2016 IEEE International Conference on Robotics and Automation (ICRA)
Stockholm, Sweden, May 16-21, 2016

Development and Experimental Validation of a Minimalistic Shape-Changing Haptic Navigation Device

Adam J. Spiers *Member, IEEE*, Janet van Der Linden,
Maria Oshodi, Aaron M. Dollar, *Senior Member, IEEE*

***Abstract*— This paper presents a minimalistic handheld haptic interface designed to provide pedestrian navigation assistance via the intuitive and unobtrusive stimulus of shape-changing. The new device, named the *Haptic Taco*, explores a novel region of robotic interfaces which we believe to have benefits over other communication methods. In previous work, we demonstrated the use of a 2DOF shape changing interface for navigation without the use of sight. In this paper we seek to explore the potential of minimal 1DOF interfaces, whose simplicity may increase intuitiveness and performance despite conveying less information. The Haptic Taco utilizes the same 'variable volume' concept as a previous device, the Haptic Lotus (2010), but with reduced body compliance and higher force exertion capability. Both devices modulate their perceived volume in relation to proximity to a navigational target (a destination or waypoint). As users walk within an environment, they also attempt to minimize the device volume, finding targets via an embodied 'steepest descent' method. Experimental comparison of the Lotus and Taco in a target-finding study revealed that the Taco interface increased motion path efficiency by 24% over the Lotus, to 47% average efficiency. This result is highly comparable to the mean motion efficiency of 43.6-48% observed in prior experiments with the 2DOF shape-changing interface, *the Animotus*. The findings indicate the potential for minimalistic interfaces in this emerging field.**

I. INTRODUCTION

Haptic interface research is an active and multifaceted area of investigation that continuous to develop a variety of technologies and techniques for generating artificial touch stimuli. Often however, it is not clear whether a selected haptic stimulus has been appropriately matched to the application or information at hand. In this work we present a novel haptic navigation device whose interface was developed to provide unobtrusive navigation guidance to pedestrians, without distracting their attention from the environment or other tasks. The little explored modality of haptic shape-changing technology was chosen as the basis of these devices, the motivation for which will be discussed in the following section.

Pedestrian navigation assistance via smartphones and GPS has become widespread, with recent indoor localization developments hoping to extended similar functionality into locations such as hospitals and shopping malls. A primary user interface for such technology involves screen based maps on smartphones, with visual instructions delivered in the form of paths, arrows and numerical displays of distance. These modes of communication are functional, but have led to concerns of diverting visual attention from walking hazards [1]. Indeed, recent hospital reports indicate increasing numbers of accidents due to mobile related distraction [2]. It has been demonstrated that pedestrians, like drivers, show reduced situational awareness and distraction from hazards when talking or texting on mobile phones [3][4]. It is clear that when humans carry out multiple tasks from the same attentional resource pool, performance typically declines [5].

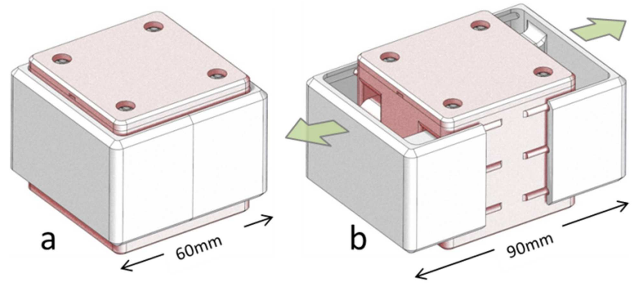

Figure 1: The handheld Haptic Taco, in (a) fully contracted and (b) fully expanded configurations.

When the visual displays of smartphones are inaccessible for visually impaired (VI) persons, audio instructions delivered during GPS navigation are an obvious alternative. However, the necessary requirement of headphones in noisy urban environments can mask the ambient sounds used to avoid hazards, appreciate one's surroundings or communicate with others [6]–[8].

For pedestrian navigation guidance, haptic interfaces may provide more appropriate stimuli to VI and sighted groups, due to the less critical role of touch during walking. Indeed, the most long-standing and successful VI mobility aids are the guide cane and guide dog, both of which provide feedback via mechanotactile haptic cues delivered through the cane's handle or dog's harness. Beyond VI individuals, the appeal and benefit of haptic navigation to sighted individuals is also apparent in consumer interest related to the Taptic interface of the Apple watch, which is capable of providing simple haptic navigation instructions [9].

Various haptic navigation and motion guidance systems have been proposed, often due to the potential of haptics to provide sensory augmentation without interfering with the other senses. A frequent stimulus choice for such applications has been vibrotactile feedback [6][7][10]. This technology has many general integration benefits (the actuators are small, lightweight, inexpensive, low power and

*Research supported by NESTA Digital Fund, London, UK.
A. J. Spiers and A. M. Dollar are with the Department of Mechanical Engineering, Yale University, New Haven, CT 06511, USA. (phone: 203-432-4380, e-mail: adam.spiers@yale.edu, aaron.dollar@yale.edu).
J. van der Linden is with the Pervasive Interaction Lab, Open University, Milton Keynes, UK (j.vanderLinden@open.ac.uk)
M. Oshodi is with the Extant theatre company, London, UK (maria@extant.org.uk)

978-1-4673-8025-6/16/$31.00 ©2016 IEEE

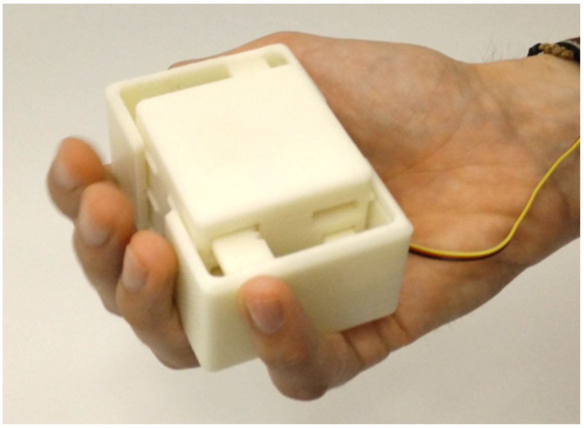

Figure 2: The Haptic Taco physical prototype, held in a user's hand

simple to control). Outside of motion guidance, vibrotactile feedback is a standard feature of mobile phones, where it is primarily used to signify discrete and infrequent events, such as a new message or incoming call. The success of vibrotactile in such an application was attributed in [11] to its "alert signifying" nature. Related to this, other authors [12][13] have suggested that alerts are not always an appropriate form of information delivery. In particular the authors of [12] suggest that technology designers should consider the place of a haptic stimulus in a user's *attention spectrum,* given the nature of the application, to ensure the feedback does not distract from more critical tasks.

Motivated by the above considerations, our work has aimed to investigate haptic feedback interfaces that are unobtrusive, providing intuitive but not distracting sensations. We believe this would make a system more appealing for longer term use than the more 'alert-based' methods of haptic feedback. In particular, it was considered that alerting stimuli could get tiring over the extended periods of time often associated with pedestrian navigation, as observed in [10].

One alternative and little-explored feedback modality may be found in haptic shape changing interfaces. An excellent example of such a technology is the dynamically tapering mobile phones cases of Hemmert, who constructed 1DOF and 2DOF systems [14][15]. In the same year, *The Haptic Lotus*, a 1DOF shape changing navigation interface, was designed for use in the immersive experimental theatre production, *The Question* [16] (www.thequestion.org.uk). Designed to be intuitive, unobtrusive and encourage embodied exploration of an unknown space, the Haptic Lotus functioned by modulating its volume in the user's hand, as they approached navigational targets.

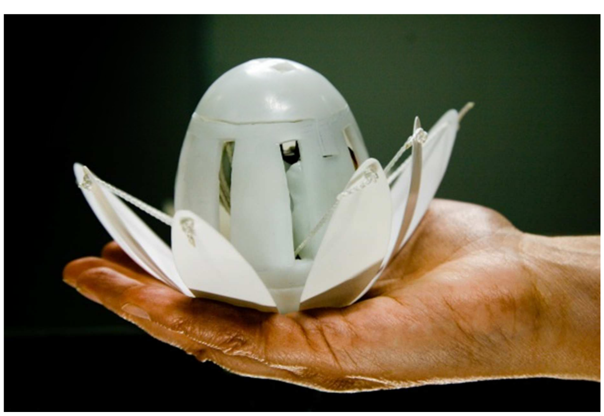

Figure 3: The Haptic Lotus variable-volume navigation aid, created in 2010 [16].

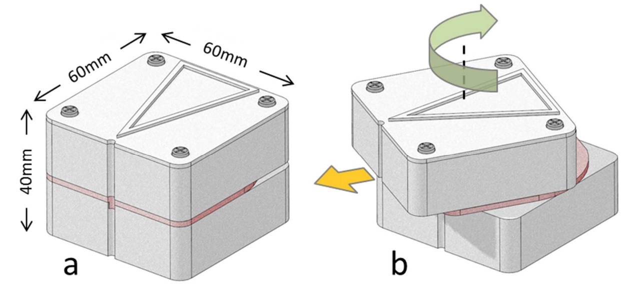

Figure 4: The Haptic Sandwich / Animotus, 2DOF shape changing device from [17][18], capable of providing simultaneous heading and proximity to navigational targets.

Though the Haptic Lotus (Figure 3) was well received, observations of user interaction during later demonstrations indicated design shortcomings that impaired user perception of the navigational information (to be discussed in Section III). These shortcomings limited the usefulness of the device, with the resulting weak navigational user performance questioning the potential of the shape-changing modality. Despite these weaknesses, study participants reacted well to the device's novel interface, which appeared suited to long term use in the theatre scenario of *The Question*. These positive user reactions inspired the further development of shape changing interfaces, leading to the development of the 2DOF *Haptic Sandwich* device (Figure 4), which provides simultaneous heading and proximity to navigational targets [17]. The device was effectively used by 94 sighted and VI persons in the 2015 immersive theatre production, *Flatland* (www. flatland.org.uk), at which point it was re-named, *The Animotus* [18]. Participants using the Animotus in *Flatland* demonstrated much better navigational capability than those who used the Haptic Lotus in *The Question.* The increase in performance was due to improvements in both the navigational interface and the localization system. Though Flatland participants generally seemed to require little familiarization with the *Animotus* device, some individuals struggled initially with the multi-DOF navigational concept.

In light of the above observations, it may be possible that a 1DOF navigational system, with similar mechanical properties to the *Animotus*, may actually be more intuitive and effective than a 2DOF shape changing system. Such factors would no doubt lead to better navigational performance. These considerations motived the design of the Haptic Taco (Figure 1, Figure 2).

The ultimate objective of these research endeavors is to develop haptic navigation interfaces for use in real-world pedestrian navigation scenarios (e.g. finding a café in a city) by sighted and VI persons. Obviously such navigation should be as efficient as possible.

In the remainder of the paper we discuss related work, consider the design of the Haptic Taco device, in relation to the Haptic Lotus, present a navigational experiment comparing these devices and finally relate the results to observations of the Animotus, the 2DOF shape changing interface used in Flatland [18]. Finally we indicate directions of future work.

II. Related Work

Various technical interfaces have aimed to offer navigation or motion assistance via sensory augmentation. Often such systems feature haptic feedback, for reasons discussed previously. Though benefits of such systems to persons with sensory impairments are obvious [7], some approaches also aim to improve the capabilities of non-impaired individuals. An excellent example is the *FeelSpace* belt of multiple vibrotactile actuators [6][10]. By constant vibration of the most north-facing actuator, the device investigated the functional and emotional effects of spatial sensory augmentation. Though the belt provided some benefits to a VI study participant, several weeks of use were required to achieve these effects [6]. Other visual to audio [19] or visual to tactile [20][21] systems have required over 100 hours of training for comprehension, even then leading to high cognitive loading. For some study participants, the constant vibration stimulus of the FeelSpace belt was described as ‘annoying’ and impairing concentration [10]. These reports match the observations of [12], in which the authors comment that many haptic feedback modalities effectively provide alerts that can become disruptive or annoying when the user wishes to focus on another task. The authors further argue that more ‘ambient’ haptic sensations would allow better management of user attention to permit appropriate multitasking. Considering the tasks of a pedestrian, it is certainly more critical to avoid walking into traffic than having to backtrack after a wrong turn [2].

Beyond vibrotactile, various techniques are available for ungrounded haptic guidance. Skin stretch tactors [22], mechanotactile / pressure interfaces [12][13] and inertial devices [23][24] have been used to convey some kind of spatial information. In [13], Stanley and Kuchenbecker compare a variety of wearable haptic interfaces (including a squeezing mechanism and vibrotactile wrist cuff) for wrist rotation guidance. In [1], Hemmert et al. proposed the use of shape-changing handheld mobile phone cases, which indicated direction in a static, simulated navigational task (users turned an office chair to match directions).

Though other prototype systems that are able to modify their forms may be found in [21][22], shape modification is often used for a visual rather than haptic effect. Indeed there are few examples of shape changing haptic feedback systems.

The appreciation of an object’s shape and volume within the hand is a fundamental sensory ability [27][28]. From this, we propose that because such sensations are more naturally encountered than other common modes of artificial haptic stimuli (e.g. vibrotactile), it may be that humans would treat a change in shape as a more ambient stimulus that does not have the same alerting and distracting properties.

Aside from haptics, many wearable navigation assistance devices have been proposed for VI individuals (reviews of which may be found in [7][29]). These can resemble instrumented and actuated jackets, corsets and motorbike helmets. In [1], Hemmert et al. highlight social acceptability and practical issues of such systems, compared to normal clothing practice. Indeed, even owners of guide-dogs have expressed ‘considerable concern’ about how their dogs made them more conspicuous [30]. In comparison, a handheld item, that may be stowed when not in use (like a mobile phone) is an attractive inconspicuous alternative that has inspired our pursuit of handheld interfaces.

III. Haptic Interface Design

In this section we shall outline the shape changing concept inherent in the original Haptic Lotus device. The design of the new Haptic Taco system will then be presented.

A. *Proximity Based Navigation*

As previously discussed, the representation of abstract or visual concepts via the low-bandwidth nature of touch is challenging and may be associated with long training times, as users learn to interpret dense data [6][20][21]. A contrasting navigation technique was proposed in [16], which aimed to reduce cognitive demands and training times via the presentation of minimal navigational information. By representing only the user’s proximity to a navigational target (hereafter simply ‘proximity’), navigation may be achieved via observation and modulation of a single scalar value. Such a variable may be easily mapped to a haptic sensation.

Navigation through proximity alone is common in a variety of scenarios, such as the ‘hotter/colder’ children’s game, avalanche beacon localization, the use of *Stick-and-Find / Tile* Bluetooth beacons and gradient descent optimization algorithms. In all cases, it is necessary for the agent to perform some local motion in the environment to determine if their proximity error has increased (they are moving away from the target) or decreased (they are moving towards the target). By attempting to minimize their proximity error, users are able to direct these motions to locate goals.

The effectiveness of this technique and length of the path to a target is dependent on the resolution of the feedback to the agent. If the agent needs to move several meters before they perceive a change in proximity, then their path will include diversions which are also several meters long. With

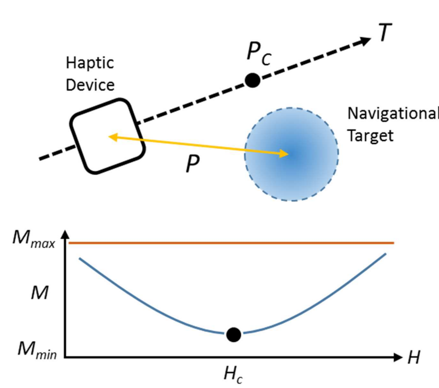

Figure 5: The response of proximity (*P*) based feedback, when a user’s straight line path (*T*) does not intersect a target. *M* represents the stimulus magnitude. P_C is the closest point on *T*.

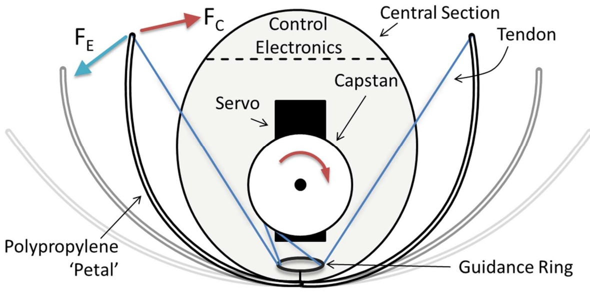

Figure 6: The Haptic Lotus underactuated expansion/contraction mechanism.

appropriate feedback resolution however, such diversions should be minimal and quickly corrected. Indeed, even user paths that do not intersect a target (Figure 5) may be quickly modified by realization that the stimulus magnitude has reached a local minimum (at P_C) and then increased as the agent begins to move away from the target (along T). This feedback may be represented by a change in some stimulus (M), e.g. the pitch of an audio tone, amplitude of a visual graph, or in the case of the Haptic Lotus and Haptic Taco, the size (volume) of the device body. In both devices, the minimum volume is used to imply that the user is at the target. The size of the device is then proportional to proximity to the target, with an upper bound that can be adjusted depending on the environment and distances to be covered. Again, as the user moves, they attempt to minimize the device volume. Increases in volume therefore lead to corrections in walking direction. These directional changes are hopefully fast, leading to minimal path divergence.

Though we currently test the proposed navigation method in a controlled scenario (a room of fixed dimension) it is not impossible for such a proximity based navigation system to be used outdoors, over long distances. By simply constructing a series of waypoints along a navigational route, a user may travel across a city, being guided from one street (or other feature) to the next. Indeed, the nature of waypoints, guiding us from one sidewalk / road intersection to another, is the general nature of GPS based smartphone navigation applications (such as Google Maps). Of course, in the case of shape changing devices, distances between targets are potentially unbounded, while actuator range of motion is not. Therefore dynamic upper bounds of motion will facilitate navigation over a range of environments.

A. Haptic Lotus

The Haptic Lotus was developed as an initial exploration into variable-volume navigation interfaces. It was created for use in the immersive theatre production, The Question (described in [16]), in which 82 sighted and 16 visually impaired audience members used Lotus devices to locate 'zones' in a completely dark space. These zones were associated with the production's plot through location based audio and tactile set pieces.

The Haptic Lotus (Figure 3) resembles a Lotus flower, with a rigid egg-shaped central section of cast thermoplastic surrounded by a ring of 8 flexible polypropylene petals. The device communicates proximity information by contraction of the petals as the user approaches a navigational target. By resting or lightly gripping the Haptic Lotus on the palm of their hand, a user is able to 'feel' their current proximity to a target, via the volume occupied in their hand by the device. By attempting to minimize device volume, users are able to move towards a target via the navigation method described in the previous section.

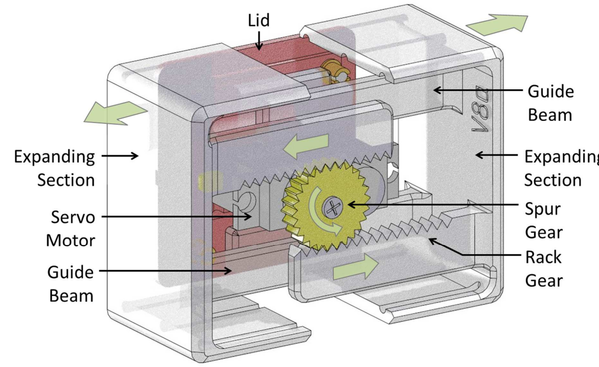

Figure 7: The dual rack-and-pinion mechanism of the Haptic Taco. The central section has been removed in this image.

The underactuated mechanism of the Lotus is illustrated in Figure 6. The petals are connected via nylon tendons to a winch pulley in the central section, actuated by a HiTec HS-82MG servo motor. Winding the pulley pulls the polypropylene petals inwards. Unwinding the pulley causes the petals to unfold into an open position, as the polypropylene attempts to return to a flat configuration. A later realized shortcoming of this design was that the actuator could only provide contraction forces (FC in Figure 6), while expansion forces (FE in Figure 6) are passively based on the flexibility of the petals. This flexibility causes a problem if a user tightly grips the Lotus, as their grip force typically overcomes the compliant polypropylene, pushing the petals inwards into a constantly closed position decoupled from tendon tension. The expansion force of the Lotus (FE) was measured as 0.1 N per petal. Contraction force (FC) was measured as 1.04 N per petal. Normally 6 or 7 petals are in contact with the user's hand. The redundant petals are provided for symmetry, to allow the device to be gripped in various orientations. The Lotus takes 600 ms to fully expand (from a fully contracted state) and 500 ms to fully contract (from a fully expanded state). The additional expansion time is due to reliance on the passive flexibility of the petals, while contraction relies on tendon tension provided by the servo actuator. The Lotus measures 73.2 mm (at widest point) when contracted and 132.8 mm when fully expanded (55 % perceived volume increase). It is 100 mm tall and weighs 150 g.

B. Haptic Taco

The Haptic Taco (Figure 1) builds on the expansion methodology of the Lotus, by aiming to improve the ability of participants to recognize variations in device size. In particular the Taco is inspired by the higher forces and rigid, multi-segment body of the 2 DOF Haptic Sandwich / Animotus, which is described in [17][18]. Specifically, the Taco replaces the compliance and underactuation of the Lotus with a rigid shell mechanism and fully actuated transmission, capable of exerting larger bi-directional forces.

The Taco resembles a cube that is able to elongate by extending two vertical faces in opposing directions, away from a central section (Figure 7). The Taco weighs 100 g and measures 60 mm × 60 mm × 47 mm (L×W×H) when contracted. When fully extended the length (L) value increases from 60 mm to 90 mm, leading to 50 % perceived volume increase. Bi-directional force exertion capability is 4.5 N per armature (9 N total). The Taco takes 380 ms to fully expand (from a fully contracted state) and 500 ms to fully contract (from a fully expanded state). The additional contraction time is most likely associated with the gradual increase in contact area (and therefore, friction) between the surfaces of the guide beams (Figure 7) and the central section, as the expanding sections are pulled inwards.

The device name comes from the vague 'hard taco shell' shape of the expanding sections. These sections were designed with 'C' shaped outer walls, to negate pinching hazards and provide a continuous contour around the side of the device. The continuous contour improves the haptic impression of the device modifying its volume, rather than simple linear motion of two faces. The top and bottom faces of the central section protrude to enable the device to be rested on the palm without the moving shells pinching the user's skin. The initial prototype does still provide some pinching hazards, though no such interactions occurred during the experiments performed for this paper. These hazards will be solved in future generations of the device.

The device can be held in a variety of orientations though most users prefer the expansion to push against the thumb and little / ring finger, with the central section resting on the palm. This arrangement is shown in Figure 2.

Like the Lotus, the Taco is actuated via a Hi-Tec HS82-MG servo, fitted with an Acetyl 32-pitch spur gear (OD = 19.22 mm). The spur gear interfaces with rack gears that extend from the two identical expanding sections. Rotation of the gear leads to the simultaneous linear motion of the expanding sections in opposing directions (Figure 7). Various linear guides prevent twisting and jamming of parts. All parts are 3D printed with the exception of the actuator, spur gear and fasteners. 3D printing permits easier fabrication and replication than with the Lotus, whose fabrication involved thermoplastic casting and skilled manual work with hand tools.

IV. Experimental Evaluation

An indoor navigation experiment was completed to evaluate performance improvements resulting from the mechanical differences between the Lotus and Taco variable volume interfaces. It is hoped that such changes increase user perception of the modality, leading to faster responses and shorter walking paths. In addition, the experiment aims to quantitatively evaluate the potential of proximity based navigation assistance and compare this to previously recorded navigation performance with the 2DOF Animotus in [18]. Though the Lotus also made use of a proximity based navigation method in [16], the simplistic nature of the localization system in that work did not permit logging or accurate evaluation of participant motion.

In the experiment, the Lotus and Taco devices (which were visually obscured) assisted sighted participants in locating sequences of ten invisible circular targets on the

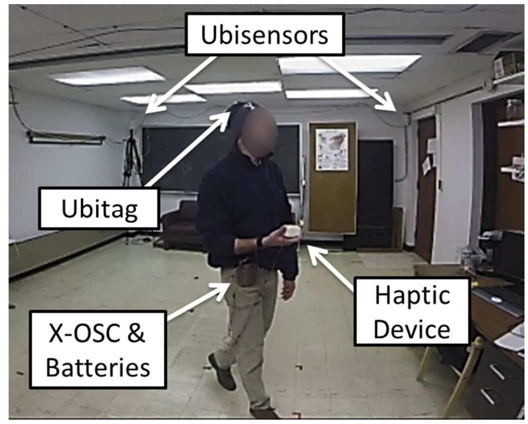

Figure 8: Experimental conditions. The device was hidden under a cloth (draped over the participant's hand) during the study.

floor of a 5.1 m × 5.3 m indoor space, cleared of obstacles. The experimental protocol was approved by Yale University's Human Subjects Committee (ref #1408014462).

A. Localization and Feedback System

In order to enable the haptic devices to indicate the proximity between users and the current target, a closed loop localization and feedback system was established using a Ubisense Real Time Localization System (RTLS) and X-OSC wireless microcontroller [31]. The system (detailed in [17]) provided significant control and resolution improvements over the localization system previously utilized with the Haptic Lotus [16]. The Ubisense system relies on Ultra-Wide Band (UWB) radio signals to locate small, powered 'Ubitags' in the workspace. Though placing Ubitags on or near the handheld haptic devices would have been preferable, fastening the Ubitag to the top of a hat provided optimum localization performance by avoiding the user's body occluding the UWB signals. Data recorded from static Ubitags illustrated continuous position fluctuations by up to 0.32 m. To account for this uncertainty, targets were established as circular areas with a 0.4 m radius. Position data was moving average filtered by the navigation software, to prevent actuator jitter.

The localization system reported the Cartesian location of the participant to a PC running custom navigation software, which was written in Processing. This software calculated proximity error to the current target. A corresponding actuator signal, scaled to the maximum dimension of the workspace and device expansion range, is then transmitted to the X-OSC. This scaling resulted in 3.9 mm of expansion (maximum 30 mm) per meter of proximity error for the Taco and 7.8 mm of expansion (maximum 60 mm) for the Lotus. The X-OSC and a LiPo battery pack (combined weight 110 g) were carried in a belt pouch by the participants and connected to each device's actuator via a cable. These elements may be integrated into the Taco in future iterations. The experimental equipment setup is shown in Figure 8. The system updates at 100 Hz.

B. Experimental Method

Participants were requested to use feedback from the haptic devices to locate sequentially presented targets in the

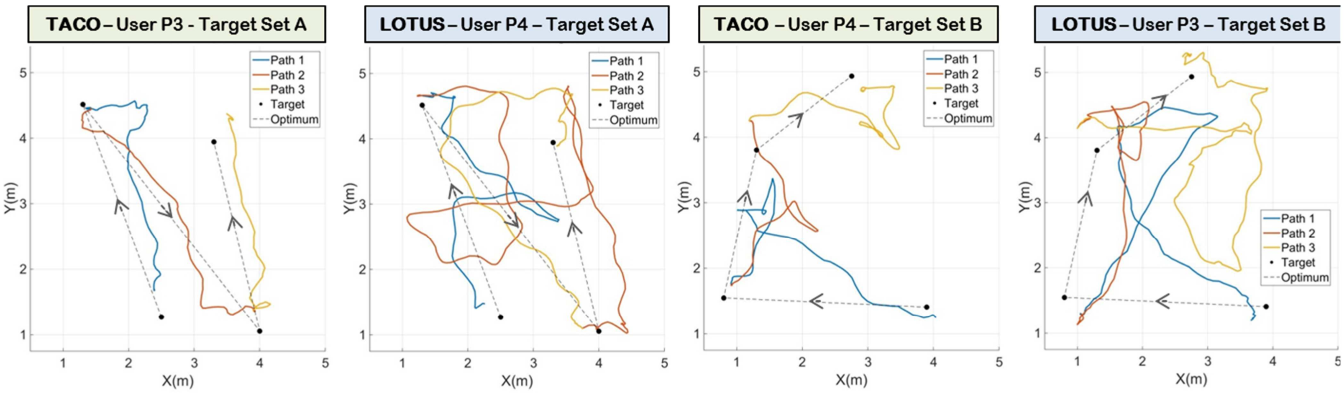

Figure 9: Example walking trajectories (for participants P3 and P4) between targets when following haptic device guidance. Two target sets were utilized to avoid participants remembering target locations between devices. Targets have a 0.4 m radius. Walking paths when being guided by the Taco are generally shorter and more direct than with the Lotus.

workspace. The haptic devices were visually obscured with black fabric, draped over the user's hand, during the study. A lightweight frame attached to the top of the Haptic Lotus prevented the fabric from interfering with the petal motion. Both devices contracted as user's approached targets and expanded as they moved away from targets. As this study focused on general navigation ability, participants were not blindfolded and the room was well lit. Targets were considered 'found' when a participant remained inside the target radius for 2 seconds. This delay prevented accidental 'finding' of targets by users who may momentarily pass through the targets during stochastic exploration. Participants were instructed to attempt to find the targets at a comfortable walking pace, rather than attempting to locate them as quickly as possible.

Each participant completed the study with both haptic devices. The order of devices was randomized and balanced between participants (as much as was possible with an odd number of users). To prevent participants remembering the locations of targets, two target sequence sets, A and B were utilized. Set A was presented first in all cases. Both sets involved ten targets in pre-defined locations, distributed around the space. Prior to using each device, participants underwent a brief (less than 10 minutes) familiarization process, beginning with a demonstration of the range of motion & haptic sensation of the device, while held by the participant. Participants were then requested to locate three training targets in the workspace (not part of sets A or B). During familiarization the device was not visually obscured.

V. RESULTS

Seven participants (ages 22-33, 1 female) completed the study. In subsequent analysis these participants are referred to as P1-P7. Due to variations in participant strategies and walking pace, location time was not considered a reliable evaluation metric. Instead, evaluation was based on efficiency of the participant's motion trajectories between each set of targets in the target sequence, compared to a straight line between the same points. Note that exact straight line walking motion between two points is uncommon, even in unconstrained normal walking to a known target [32]. In our case, participants obviously do not know where they are being guided to.

A. *Motion Trajectories*

Typical trajectories are illustrated in Figure 9. The figure shows path trajectories of participants P3 and P4 with both the Lotus and Taco devices, balanced across target sets. To aid clarity in Figure 9, only trajectories between the first four targets (3 motion paths) are shown in each case. The radius of each target (0.4 m) is also omitted for path clarity. This data was smoothed with a moving average filter (as in the navigation software) to reduce localization noise. It is clear in these figures that path length between the targets is generally shorter and more direct with the Taco than Lotus, identifying better user response to stimulus changes. Straight line paths between targets have been included for comparison; these indicate that though Taco paths are better than Lotus paths, there is still room for improvement.

A. *Path Efficiency Evaluation*

For numeric path efficiency comparisons, the following normalized Path Efficiency metric (PE) was applied to each of the segmented paths between targets:

$$PE\ (\%) = \frac{E_P}{U_P}$$

EP is the Euclidean distance between targets (a straight line), UP is the distance covered by the participant's path and PE is the resulting path efficiency ratio. A 50% path efficiency ratio would indicate the user has travelled twice as far as the straight line path between targets. Higher

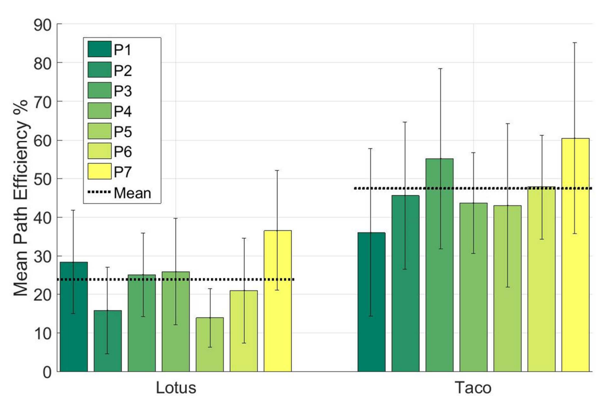

Figure 10: Mean path efficiency for all participants (P1-P7) for the two devices. Error bars show standard deviation while the dotted lines are the overall mean per device.

efficiencies relate to shorter user paths.

The mean of each participant's path efficiencies per device has been displayed in Figure 10, along with standard deviation error bars. The overall mean efficiencies for all results (per device) are shown as dotted lines. All users showed greater path efficiency for the Taco than Lotus. An overall mean of all user path efficiencies gives 23.8 % efficiency for the Lotus and 47.4 % for the Taco (a 23.6 % increase). A paired two-tailed t-test of participant mean efficiencies indicated statistically significant ($p<0.05$) path efficiency improvement with the Taco over Lotus ($p = 2.8\times10^{-4}$). Analysis of all 126 individual path efficiency measures also illustrated a statistically significant improvement in user performance with the Taco over Lotus ($p=4.3\times10^{-6}$), independent of participants.

Additional participant comments following trials favored the Taco. Descriptions included improved "clarity", "responsiveness" and more "confidence when moving around the space" than with the Lotus. Several participants described the Lotus interface as 'difficult' and 'hard to feel' compared to the Taco.

B. Comparison to Haptic Sandwich / Animotus

In [17] the same navigation experiment was conducted with the 2 DOF Haptic Sandwich as part of a pilot study, leading to a PE = 43.56 % mean over three participants. In [18], 94 participants in the less structured Flatland (see Section 1) scenario led to an average PE = 47.5 % with the Animotus. Indeed, these values are comparable to the PE = 47.4 % of the Taco.

VI. Discussion and Future work

Experimental results indicated significant improvements in target-finding efficiency of participants when using the Haptic Taco compared to the Lotus. As both the Taco and Lotus devices are variable volume interfaces with similar actuator mapping, the study outcome reflects the increased stimulus perception capability of users with the Taco and the capability to respond to this information in a way that improves navigational efficiency.

An objective of this research was to consider the potential of minimalistic 1DOF shape-changing feedback compared to a previously tested 2DOF shape-changing device (Figure 4). Though the 2DOF system provides more information, it may be the case that the simultaneous articulation is more difficult to perceive. As such a 1DOF feedback device may actually be more intuitive and lead to better user experience and performance, despite the reduced data to the user. The motion efficiency (PE) value of the Haptic Taco, determined from the current experiments, is between previously PE reported values of the 2DOF Animotus, indicating that this may be the case. Supporting this idea are extreme examples of data-rich sensory substitution schemes whose use is associated with highly demanding user concentration and training periods that have exceeded 100 hours [19]–[21].

1DOF navigational feedback may also be used to represent direction to a target, rather than proximity. Testing with a direction-feedback-only shape changing system is currently underway.

The systems that have been presented in this work were designed to achieve unobtrusive (i.e. non-alerting) communication that does not interfere with environmental perception, be that by sight or sound. In these initial studies we have aimed only to prove the navigational concepts of these novel shape changing systems, without addressing factors of attention. Future work would benefit from comparative attention loading tests (as in [12]) of the shape changing interface against notable alerting stimuli (such as vibrotactile), over various periods of time.

In addition, more realistic navigation will be attempted in outdoor, urban environments with constraints formed by features such as sidewalks and buildings. This will indicate practical applicability of this minimal system while also considering the representation of long distances via factors such as waypoints and dynamic feedback scaling.

VII. Conclusions

This paper has presented the development and validation of a handheld shape changing haptic navigation interface built on lessons learned from previously implemented devices. Such an interface may provide an alternative method of pedestrian navigation compared to screen-based or audio interfaces. This study aims to pave the way for future development and investigation into general shape changing haptic interfaces, as an alternative to other haptic interface methods.

VIII. ACKNOWLEDGMENTS

We thank all volunteers who took part in this study.

IX. References

[1] 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 Human-Computer Interaction*, 2010.

[2] J. L. Nasar and D. Troyer, "Pedestrian injuries due to mobile phone use in public places.," *Accident Analysis and Prevention*, vol. 57, pp. 91–5, 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*, vol. 45, pp. 266–271, 2012.

[4] J. Nasar, P. Hecht, and R. Wener, "Mobile telephones, distracted attention, and pedestrian safety.," *Accident Analysis and Prevention*, vol. 40, no. 1, pp. 69–75, Jan. 2008.

[5] N. Medeiros-Ward, J. M. Cooper, a. J. Doxon, D. L. Strayer, and W. R. Provancher, "Bypassing the bottleneck: the advantage of fingertip shear feedback for navigational cues," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 54, no. 24, pp. 2042–2047, Sep. 2010.

[6] 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.

[7] R. Velázquez, "Wearable assistive devices for the blind," *Wearable and Autonomous Biomedical Devices and Systems for Smart Environment*, pp. 331–349, 2010.

[8] N. a. Bradley and M. D. Dunlop, "An experimental investigation into wayfinding directions for visually impaired people," *Personal and Ubiquitous Computing*, vol. 9, no. 6, pp. 395–403, 2005.

[9] "Apple watch technology," 2015. [Online]. Available: https://www.apple.com/watch/technology/.

[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] 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.
[12] 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.
[13] 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.
[14] F. Hemmert, S. Hamann, M. Löwe, A. Wohlauf, and G. Joost, "Shape-changing mobiles : tapering in one-dimensional deformational displays in mobile phones," in *TEI'10: Proceedings of the 4th International Conference on Tangible, Embedded and Embodied Interaction*, 2010, pp. 3075–3079.
[15] F. Hemmert, S. Hamann, J. Zeipelt, and G. Joost, "Shape-changing mobiles : tapering in two-dimensional deformational displays in mobile phones," *CHI 2010*, pp. 3075–3079, 2010.
[16] J. van der Linden, Y. Rogers, M. Oshodi, A. Spiers, D. McGoran, R. Cronin, and P. O'Dowd, "Haptic reassurance in the pitch black for an immersive theatre experience," in *ACM Ubicomp Conference*, 2011, pp. 143–152.
[17] 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.
[18] 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," in *IEEE World Haptics Conference (WHC)*, 2015.
[19] S. Shoval, I. Ulrich, and J. Borenstein, "NavBelt and the GuideCane," *IEEE Robotics and Automation Magazine*, vol. 10, no. 1, pp. 9–20, 2003.
[20] C. C. Collins, "On mobility aids for the blind," in *Electronic Spatial Sensing for the Blind*, no. 26, 1985, pp. 35–64.
[21] P. Bach-Y-Rita, "Vision substitution by tactile image projection," *Nature*, vol. 224, pp. 177–8, 1969.
[22] B. Gleeson, S. Horschel, and W. Provancher, "Design of a fingertip-mounted tactile display with tangential skin displacement feedback," *IEEE Transactions on Haptics*, vol. 3, no. 4, pp. 297–301, Oct. 2010.
[23] J. Rekimoto, "Traxion: a tactile interaction device with virtual force sensation," in *Symposium on User Interface Software and Technology*, 2013, pp. 427–431.
[24] T. Ando, R. Tsukahara, M. Seki, and M. G. Fujie, "A haptic interface 'force blinker 2' for navigation of the visually impaired," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 11. pp. 4112–4119, 2012.
[25] A. Roudaut, R. Reed, T. Hao, and S. Subramanian, "Changibles : Analyzing and designing shape changing constructive assembly," pp. 2593–2596, 2014.
[26] 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," *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp.* 735–744, 2012.
[27] S. J. Lederman and R. L. Klatzky, "Hand movements: a window into haptic object recognition.," *Cognitive Psychology*, vol. 19, no. 3, pp. 342–368, 1987.
[28] 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.
[29] 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.
[30] C. R. Sanders, "The impact of guide dogs on the identity of people with visual impairments," *Anthrozoos*, vol. 13, no. 3, pp. 131–139, 2000.
[31] S. Madgewick and T. Mtichell, "x-OSC - A versatile wireless I O device for creative music applications" in *SMC Sound and Music Computing Conference*, 2013.
[32] G. Arechavaleta, J.-P. Laumond, H. Hicheur, and A. Berthoz, "The nonholonomic nature of human locomotion: a modeling study," *Biomedical Robotics and Biomechatronics (BioRob),* pp. 158–163, 2006.