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Outdoor Pedestrian Navigation Assistance with a Shape-Changing Haptic Interface and Comparison with a Vibrotactile Device

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***Abstract*— By targeting haptic sensory channels when walking, pedestrian navigation systems (as found in smartphone apps) have the potential to allow both visually impaired and sighted users to pay greater attention to their surroundings, compared to typical audio or visual based feedback. In line with this idea, we have proposed mechanotactile shape-changing interfaces as an alternative to the more commonly used haptic modality of vibrotactile feedback. In this paper, we evaluate the potential for haptic guidance in a realistic outdoor navigation task. Participants were guided along pre-determined footpath routes in a ~3,500m^2 outdoor public environment, via 'equivalent' handheld shape-changing and vibrotactile feedback devices, capable of providing heading and proximity information. Localization was based on real-time GPS data provided by a smartphone. Many other pedestrians (not part of the study) shared the space and had to be avoided, as in typical urban settings. All participants located all waypoints with both devices, walking between 270m-600m per trial. Walking efficiency was similar for both devices, though participants took over twice as long (on average) to complete the routes with the vibrotactile device. In a questionnaire, participants preferred the shape-changing interface, considering it more intuitive and pleasant to use than the vibrotactile system. Though haptics can certainly be used for practical navigation, the relatively low resolution of unprocessed GPS positioning can lead to erroneous instructions that are harder for a (sighted) user to notice and correct than in screen based systems utilizing visual maps.**

I. Introduction

Navigation assistance technology for visually impaired (VI) persons was proposed in academic literature long before GPS based navigation became commonplace in automobiles and smartphones [1]. Though navigation technology is now ubiquitous, the user interfaces to such systems are predominately visual, with screens displaying maps, arrows and recommended paths to a destination. Though highly informative, such displays are inaccessible to VI users and can lead to distraction from the surrounding environment in hearing impaired and sighted pedestrians. This is illustrated in [2], where hospital reports over the last decade show significant upward trends in pedestrian accidents related to distraction when using cell-phones. Both talking and texting on cell-phones have been shown to divert attention away from the environment and hazards contained therein [3].

A secondary output of many navigation technologies is spoken voice commands, which are considered more

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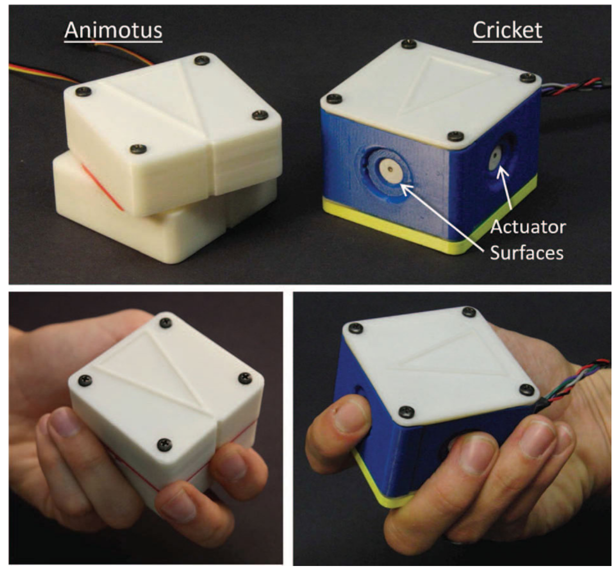

Figure 1: The shape-changing *Animotus* and vibrotactile 'equivilant' *Haptic Cricket*. Note that the Cricket has actuators on three faces.

appropriate for use by VI individuals. Unfortunately, the often necessary use of headphones to listen to such commands obscures the sounds of the natural environment [4]. For VI persons ambient sounds are used for orientation, landmark recognition (e.g. the sound of a fountain), danger (e.g. an approaching vehicle) or simply social interaction and the appreciation of one's surroundings [5].

Haptic interfaces have the potential to sidestep such issues, by channeling navigation information into the sense of touch, which is less used for environmental appreciation than sight or sound when walking. It is certainly the case that the most popular and longstanding navigation aids for VI persons, the guide cane and guide dog, are both haptic interfaces that deliver mechanotactile sensations to the hand.

The use of haptics for navigation has been considered by a number of researchers, many of whom choose vibrotactile as the feedback mechanism for their prototype systems. In [6], [7], it was noted that vibrotactile actuators are small, lightweight, highly affordable and easy to interface with, making them an appealing technical solution. In [8], Oakley noted the excellent fit of vibrotactile feedback in the usability constraints of providing 'alerts' in mobile phones, which was seconded in [7]. Such feedback is characterized by short and generally infrequent attention-grabbing stimulus for discrete and important events, such as an incoming text message. As such, it has been highlighted that vibrotactile feedback may not be as well suited to tasks that involve long-term stimulation [9]. This may be due to the constantly alerting nature of the sensation leading to cognitive loading and fatigue. Indeed, in the long term study of [10] some users commented on a belt of vibrotactors being 'annoying' and 'making it difficult to think'. This was annoyance was also reflected in the shorter, static study of [7].

Alternative (non-vibratory) ungrounded haptic interfaces for certainly do exist, though they have been less popular in the field of motion guidance [6]. In recent work we developed *The Animotus,* a novel shape-changing navigation interface (also called *The Haptic Sandwich*) [11], [12]. This device was motivated by the idea that shape appreciation is a subtle, natural and frequently encountered innate human capability [13], [14]. We consider it probable that for certain tasks, an interface that interacts with this natural sensation would be unobtrusive, less cognitively demanding and more pleasant than the stimulus generated by vibrotactile actuators. A similar hypothesis was considered for skin stretch feedback in [7]. Though we appreciate that texture detection is also a natural and common sensation detected via vibration, this is at a much finer level with lower amplitude.

In this current work we consider two questions. Firstly, whether haptic interfaces can replace visual or audio interfaces for navigation in *realistic* urban scenarios, without extensive training. Secondly, we wish to compare user performance and opinions between shape-changing and vibrotactile interfaces (shown in Figure 1) also via the realistic navigation scenario. As will be further explained in Section III, the vibrotactile interface, named the *Haptic Cricket*, was based on examples from literature, while also aiming for equivalence with the Animotus.

II. Related Work

The potential of using haptic sensations to augment perception with additional data has received great attention in the research community for a number of decades [1]. This has in turn led to a wide range of devices that aim to improve life for VI persons by enabling safe and independent navigation. Surveys of such systems may be found in [15] and [16]. A review of related literature quickly indicates what Stanley and Kuchenbecker refer to as the 'dominance' of vibrotactile actuators in such approaches [6]. A key example of a vibrotactile navigation aid is the wearable *FeelSpace* belt of vibrotactors, the north-most of which is always active [5], [10]. By expanding beyond such traditional actuation, the authors of [6] aimed to achieve natural sensations akin to physical interactions with a human.

An alternative haptic interface may be found in shape-changing devices. This is a little explored modality with few haptic examples [17]. A notable contribution however is from Hemmert et al, who proposed dynamic tapering of mobile phone cases as a method of navigational instruction [18].

Though Hemmert's navigation interfaces were highly promising, these concepts were never tested in embodied navigation experiments, instead being verified via desk based simulations [18]. Certainly, a limited number of proposed haptic navigation interfaces are tested 'in-the-field'. In [5] a blind participant used the vibrating *Feelspace* belt to walk around polygonal trajectories in a hall, while in [10] this was repeated in a 'empty courtyard', prior to completing a maze in virtual reality. In the pioneering work of [1], Collins describes how tactile sensory-substitution interfaces that

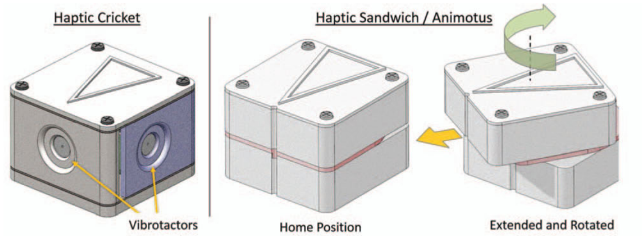

Figure 2: The Haptic Cricket vibrotactile interface (left) and Haptic Sandwich shape-changing interface (middle & right).

functioned well for VI persons in constrained indoor spaces produced overwhelming tactile noise in a less structured outdoor sidewalk environments. Indeed the concentration associated with making sense of this outdoor noise was described as unsustainable, with outdoor use of their system eventually recognized as unobtainable. Clearly, there is great potential for unexpected and decisive insights via in-the-wild device evaluation in realistic / less controlled use scenarios.

III. Materials

We make use of two novel navigation interfaces, the *Animotus*, a shape-changing interface previously introduced in [11], [12] and the *Haptic Cricket*, a new vibrotactile based interface designed for equivalence to the Animotus. Both systems provide the same two quantities of navigational information: *heading* and *proximity* to targets. In work currently under review we demonstrated that these quantities complement one another to optimize *path efficiency*, *speed* and *time facing targets*.

Though a wealth of vibration based interfaces exist in prior literature (as was alluded to in the previous section) these systems do not match the data structure, form or objectives of the Animotus. This makes reliable comparisons between systems difficult, as differences in participant performance or opinions may be due to indeterminate factors.

The Animotus was designed as handheld, rather than wearable interface, as we feel that, just like a common smartphone with a navigation application, it is convienient for the user to be able to put the device in a bag or pocket when not navigating (which proved beneficial in the theatre application described in [12]). We consider the success of the mobile phone as indicative of the benefits and appeal of handheld technology that can be stowed when not in use. We will now provide an overview of the Animotus and Cricket.

A. The Animotus

The Animotus is a cube shaped device with an upper half that is able to rotate (±30 deg) and extend (12.5 mm) relative to its bottom half (Figure 2). The rotation DOF corresponds to the heading to a navigational target (Figure 4.b), while the extension DOF corresponds to the proximity to the target (Figure 4.c). Both DOF update simultaneously (Figure 4.d) and continuously in real-time, based on the user's position and orientation in an environment, relative to a navigational target. The form of the device allows both DOF to be simultaneously perceived when the device is held in the users' hand (as in Figure 1) this was formally demonstrated in [11]. When navigating with the device, users attempt to reduce rotational and proximity errors. As these errors are

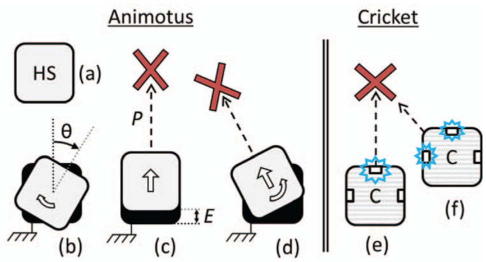

Figure 4: Response to position and heading errors with the Animotus (a-d) and Cricket (e-f).

reduced, the extension and rotation DOF approach the home position (Figure 4.a). When the user reaches the navigational target, the device assumes the home position and resembles a cube. A particularly appealing aspect of the interface method is that the device continues to communicate shape (and therefore navigation information) when not moving. As such, the continuous feedback of the device may be voluntarily ignored if the user chooses to interrupt their navigation and stand still (for example, to talk to someone).

B. *Haptic Cricket*

The Haptic Cricket (Figure 1, Figure 2) is a vibrotactile based navigation interface designed for equivalence to the Animotus. The Cricket was designed with the same materials, form and dimensions as the Animotus in its 'home' position (Figure 2). The Cricket also provides equivilant navigational information via the same stimulus mapping. The Cricket strives to match predominant vibrotactile themes in notable haptics literature (e.g. constant vibration stimulation of [5], [10] and some examples of [16]). Such constant guidance feedback is also provided by the Animotus.

The Cricket communicates via three 12mm diameter vibrotactile 'pancake' actuators mounted on three vertical faces of a cubic structure (Figure 5). The front actuator communicates proximity to a navigational target, with higher intensities relating to greater distances (Figure 4.e). This is equivalent to the extension DOF of the Animotus (Figure 4.c). The left and right vibrotactile actuators correspond to heading error to the target, with a clockwise (CW) heading activating the right actuator and a counterclockwise (CCW) heading activating the left actuator. Again, larger headings error will lead to greater stimulus, with a ±30 degree error

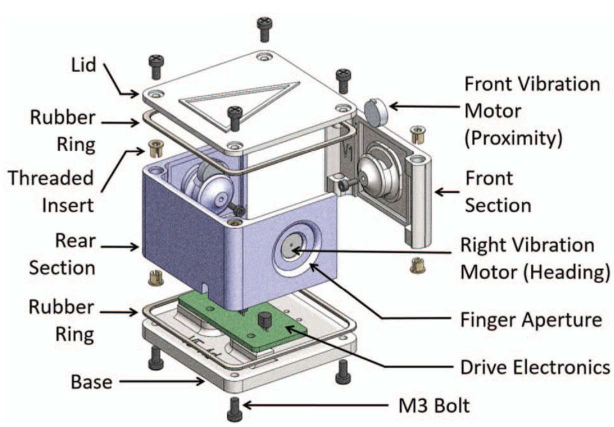

Figure 5: Elements of the Haptic Cricket. Several mechanical features strive to limit vibrtation propogation between the actuated surfaces. Similar illustrations of the Animotus are available in [11].

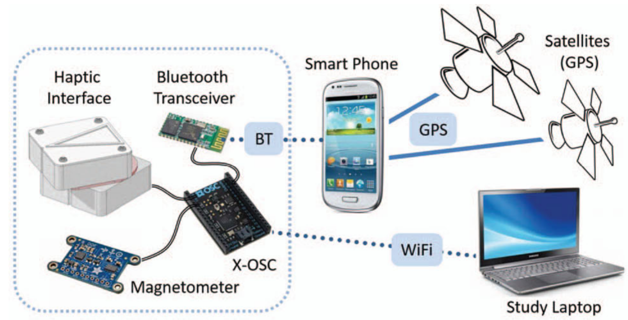

Figure 3: The navigation system, which makes use of an Android smartphone for GPS localisation. The Haptic devices connecct to the smartphone via Bluetooth (BT) and the study laptop via WiFi.

leading to 100% activation of the appropriate left/right actuator. The proximity and heading actuators actuate simultaneously during navigation, in real-time response to user position and heading, relative to a target (Figure 4.f).

Many multi-actuator vibrotactile interfaces are wearable, with isolated actuators held against the skin via soft straps [5], [6], [10], [15]. These mechanisms naturally isolate the vibrations of each actuator to some degree. In order to achieve a comparable device to the Animotus, such techniques could not be employed, as the actuators needed to be placed within a handheld cubic structure. A number of mechanical techniques were therefore employed to reduce propagation of vibration signals between the active faces of the device, thus making the actuator signals perceptibly distinct. In particular, actuators were mounted on flexible, vibration-absorbing and/or isolated structures, as shown in the assembly diagram of Figure 5. Here, the U-shaped 'Rear Section', which holds the left and right actuators, is anchored only at the rear corners, causing the side walls to act as flexible cantilever beams. Similarly, the front actuator is mounted on a separate 'Front Section'. Both front and rear sections are separated from the top and bottom of the device via rubber rings, to limit vibration propagation.

Actuators are mounted within integrated 'pockets' in the internal body of the Cricket, surrounded by 1mm thickness ABS, intended for higher flexibility than the rest of the 3mm walls. Actuators are secured in place via a shim and M2 bolt, to prevent rattling within the pockets. The actuator surfaces are directly exposed to the user's fingers through openings in the device walls. Recessed finger guides aid finger alignment. Users place the base of the device in their palm and grip the front three faces with a 'tripod grip' (Figure 1). For a right-handed individual this would place the thumb on the right actuator, the index finger on the front actuator and the middle finger on the left actuator. The vibrating nature of the device gave it the name 'Cricket'. Like the Animotus, the device measures 60×60×40 mm and weighs 100 g.

C. *Navigation System*

In previous applications of the Animotus, we made use of an indoor localization system (*Ubisense*) that provided ~0.3m position resolution in combination with a wrist worn tilt-compensated magnetometer [11], [12]. In practical, outdoor-use scenarios, it is most likely that the interface would be driven via a smart phone application, as a wireless peripheral. This would make use of the various hardware and processing capabilities of the smartphone, enabling GPS sensing,

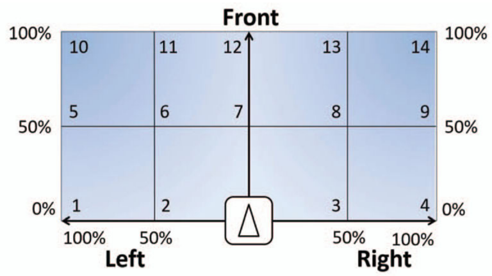

Figure 6: User choice sheet for the Cricket static test.

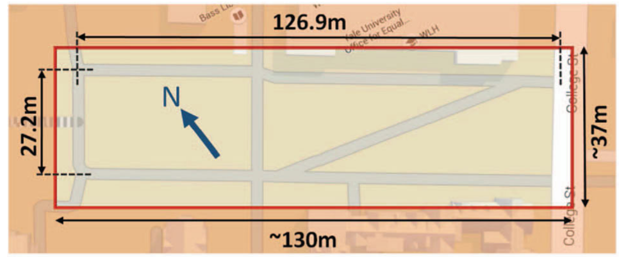

Figure 7: The navigation study took place in a pedestrianized area with a network of paths. This image is modified from a *Google Maps* view.

internet connectivity and powerful processing. A future iteration of the Animotus interface may even be integrated into a smartphone's body or case.

In this current work a smartphone (*Samsung S3-mini GT-I8190N* running Android 4.1.2) is used for GPS co-ordinate acquisition. These co-ordinates are transmitted via Bluetooth (using the *Sensorduino* application) to a *HC-05 Bluetooth module* (generic manufacturer) connected to an *X-OSC* embedded electronics platform. This platform is also connected (via wires) to a wrist worn tilt-compensated magnetometer (*Adafruit 9DOF*), the actuators of the Animotus / Cricket and *LiPo* power supply. The electronic components are currently carried by participants in a small camera bag during the study, but can certainly be miniaturized for future use. The X-OSC is a Wi-Fi enabled platform that communicates with a laptop (*Intel i7, Windows 7)* that runs the navigation software and static testing software (both written in *Processing*). The navigation software generates actuator positions based on a stored map of the environment, target locations and the user's current heading and position. Though the GPS co-ordinates update at 10Hz, the rest of the system updates at 100Hz. The study laptop also logs user motion data for offline analysis (in Matlab). This setup is displayed in Figure 3. Though it would be possible to realize the full navigation software as an Android application, this is unnecessary at this experimental stage, where the laptop provides a more flexible interface for participant monitoring and system debugging.

IV. Experimental Methods

This study was approved by the Yale Human Subjects Committee – HSC #1509016510.

A. *Haptic Cricket Perceptual Study*

Prior to comparing the two devices in a navigation task, the vibrotactile device was first verified as being able to provide discernable information to users. This was achieved via a static (i.e. seated) study in which the device sequentially assumed combinations of actuator vibration intensities which participants attempted to identify from a visual chart (Figure 6). A similar study was completed for the Animotus in [11], and so was not repeated here.

Fourteen 'poses' are presented on the chart, made up of combinations of 0, 50 & 100 % actuator intensity (related to the duty cycle of a 100 Hz PWM signal driving each actuator). Note that the left and right actuators are used to indicate CCW and CW heading magnitude and so never activate simultaneously. Two pre-determined random sequences are used, in which each pose is presented twice for a total of 28 poses. These are balanced between participants. An initial 'training period' demonstrates the various poses to participants. During the study, the poses are presented for one second each, followed by a period where participants either provide their perceived pose number or request the pose to be repeated. Participants wear headphones playing white noise to obscure actuator sounds in the quiet study room. These sounds can indicate active actuator intensity.

B. *Navigation Experiment*

An objective of this work is to evaluate the potential of haptic navigation interfaces in realistic scenarios. In our previous studies [11], [12] and work such as [5], [10] prototype navigation systems have been tested in open spaces, free of path constraints and obstacles. However, typical navigation scenarios (i.e. for pedestrians in urban environments or automobiles on roads) require guidance along man-made constraints, such as sidewalks / footpaths. Indeed, this changes the nature of the navigation problem, as the pedestrian user typically cannot move in any direction, due to traffic, buildings and other obstacles. As such, users of typical 'urban' GPS systems (as opposed to those used for wilderness hiking) follow a series of instructions at road and sidewalk intersections. Realistic environments also include a variety of other features, such as static and dynamic obstacles caused by objects, vehicles and people. These features are factored into both blind and sighted user's internal path planning process, as they attempt to follow guidance instructions from the navigation systems.

To achieve a similar set of realistic constraints and conditions, the navigation experiment was conducted in a largely pedestrianized area of Yale University known as *Cross Campus*, a map of which is shown in Figure 7. The space is attractive for this study due to its large size (the limits of the workspace measure approximately 37m×130m), network of footpaths, lack of road traffic (aside from cyclists)

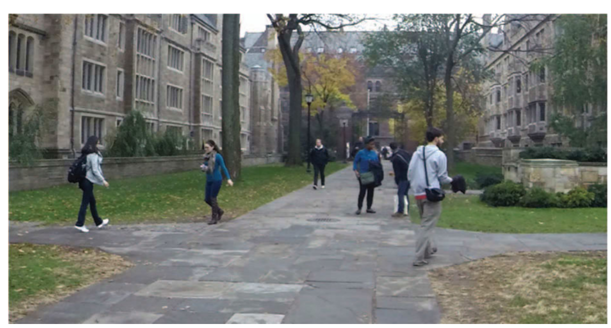

Figure 8: A participant (farthest right) navigating an intersection with the Cricket. Other pedestrians are not involved in the study. Both devices were covered with a cloth during the study.

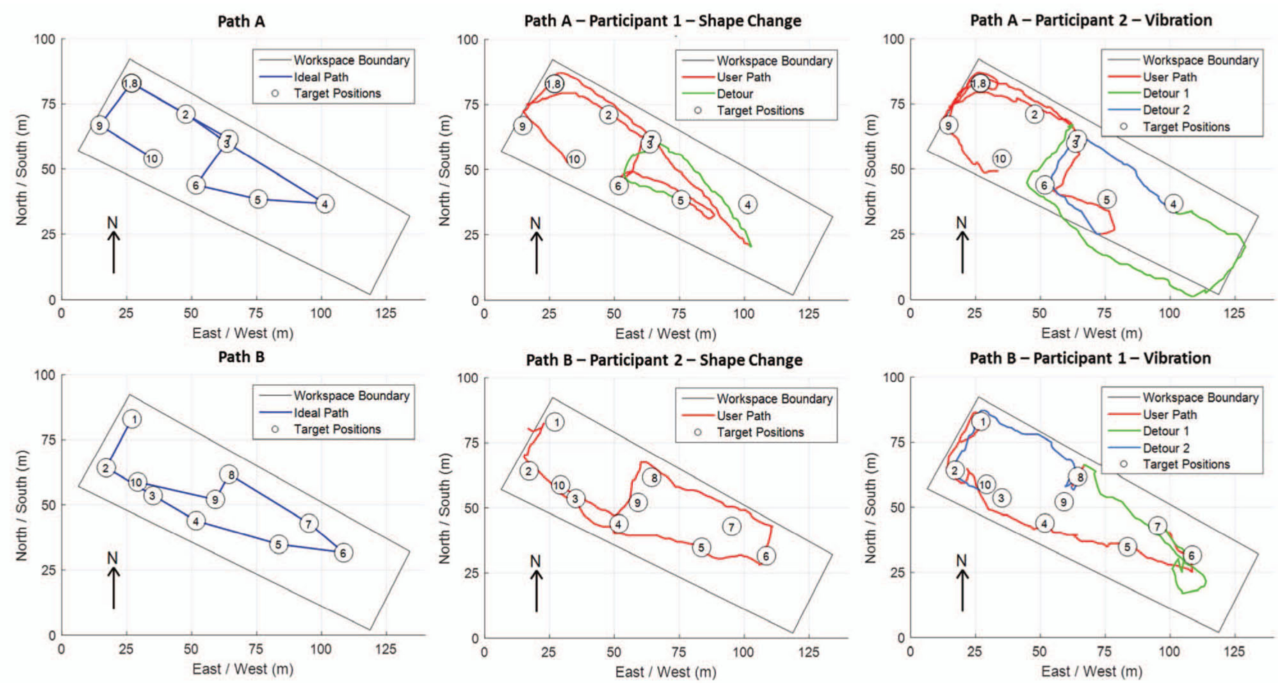

Figure 9: Walking paths of participants P1 and P2, from logged GPS data, when navigating with both devices. Users stayed on the footpaths (shown in Figures 7 and 8) at all times. Two target sets (i.e. waypoints that makeup Paths A and B) were used to prevent learning effects. All targets were located by all participants in each case, though more time, distance covered and detours were present with the vibrating device.

and relatively good GPS resolution (~3-7 meters) compared to other campus locations. The GPS resolution is notably lower and prone to distortion in the South East quadrant, which has buildings on both sides and a number of large trees. This variation in sensing accuracy may also be considered as a realistic feature outdoor navigation.

During the study participants used the devices to locate a series of 10 sequential targets, which together formed waypoints along one of two routes along the pedestrian walkways. These paths are shown in the left images of Figure 9. Each waypoint was determined via practical measurement, as it was found that map co-ordinates did not always coincide with actual measurements. Route A has a total Euclidean distance of 60.6m while Route B has a distance of 73.3m. Each waypoint / target was defined by GPS co-ordinates as a circular area with a radius of approximately 2m diameter – this size was based on GPS localization accuracy. The targets have no distinctive visual or physical markers, they are effectively invisible. To locate a target, participants were required to stand inside the circular area for one second. This was to prevent targets being found accidently. Once a target was located, the navigation system would automatically guide participants to the next target. The navigation system updated device pose and heading feedback in real-time based on available data. The haptic devices were covered with thick opaque fabric during the study (secured around the subjects hand and arm with a clip). This obscured both visual and audio cues from the devices.

Note that participants did not wear blindfolds or white noise headphones for safety reasons. The study environment is used by many pedestrians (some with small children) and occasionally cyclists. We feared that obscuring peripheral senses could increase chances of collisions with the participants. After the experiment, participants were asked to complete a 26 point questionnaire which aimed to investigate user opinion of navigating with the two haptic devices.

Total Mean Error Score

2.6	2.1	1.2	2.5	1.5
1.4	1.9	1.3	1.2	2.3
0.5	0.3	H	0.4	0.6

Heading Average Error

1.5	0.8	0.5	1.0	0.0
1.3	0.8	0.3	0.5	1.5
0.5	0.0	H	0.3	0.3

Proximity Average Error

1.3	1.8	1.0	2.0	1.5
0.3	1.8	1.0	1.0	1.3
0.0	0.3	H	0.3	0.5

Figure 10: Results of the static study for the Cricket. Numbers are Euclidean error scores.

V. RESULTS

For this proof-of-concept study, four participants (all male age 27-32) took part in the study. All participants had previously taken part in the static and indoor navigation experiments with the Animotus in [11].

A. Static Cricket Study

Average results (across all participants) of the static experiment are illustrated in an error matrix in Figure 10. In this representation each cell corresponds to the equivalent pose of the user choice sheet (Figure 6), with the number corresponding to an error score for that pose. The 'H' cell represents the 'home' state, where all actuators are deactivated. The error scores are determined via a Euclidean distance measure, so that if a user is presented with pose 6 but selects poses 2, 5, 7 or 11, then their the score will be '1', as the selection is in an adjacent cell. Note that errors have

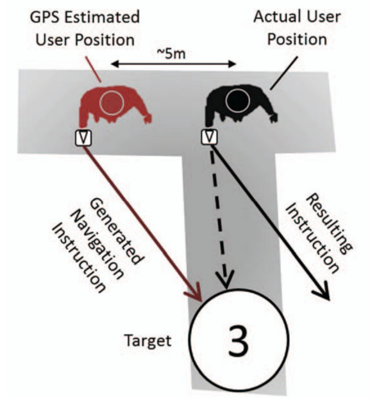

Figure 11: Poor GPS resolution can lead to erroneous heading instructions. The dotted arrow shows the correct heading instruction.

also been separated into heading (horizontal error) and proximity (vertical error) contributions. Combining heading and proximity errors will not necessarily equate to the total error, as some errors are in both heading and proximity.

The majority of errors accumulated in regions where forward and side actuators are simultaneously active, with at least one actuator at 100% activation. Participants reported that such stimulus is apparent but difficult to accurately locate. The lowest errors are related to regions where only one actuator is active (i.e. the bottom row and central column). During navigation, users tend to use the Animotus to simultaneously correct heading while reducing proximity. If the 'heading error' matrix of Figure 10 is considered, it can be seen that heading errors (which are lower than overall error) still permit such correction to take place, as erroneous selections are generally in the correct quadrant of the device. As we shall see in the next section, the Cricket performed sufficiently well to enable navigation for all participants.

B. Navigation Experiment

All participants completed both routes of the navigation experiment, locating all targets with the two devices. In all cases, set A was presented first, though the order of devices was varied and balanced. During each trial, each participant was logged as walking between 270-600m per device and between 790-883m in total. Example walking paths are shown in Figure 9 (based on logged GPS data), for participants P1 and P2, with both devices and both target sets.

1) Comment on GPS localization during navigation

GPS localization proved somewhat problematic during the study, with targets that had been set at particular locations appearing to 'relocate' by up to 5m less than an hour later. The approximate 2-7m resolution of the raw GPS Longitude/Latitude data was occasionally prone to slow updates, with participants finding themselves on the edge of a target for some time, and the system only updating after they had walked another several meters. This resolution also led to occasionally misleading heading guidance information, as calculations were based on accurate magnetometer data, but inaccurate GPS. Figure 11 demonstrates how this confused one participant, who was instructed to turn left at an intersection, though he was actually facing the target. The lowest resolution occurred in the southernmost part of the workspace, which is why waypoints were not placed here. The position error of participant P2 during a 'detour' along this Southern area may be seen in Figure 9 (top, middle), where GPS co-ordinates leave the workspace despite the real user remaining on the path. Clearly, movement errors in such cases are caused by the localization and navigation system, rather than the haptic interface. It should be noted however, that in screen based systems, it is easy to communicate location uncertainty to a user via a simple proportionate radius around the user's location on a map. The user may also use local landmarks (e.g. path intersections) to position themselves within this region and locate waypoints on the screen. Such dense information and redundancy is certainly difficult to convey with mobile haptic interfaces of the type presented here. In future work, GPS correction techniques (such as map-matching [19]) will hopefully address such uncertainty. For all participants, the two devices were tested in quick succession, so that GPS resolution / errors would remain consistent for that participant.

Table 1: Walking path efficiency

Participant	Shape (S)	Vibro (V)	Difference
P1	**14.5%**	**15.8%**	**1.3% (V)**
P2	**27.1%**	**10.1%**	**16.9% (S)**
P3	**21.4%**	**12.6%**	**8.8% (S)**
P4	**16.0%**	**17.7%**	**1.7% (V)**
Average	**19.7%**	**14.1%**	**5.7% (S)**

Table 2: Time to complete course (seconds)

Participant	Vibro (V)	Shape (S)	Difference
P1	**1098**	**462**	**+238% (V)**
P2	**1034**	**422**	**+245% (V)**
P3	**1297**	**737**	**+176% (V)**
P4	**1287**	**521**	**+247% (V)**
Average	**1179**	**535**	**+220% (V)**

2) Navigation Results

In the user paths of Figure 9, it may be observed that participants generally followed the 'correct' routes between paths, with a limited number of indirect routes. These 'detours' (which have been highlighted in different colors) were generally more common with the vibrotactile device, as participants interpreted heading with less resolution than the Animotus. It can be seen that the detours were not stochastic and are likely to be an effect of GPS error, as in Figure 11.

Numeric reports on walking path efficiency (calculated as *Ideal path between all targets / User path length*) and time to complete each course (adjusted for the additional 18.7m length of course B) are given in Tables 1 and 2. Table 1 indicates that equal numbers of participants performed more efficiently with the vibration and shape-changing devices. On average, a higher efficiency score was achieved with the shape-changing device though comparison between the groups (paired t-test) showed no significant ($p<0.05$) difference ($p=0.293$). Table 2 illustrates that all participants took more time to complete the courses with vibration feedback than shape-changing feedback (following correction for the extra physical length of path B). This difference in time was highly significant ($p=6.8\times10^{-4}$). In many cases, participants were observed standing in one place with the vibrating device, in an effort to interpret the vibrating signals when not walking. This action would not increase path length (leading to efficient motion) but would increase time.

C. *Questionnaire*

The questionnaire asked 27 questions related to the experiment as a whole and specific device use. Answers were based on a multiple choice scale with average results across all participants indicated in Table 3. In all cases participants reported more desirable characteristics in the shape-changing device. Additional general questions indicated that some participants felt very self-conscious during the experiment, though this was likely due to pedestrians being drawn to the user's prominent arm draped with a thick cloth. In open questions one participant commented that their hand felt numb after 10 minutes with the vibrating device. Participants did not report physical fatigue after the study.

VI. Conclusion

In this work we have applied mobile shape-changing and vibrotactile haptic interfaces to realistic semi-structured pedestrian navigation in an outdoor urban environment. This environment featured footpath constraints, large walking distances and other pedestrians and cyclists. The two devices successfully guided the users between the waypoints of two pre-determined walking paths, via simultaneous presentation of heading and proximity data. Prior to the navigation study, user perception of the new vibrotactile 'Haptic Cricket' was validated via a static experiment, indicating sufficient resolution for differentiating navigation instructions.

Despite the impact of uncertain GPS localization, both devices enabled participants to locate all targets/waypoints in the environment. User motion efficiency was statistically equivalent for both devices, though time taken was significantly longer (often over 200%) with vibrotactile feedback. Participants spent more time standing still or walking slowly with the vibrotactile system, in order to better interpret the output (also reflected in questionnaire results).

User opinions greatly favored the shape-changing device. The constant stimulation of the Haptic Cricket was based on examples in literature, this was determined to be relatively annoying, confusing, distracting and cognitively demanding, in comparison to the Animotus shape-changing system.

A notable general issue encountered during this study is the uncertainty of GPS localization, which can lead to incorrect navigation information for the user, particular in the case of heading feedback (Figure 11). Though this may certainly be improved by various algorithms and map-fitting techniques, it was considered that in conventional screen-based apps, the view of a map can help a sighted user estimate their actual position in the environment and correct for errors in the navigation system. It is not clear whether such redundancy is possible, or should be necessary, in low bandwidth mobile haptic navigation interfaces of the type explored here. This will be investigated in future work.

Table 3: Average questionnaire results: 1 = Strongly Disagree, 3 = Neutral, 5 = Strongly Agree. Brackets indicate standard deviation.

Questions	Shape	Vibro
The device was **confusing**	1.25 (0.4)	3 (0.7)
The device was **intuitive**	4.75 (0.4)	2.75 (0.8)
Direction was easy to interpret	4.75 (0.4)	2.5 (0.5)
Distance was easy to interpret	4.25 (0.8)	2.75 (1.3)
The instructions felt **accurate**	4 (0.0)	3 (0.0)
I got **mentally tired** using the device	2 (0.8)	3.5 (0.9)
I **enjoyed** using the device	3.75 (1.6)	2.75 (0.4)
I felt **confident** in the device	4 (0.7)	2.25 (0.4)
I found the device **annoying**	1.75 (0.4)	3.5 (0.5)
I think I could **navigate a city** with this	4 (0.7)	2.25 (0.4)
I paid less **attention** to my surroundings	2.25 (1.1)	3.5 (0.9)

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References

[1] C. C. Collins, "On Mobility aids for the blind," in *Electronic spatial sensing for the blind*, no. 26, 1985, pp. 35–64.

[2] J. L. Nasar and D. Troyer, "Pedestrian injuries due to mobile phone use in public places.," *Accident; analysis and prevention*, Aug. 2013.

[3] D. C. Schwebel, D. Stavrinos, K. W. Byington, T. Davis, E. E. O'Neal, and D. De Jong, "Distraction and pedestrian safety: How talking on the phone, texting, and listening to music impact crossing the street," *Accident Analysis and Prevention*, pp. 266–271, 2012.

[4] J. Borenstein and I. Ulrich, "The Guidecane - A Computerized Travel Aid," in *Robotics and Automation*, 1997, no. April.

[5] S. M. Kärcher, S. Fenzlaff, D. Hartmann, S. K. Nagel, and P. König, "Sensory augmentation for the blind.," *Frontiers in human neuroscience*, vol. 6, no. March, p. 37, Jan. 2012.

[6] A. A. Stanley and K. J. Kuchenbecker, "Evaluation of tactile feedback methods for wrist rotation guidance," *IEEE Transactions on Haptics*, vol. 5, no. 3, pp. 240–251, 2012.

[7] K. Bark, J. W. Wheeler, S. Premakumar, and M. R. Cutkosky, "Comparison of Skin Stretch and Vibrotactile Stimulation for Feedback of Proprioceptive Information," *2008 Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*

[8] I. Oakley and J. Park, "Did you feel something? Distracter tasks and the recognition of vibrotactile cues," *Interacting with Computers*, vol. 20, no. 3, pp. 354–363, May 2008.

[9] Y. Zheng and J. B. Morrell, "Haptic actuator design parameters that influence affect and attention," *2012 IEEE Haptics Symposium (HAPTICS)*, pp. 463–470, Mar. 2012.

[10] S. K. Nagel, C. Carl, T. Kringe, R. Märtin, and P. König, "Beyond sensory substitution--learning the sixth sense.," *Journal of neural engineering*, vol. 2, no. 4, pp. R13–26, Dec. 2005.

[11] A. Spiers, A. Dollar, and M. Oshodi, "First Validation of the Haptic Sandwich : A Shape Changing Handheld Haptic Navigation Aid," in *ICAR 2015: International Conference on Advanced Robotics*, 2015.

[12] A. Spiers, J. Van Der Linden, M. Oshodi, S. Wiseman, and A. Dollar, "Flatland : An Immersive Theatre Experience Centered on Shape Changing Haptic Navigation Technology," *IEEE World Haptics Conference (WHC)*, 2015.

[13] R. Klatzky, R. Bajcsy, and S. Lederman, "Object exploration in one and two fingered robots," *Proceedings 1987 IEEE International Conference on Robotics and Automation*, vol. 4, pp. 1806–1810, 1987.

[14] M. a Plaisier, W. M. B. Tiest, and A. M. L. Kappers, "Salient features in 3-D haptic shape perception.," *Attention, perception & psychophysics*, vol. 71, no. 2, pp. 421–30, Feb. 2009.

[15] R. Velázquez, "Wearable Assistive Devices for the Blind," *Wearable and Autonomous Biomedical Devices and Systems for Smart Environment*, pp. 331–349, 2010.

[16] P. B. Shull and D. D. Damian, "Haptic wearables as sensory replacement, sensory augmentation and trainer – a review," *Journal of NeuroEngineering and Rehabilitation*, vol. 12, no. 1, p. 59, 2015.

[17] M. K. Rasmussen, E. W. Pedersen, M. G. Petersen, and K. Hornbæk, "Shape-Changing Interfaces : A Review of the Design Space and Open Research Questions," pp. 735–744, 2012.

[18] F. Hemmert, S. Hamann, and M. Löwe, "Take me by the hand: haptic compasses in mobile devices through shape change and weight shift," *Proceedings of the 6th Nordic Conference on HCI*, 2010.

[19] Y. Lou, C. Zhang, Y. Zheng, X. Xie, W. Wang, and Y. Huang, "Map-matching for low-sampling-rate GPS trajectories," *Proceedings of the 17th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems - GIS '09*, no. c, pp. 352–361, 2009.