally positive and encouraged further development of the system, including implementation of new functionality and/or modifications to existing features.

For example, the default low quality TTS engine was replaced and audio files were instead pre-rendered using the AT&T Natural Voices® Text-to-Speech Demo[4] before being loaded into the system. This improved the discernibility of delivered information and also made the ATM more pleasant to use. Large electronic push-buttons (visible in Figure 4) were another addition, providing robust and reliable selection events. These are interfaced with the host computer using an Arduino microcontroller[5] over a USB serial connection.

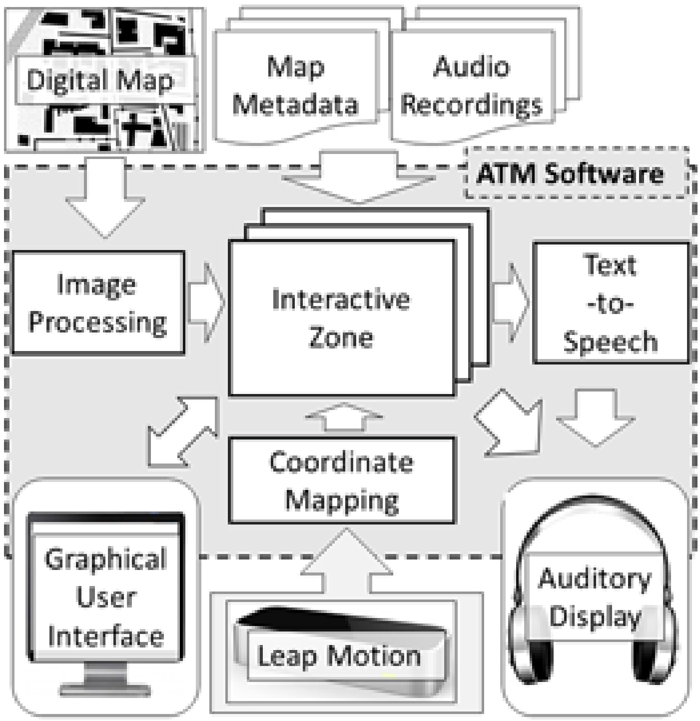
However, in testing, it was found that the Leap Motion did not always provide robust tracking in an uncontrolled environment and required repeated set-up and calibration. Using the device to track hands which were in contact with a surface was problematic. In lieu of this, an alternative approach was undertaken to allow the use of a mobile tablet interface and further test the system software. This also allowed investigating the feasibility of deploying the system on mobile platforms and widening the potential user base.

Mobile Interface

A mobile interface version was developed that was designed to use a tactile paper overlay on a touchscreen device. Affordable mobile tablets do not have screen sizes that would allow the production of larger tactile maps (i.e. A4 paper size and larger), but such devices are now so commonplace that it was deemed necessary to investigate their use as the sensing component of an ATM.

An OSX application was therefore developed that sends control information (currently from a single point of touch) to the system software.

Figure 3. Functional overview of the ATM prototype software system



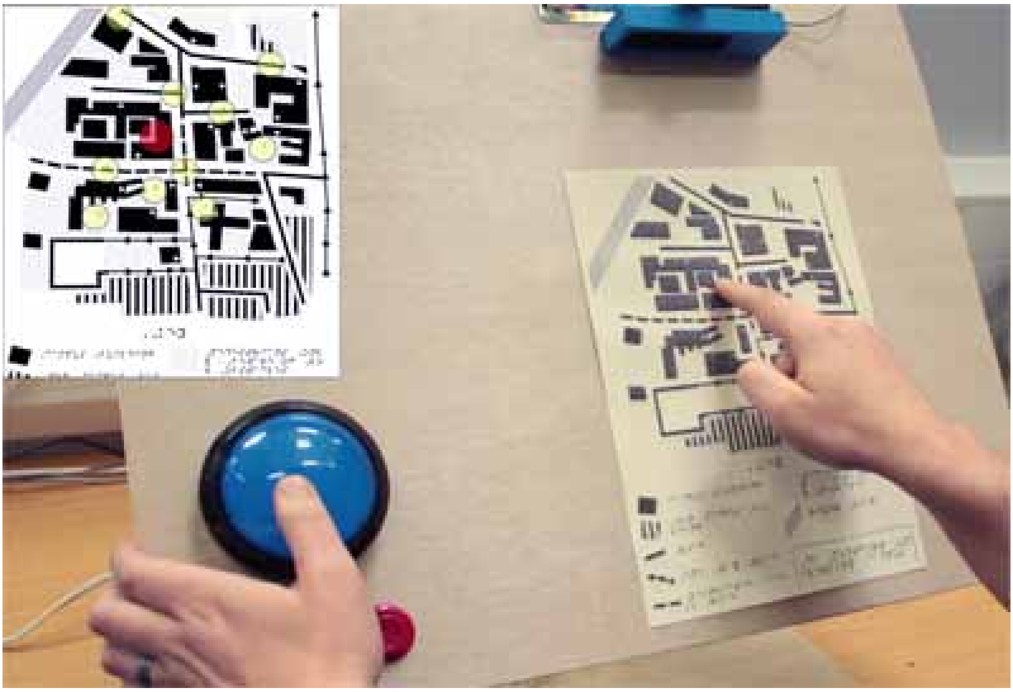
The messaging format used Open Sound Control (OSC), which is an effective means of sending control information via User Datagram Protocol (UDP) over a network (Wright, 2005). Adoption of this popular communications approach allows easy integration with other systems, as many OSC clients exist for common development environments as well as code libraries for standard programming languages (e.g. Java, C++). A module for receiving and parsing OSC messages was therefore integrated into the existing ATM software. In light of the experiences of Brock et al. (2010), a mono-touch interaction mechanism was implemented that used single- and double-tap selection gestures.

The mobile version of the interface described above has been used to evaluate the usability of the ATM, the results of which are presented in the following sections. However, development on the project has now progressed to include an integrated ATM software system on the iOS platform for Apple mobile devices. This has been verified to work on an Apple iPad tablet but has not been formally evaluated at the time of publication.

Map Design

The tactile paper was found to be suitable for use as an overlay for an Apple iPad touchscreen only with some modifications to the designs of the maps. Using higher settings of the fuser oven results in a more raised surface of the tactile paper, preventing the screen from detecting a touch through its capacitive sensing mechanism. To circumvent this issue, the maps were redesigned so as contain voided areas within tactile features e.g. as buildings were represented as dark-printed raised blocks, a light area placed within would be rendered as a flat region. This had the advantage of specifying a discernible area which acted as the selection point for a feature of interest. In Figure 5, the modified version of the

Figure 4. The hardware setup for the fixed interface version of the ATM. The Leap Motion controller is visible above the tactile paper map. Selections are made using large pushbuttons to the bottom left. The picture insert shows the graphical user interface of thesystem; the currently tracked finger positon is shown by a red circle and the locations of sound recordings embedded in the map are shown in yellow



DMU campus map shows the circular voids (in white) which were designed to be easily identifiable among the rectangular buildings. Touching at these areas produced reliable touch coordinate and gesture information. As this map is of buildings from an exterior view, it was also possible to use circles to indicate the locations of outdoor auditory icons containing environment sounds. The Queen's Building map shown in Figure 6 necessitated a different design as it depicts interior spaces. The use of voided circles for both room information and auditory icons made the interface confusing for users, so circles were only employed as icons containing both environmental and self-produced sounds. The selection gesture made at these locations determined the sound played back- a single tap played environment sounds and a double tap played the self-produced sounds. The rooms themselves are bounded by thick outlines; making a section gesture anywhere within a space returned the associated information.

Application Design

The original ATM prototype is comprised of different components: a tactile paper map, a Leap Motion camera and electronic circuit, with a laptop running the system software. As previously discussed, use of the Leap Motion was found to require some set-up and that the sensor be calibrated occasionally. The mobile version of the interface communicates with the system software over a network. In order to explore the feasibility of a simpler architecture, a second prototype called *ATMPad* has been developed as a tablet application for the iOS platform. The application displays a map of the current

Figure 5. The DMU campus map modified for use in a tactile overlay for a mobile tablet. Touch interaction is not registered by the touchscreen due to the increase in paper thickness at dark areas. Buildings are selected by tapping within the light circles inside the buildings' boundaries. Auditory icons for exterior environmental sounds are also indicated by circles

environment and detects touches on areas of interest. Auditory feedback is then provided through the internal speaker or via wired or Bluetooth headphones. Different environment representations can be loaded by pointing the tablet camera towards a QR code printed on a tactile map, which may then be placed over the tablet screen as shown in Figure 7.

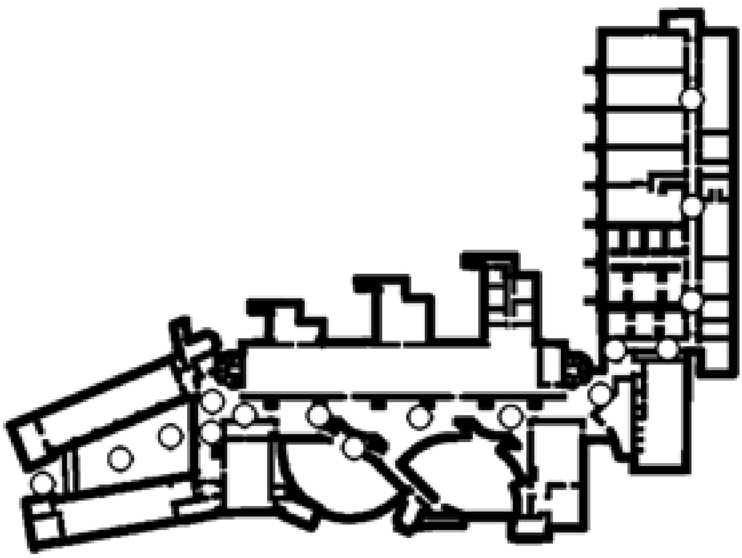
EVALUATION OF MOBILE INTERFACE

From the beginning, this project was concerned with the impact on the blind and visually impaired community and with the usability of the developed tool. For this reason, the involvement of blind and visually impaired individuals was necessary as early as possible in the process of design and implementation of the ATM system, and in the preliminary evaluation of the prototype (O'Sullivan et al., 2014a, 2014b). The testing stage presented in the following sections was therefore important not only to technically ensure that the system was working adequately, but also to gain feedback on the usability of the application, and on its suitability for the use of blind and visually impaired individuals. These first tests analyzed the exploration mode of the ATM only.

Test Set-up

A total of five visually impaired individuals (three completely blind, and two with residual vision) carried out the test, two of whom were

Figure 6. The modified Queen's Building map for the mobile application. Rooms and other interior spaces are represented as thick outlines and may be selected with a single-tap gesture within the space. Auditory icons are indicated by circles and may be selected using taps within their circumferences



females. Testing was carried out in November/December 2014 on one open environment map (the DMU Campus map) and one closed environment map (the Queens Building map). The touch gestures used to interact with the maps were as shown in Table 1.

The evaluation was structured in the following way:

1. Brief introduction to the ATM project and system (5 minutes).
2. Exploration of the open environment map (15 minutes).
3. Exploration of the closed environment map (15 minutes).
4. System Usability Scale questionnaire (5 minutes).
5. Computer System Usability questionnaire (5 minutes).
6. Interview (5 minutes).

To navigate the map the individuals used an Apple iPad over which the swell paper map was positioned and which communicated with the ATM software over a wireless network, as previously described. The individuals wore a pair of Beyerdynamic DT770 headphones for the delivery of both mono and binaural signals.

Questionnaires

Two questionnaires were presented to the individuals after the exploration stage. These were the System Usability Scale (SUS) questionnaire (Brooke, 1996) and the IBM Computer Usability Satisfaction questionnaire (Lewis, 1995). Users were asked to rate their levels of agreement with a series of statements regarding use of the system. Note that statements have been shortened in the figures presented below to aid illustration, but these were presented to subjects with strict adherence to recommended wordings.

SUS Questionnaire

For the SUS questionnaire, the possible answers to each question could go from 1 ("Strongly

Table 1. Selection gestures and associated audio feedback used in the evaluation of the ATM mobile interface

Selection Gesture	Auditory Display
DMU Campus Centre	
Single-tap on circle within building	Mono text-to-speech with location information
Single-tap on circle on the roads/ outdoors	Binaural location recording
Queen's Building	
Single-tap on any location inside building	Mono text-to-speech with location information
Single-tap on circle inside/outside building	Binaural location recording (environmental/ background sound)
Double-tap on circle inside/outside building	Binaural location recording of finger snapping sound

Disagree") to 5 ("Strongly Agree"). For the odd-numbered statements, a high number corresponded to a positive feedback on the system, while for the even-numbered statements it was the inverse. For this reason, the statements have been re-ordered in Figure 8 (with statement order, moving downwards; 1-3-5-7-9-2-4-6-8-10).

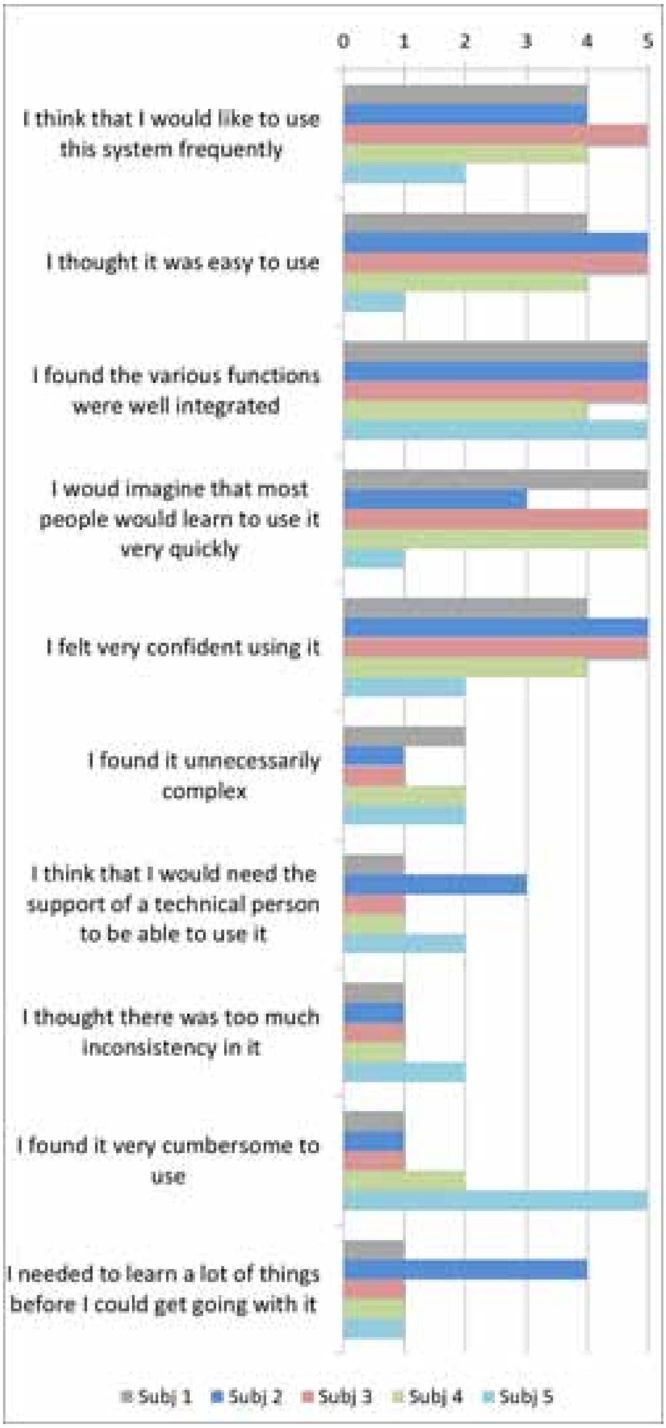
Considering the odd-numbered statements, the mean response value was 4.04 (±1.27 standard deviation), while for the even-numbered statements the mean response value was 1.6 (±1.04 standard deviation). Subject 5 was by far the most unhappy about the system evaluation; it is in fact true that without considering his responses the mean value would increase to 4.5 (±0.61 standard deviation) for the odd-numbered statements and decrease to 1.4 (±0.82 standard deviation) for the even-numbered statements.

IBM Computer Usability Questionnaire

For the Computer Usability Questionnaire the possible responses to each statement could range from 1 ("Strongly Disagree") to 7 ("Strongly Agree"), with the possibility of selecting the

Figure 7. Apple iPad with tactile map overlay

Figure 8. Responses of subjects to the statements presented in the SUS questionnaire



value 0 for answers which did not apply to the system currently evaluated ("n/a"). In this case, for all statements a higher response value corresponded to a more positive feedback on the system.

Seven statements from the original questionnaire did not seem to apply to the ATM system (at least 60% of the subjects answered "n/a"), and were therefore removed from the analysis. The responses of each subject to each of the 12 statements are reported in Figure 9.

The mean response value across all subjects was 6.39 (±0.86 standard deviation), which increased to 6.57 (±0.71 standard deviation) excluding Subject 5, who was again the most unhappy about the system. The two "n/a" responses given by Subject 5 (score 0) were not considered in the mean calculations.

The IBM questionnaire also gave the opportunity for each subject to report up to three positive notes regarding the system, and three negative ones. These lists of positive and negative comments are presented below:

Positive Comments

It's a very good system, especially if someone was coming new to the place and had very little or no vision.
Very interesting system, which could potentially be very useful. I would like now to try to go to the actual location of the map and see how much I've learnt.
The audio (speech and sounds) was pleasant and informative.
Very informative and easy to use.
I feel that I really know the environments.
Interesting approach to learning maps before going in the place.
Potentially useful also when you are in the place, maybe with guidance while walking.
The maps are clear, but mainly using my residual vision. The tactile design is clear though.
The circular features works quite well when feeling them, even though apparently they are too small for the touch action.

Negative Comments

Some of the circles were very insensitive, while some were hypersensitive...the level of sensitivity needs to be more equal.
It might work better if the whole circles were raised (like button press).
Some difficulties in starting the audio playback.
Audio playback locations were limited in number.
Start play of the click noise is difficult to activate.
Takes some time to get used to navigating the map.
The environmental sound couldn't be stopped, once when you knew what they were, and they were overlaying the other sounds when playing.
It would be nice to know what the streets were... names of the streets.
The responsiveness is an issue...either related with the iPad or the touch response, but it is sluggish.

Interview Questions

A brief interview was carried out after the two questionnaires. The subjects were all asked four questions, which are reported here followed by a brief summary of the responses.

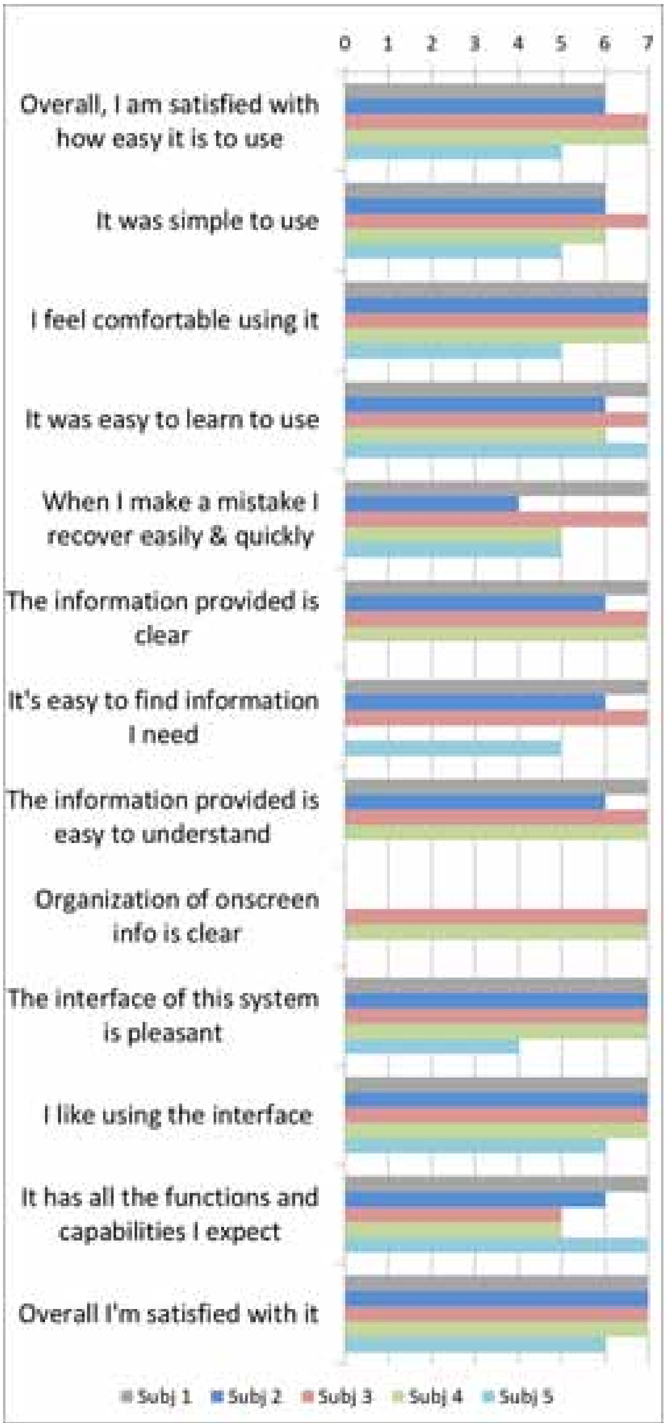
Did you find the non-speech audio informative?

All subjects did, except for Subject 5, who reported that for him it was not particularly informative, but that they could potentially be informative for visually impaired individuals with no residual vision (it is important to note that Subject 5 was one of the two subjects with residual vision who did this evaluation).

Did you find both finger snap and background noise informative?

Again, except for Subject 5 all subject found the two types of audio feedback informative. Three subjects clearly preferred the background noise, and one the click noise.

Figure 9. Responses in the Computer System Usability questionnaire



What features would you like to see in future versions of the system?

Here follows a list of the answers given to this question:

Ability to program two locations and give guidance description on how to move from one to the other.
Use buttons instead of circles.
Considering the answer of buttons, the possibility of using an extra button (not on the map) with the other hand for triggering sounds could be interesting. Another option could be to change the textures in the circles (maybe little dots).
Simpler selection of the sound to play back, and possibly more recordings of noise and clicks in different locations.
Maybe an error report for when the playback is not triggered properly.
More audio playback areas. Maybe also interactive audio playback, which changes as I move in the environment.
More interactivity, maybe sound which is changed continuously while moving in the environment.
Surely simpler trigger for the click noise.
Audio playback stop, and better audio quality.
Where the crossing is in Mill Lane, for example, it'd be useful to know that that is a crossing.
Add more tactile and audio description features regarding, for example, roads, etc.

As can be observed, some of these responses refer to features which have been developed for the ATM system, but which were not evaluated in this stage (e.g. the use of push buttons to select features). Other responses are related to potential improvements that could be implemented in a further version of the ATM system.

Do you think the system is useful in forming a mental map of the associated area prior to visiting it?

Two of the five subjects had a good knowledge of both the DMU Campus and the Queen's Building configuration, but reported that the ATM system could potentially be 'extremely useful' for learning the configuration of environments they did not already know. Two of the subjects who were not familiar with the real environments reported that they felt they had a good mental representation of the environments after navigating them through the ATM system. One of the subjects reported that he was not sure about this, but that he would have liked to have the possibility to navigate the real environments and verify if he could remember something from the ATM navigation.

Summary

In general, considering the results of both questionnaires and of the interviews, the system was very well received. Relevant feedback was gathered regarding technical issues, problems and potential improvements for the ATM system. As reported in the previous sections, Subject 5 gave lower scores overall and had more critical comments on the usability of the system. The feedback of all subjects was nevertheless constructive and often addressed real technical problems that are being resolved before the deployment of future prototypes and evaluation stages.

CONCLUSION

Tactile surfaces may be produced using inexpensive heat-reactive paper, providing touchable information display for a variety of applications. The addition of inexpensive sensing technology can add interactivity through a computerised system with potential for multimodal information delivery. Initial development work on such a system was presented; a prototype Audio-Tactile Map (ATM) that provides specialised audio feedback based on user interaction with the tactile element.

The delivery of information through audio and tactile channels is of benefit to blind and visually impaired individuals and this first application is designed to help in the formation of a cognitive spatial map of a location prior to journeying. The auditory display provides both verbalised information and environmental sounds for map locations. Previous research has shown that these can be beneficial for the formation of cognitive maps in visually impaired individuals and can aid in navigation. In addition, advanced auditory display can present audio recordings that preserve some of the acoustic sues used in psychoacoustic and spatial cognition. Initial testing on two versions of the system has been undertaken. The first of these is designed as a larger format fixed information point; the movement of a user's hands are tracked over the tactile paper map with selections being made through large push-buttons. At present the system has been tested with one partially-sighted individual and the specifics of the hand-tracking mechanism means further development is required before evaluating with additional subjects. The second version of the system uses a tactile paper overlay on a mobile tablet. Usability testing with five visually impaired subjects met with positive results. Parallel development of the mobile version includes an application which dynamically loads map information using QR codes.

FUTURE WORK

The current prototype system is seen as a test-bed to establish how an auditory display can help visually impaired individuals form cognitive spatial maps to aid navigation. More sophisticated treatment of audio content is being implemented including; dynamic, real-time acoustical rendering of sounds reproduced by the user during map exploration, integration of head tracking facilities for a more realistic binaural rendering and an improved real-time TTS synthesiser with realistic reverberation. Technical development of the ATM system will improve performance and usability and allow experimentation with the addition of new features. Mobile interface development will investigate the use of accelerometer input to improve the robustness of selection gestures, in the absence of pressure sensing multi-touch devices. Advances in the capabilities of the Leap Motion controller include integration with mobile devices operating on the Android platform. This opens up the potential for embedding the functionality for future ATM versions on additional mobile devices and negating the need for a separate computer. The ATM is also seen as a platform for experimenting with tactile map characteristics, something which has so far been beyond the scope of the project; for example, what textures are useful and effective on tactile paper maps and what ranges and tolerances exist in their properties? The provision of a fully-functional administrator mode is also underway, as is development of the route-navigation function; a complex problem for optimum path identification between any two points on a map.

Additional Applications

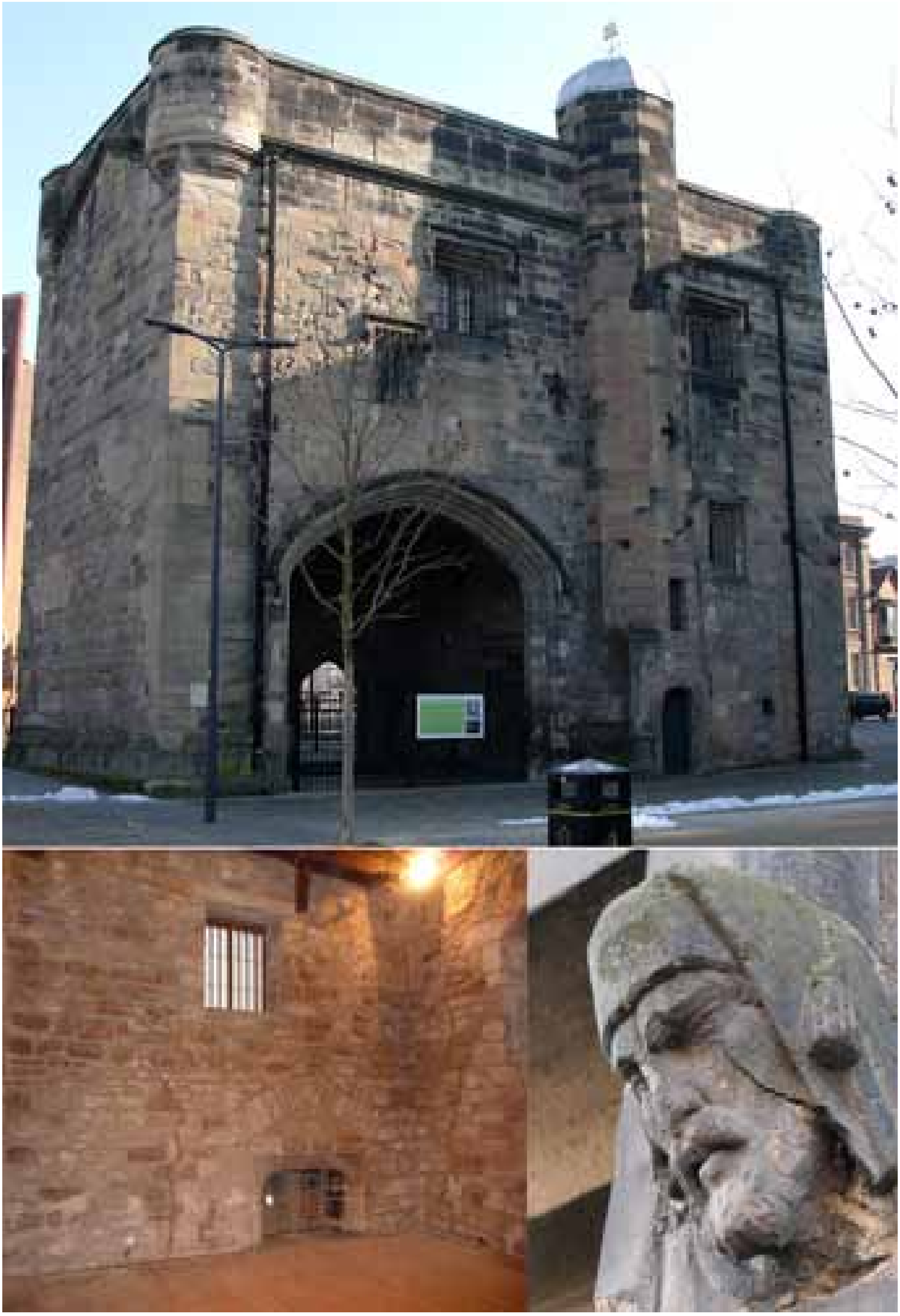
A number of additional applications and use-cases for the system are being actively investigated in order to facilitate additional testing of the ATM in the wild and to inform iterative improvement of the technology

Digital Heritage

The ATM system will be beneficial to visually impaired visitors to heritage sites by increasing accessibility as a navigational aid. It will also be of benefit to all those wishing to experience historic sites when employed as a portal to virtual representations, as previously described (O'Sullivan et al., 2014a). DMU has an ongoing project to digitally reconstruct medieval campus buildings to show how they would have existed historically. The acoustic and tactile affordances buildings such as The Magazine (shown in Figure 10) offer are being incorporated into our system to bring them to a wider audience.

Museum exhibits and artworks can also be made interactive using our approach, providing a richer experience for the gallery patron. The ATM technology offers the potential to provide tactile experiences of artwork reproductions

Figure 10. The Magazine, a medieval gateway on DMU campus



which must usually be restricted for conservation purposes.

Social Inclusion

A second application of the ATM technology examines the potential for promoting social inclusion. The target scenario is that of fitness training in a gymnasium; an ATM system can deliver information on layout and specifics of equipment use for all users, but this can be of particular benefit to those with vision-impairment or with a learning difficulty. The approach presented is also promising for the creation of more general multi-modal interfaces for all users.

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