Design and Evaluation of Shape-Changing Haptic Interfaces for Pedestrian Navigation Assistance

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Abstract—Shape-changing interfaces are a category of device capable of altering their form in order to facilitate communication of information. In this work, we present a shape-changing device that has been designed for navigation assistance. *'The Animotus'* (previously, *'The Haptic Sandwich'*), resembles a cube with an articulated upper half that is able to rotate and extend (translate) relative to the bottom half, which is fixed in the user's grasp. This rotation and extension, generally felt via the user's fingers, is used to represent heading and proximity to navigational targets. The device is intended to provide an alternative to screen or audio based interfaces for visually impaired, hearing impaired, deafblind, and sighted pedestrians. The motivation and design of the haptic device is presented, followed by the results of a navigation experiment that aimed to determine the role of each device DOF, in terms of facilitating guidance. An additional device, 'The Haptic Taco', which modulated its volume in response to target proximity (negating directional feedback), was also compared. Results indicate that while the heading (rotational) DOF benefited motion efficiency, the proximity (translational) DOF benefited velocity. Combination of the two DOF improved overall performance. The volumetric Taco performed comparably to the Animotus' extension DOF.

Index Terms—Haptics technology, assistive technology, human factors and ergonomics, system design and analysis

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1 INTRODUCTION

SMARTPHONES with GPS capabilities have made outdoor pedestrian navigation guidance commonplace. Recent commercial developments in Bluetooth and WiFi based localization further aim to bring such technology into indoor spaces, such as shopping malls and hospitals (e.g., www.wifarer.com, http://indoo.rs/). The primary user interface for such systems has been screen based, with maps, routes, arrows and distance information guiding sighted pedestrians to destinations. This choice of modality has been described as surprising by Hemmert et al. [1], who consider walking to be an activity that requires visual attention to the environment. Supporting this argument is an increasing number of pedestrian accidents and injuries related to mobile phone use [2]. Pedestrians exhibit reduced situational awareness and distraction from potential hazards when talking or texting (i.e., reading and typing) on cellular phones [2], [3], [4], [5]. The same effects have been noted as a cause of road traffic accidents by drivers using cell phones [6], [7], [8], [9]. When multiple tasks rely on the same attentional resource, performance typically declines [10].

An alternative interface for navigation systems is via audio cues, which are offered on many platforms such as automobile GPS systems (e.g., *'TomTom'* www.tomtom.com), smartphone applications (e.g., *Google Maps* www.google.com/maps/) and several research prototypes [11], [12], [13], [14]. For many visually impaired (VI) pedestrians, screens are inaccessible, making audio a natural interface choice for mobile navigation apps. Unfortunately, the requirement to use headphones in typically noisy urban spaces can obscure or distract from sounds of the environment [12]. Such ambient sounds may be used for orientation, landmark recognition (e.g., a sidewalk cafe or noisy traffic intersection), danger (an approaching vehicle) or simply social interaction through conversation and the appreciation of one's surroundings [13], [15], [16]. Social exclusion and clashes with cultural values have been indicated as factors in the abandonment of assistive technology [17], [18] and may eclipse the benefits of usability and function [19]. For deafblind individuals, both visual and audio interfaces are inaccessible.

Haptic interfaces may provide a more appropriate stimulus to sighted, VI, and hearing impaired (HI) individuals, by targeting the sense of touch, which has a less critical role during walking than other senses. Indeed, the most popular and long-standing VI mobility aids are the guide cane and guide dog, which both provide feedback by mechanotactile haptic cues delivered to the user's hand via the cane's handle or dog's harness. The appeal and benefit of haptic navigation interfaces beyond VI persons is apparent in consumer interest in the 'Taptic' interface of the recent Apple watch [20]. The binary 'Taptic Engine' provides simple navigation instructions by 'tapping' on the wearer's wrist. Many prototype VI devices have utilized vibrotactile feedback to represent spatial/guidance data [13], [15], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32]. In our work we consider the potential of a shape-changing interface, *The Animotus* (Fig. 1), as a method of providing

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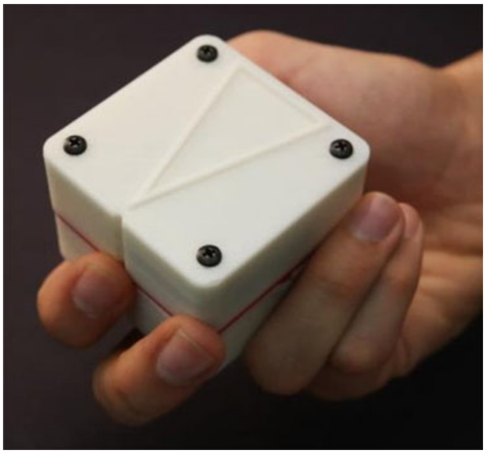

Fig. 1. The Animotus, held in a user's hand.

intuitive pedestrian navigation guidance. We believe that such an interface sidesteps the 'attention-grabbing' nature of vibrotactile feedback for better integration into realistic use scenarios, while also exhibiting the convenience and subtlety of a cell phone-like handheld tool.

The Animotus has the somewhat unusual objective of providing navigation assistance to sighted, VI and HI individuals. Similar to the Apple Watch [20], VI persons may navigate with the Animotus solely via haptic feedback, while sighted / HI people do not *need* to look at the device to use it, enabling them to be more visually attentive of their surroundings. As with smartphone navigation applications, a user also does not *need* to be constantly attentive of the device, and may choose to refer to it at their own frequency, placing the device it in a pocket / bag when not needed or simply lowering their arm, as with a phone.

Shape-changing is a little explored modality, with few examples that facilitate haptic feedback (reviews are provided in [33], [34], [35], [36]). Notable contributions from Hemmert et al. [1], [37], [38] and Imamura et al. [39] implement dynamic tapering and curving of handheld interfaces to provide navigation instructions. Regrettably, validation of these systems has been extremely limited, with users either remaining stationary in simulated tests [1], [37], [38], or no testing results being reported at all [39].

1.1 Shape-Changing Device Motivation

Shape-changing interfaces have a number of potentially attractive features. One aspect is the naturalistic nature of the modality, which may be better suited to representing particular data and tasks [40]. Perception of shape is an innate haptic ability that humans perform with little effort [41], [42]. This is demonstrated when reaching into a pocket or bag to locate keys or another item through touch [43]. Shape variations are encountered and perceived frequently in daily life, more so than some other haptic sensations, such as those generated by vibrotactile actuators (e.g., [13], [15], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32]), which are notably different to the stimulus encountered during texture perception. Vibrotactile stimuli has been attributed to generating 'altering' sensations [44], which can potentially lead to distraction from more important tasks [40], [45], [46] or become annoying over time [21], [45]. As pedestrian navigation can be a lengthy activity, negative user perception of an invasive stimulus is likely. The Animotus was designed with the intention of presenting highly intuitive navigation information in an unobtrusive haptic interface to avoid such distracting or annoying effects.

One major feature of the device concept is that once a shape is assumed by the device, the information represented by that shape will continue to be communicated to the user without any active stimulation. This is in comparison to other systems that may provide repetitive or constant active vibration, tapping, audio etc. Non-active communication is useful if a user chooses to stand still (e.g., because they have noticed something interesting or are talking to someone). A static pose of the system will continue to provide guidance without vying for user attention.

The Animotus is a cube shaped handheld device capable of providing two axes of navigation information simultaneously via rotation and extension (radial translation) of the upper half of the device body. The nature of this articulation is presented in Fig. 2. By holding the device (as in Fig. 1, or via other grasps) as it articulates to different 'poses', a user is able to feel shape variation and interpret instructions through natural object shape perception.

1.2 Initial in-the-Wild Theatre Evaluation

The Animotus was previously evaluated 'in-the-wild' by blind and sighted users as an integral part of a large scale immersive and inclusive theatre production, *Flatland* [47] (flatland.org.uk). The production was created in collaboration with a visually impaired theatre group *Extant*, based on an 1,884 novella [48]. The unobtrusive nature of the interface was intended to allow audiences to appreciate the audio, tactile and narrative aspects of the production while being

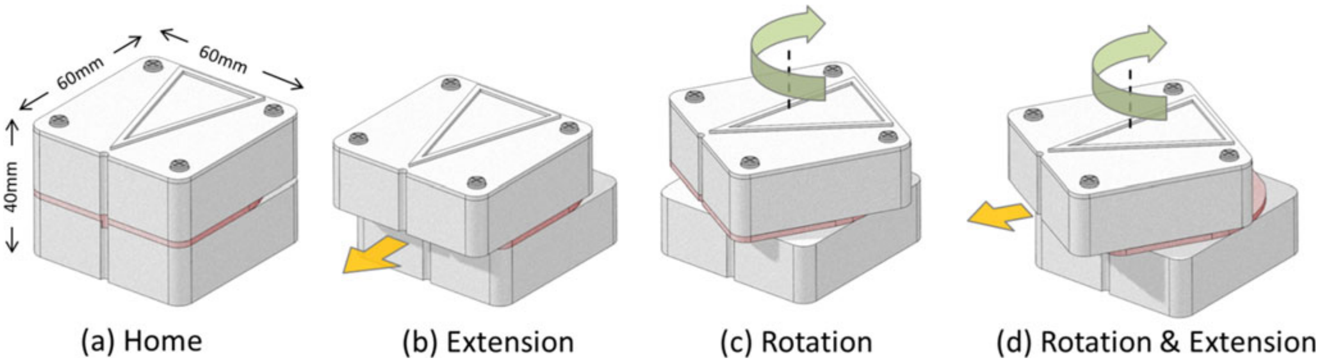

Fig. 2. Articulation of the haptic device via rotation and extension DOF, which are independently actuated. Extension relates to target proximity while rotation relates to heading to the target.

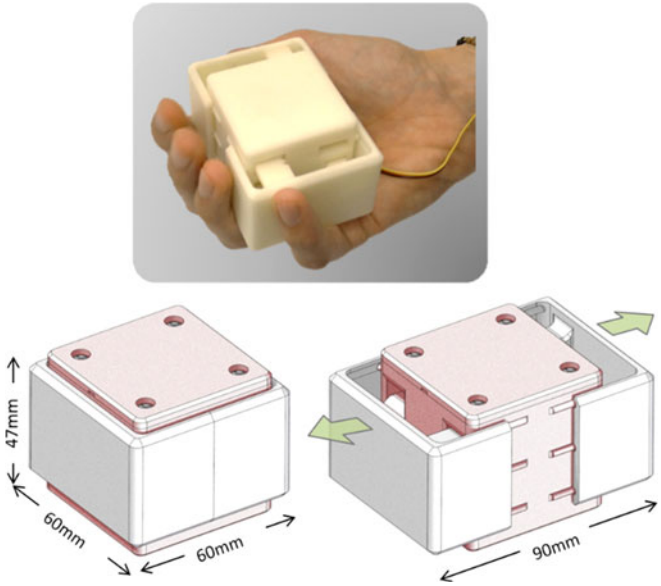

Fig 3. The Haptic Taco—An expansion based shape changing interface (illustrated in fully closed and expanded states).

guided by the device. 94 participants (15 VI) each used the haptic device to navigate a 115 m^2 pitch black space for approximately 40 minutes, gradually uncovering the production's plot. As in similar prior work [49], Flatland was primarily theatre experience rather than experimental study. This led to many practical device design objectives of intuitiveness, robustness, cost, weight and ease-of-assembly.

1.3 Goal of This Paper

Though *Flatland* led to a wealth of encouraging user insights and navigation data [47], the in-the-wild / theatrical nature of the application did not permit the level of experimental control granted via laboratory testing. In this current paper, specific analysis of the Animotus' multi-DOF, shape-changing interface modality is experimentally evaluated via navigation tasks. The utilized indoor environment negates distraction by environmental factors and inter-participant encounters, while also increasing localization accuracy [47]. This allows isolation of specific variables, while the other conditions are maintained.

Prior work has suggested the potential for pedestrian guidance via only proximity [50] or heading [1], [39], [51] based feedback. The Animotus simultaneously makes use of both mechanisms, which are tested independently and in combination in this paper. As the proximity feedback of the Animotus is also coupled to heading (Fig. 2), an additional device, *The Haptic Taco* (Fig. 3 - Section 3.2) was created with a bilateral expansion mechanism that imparts a perceived volumetric change, decoupled from direction.

Note that while this work compares several shape-changing conditions, comparison to a vibrotactile navigation device is not provided. To create a fair comparison to the Animotus, a simultaneous representation of both proximity and heading via handheld vibrotactile system is required. This has a number of potential design solutions, none of which are reflected in the literature in a unanimous/popular fashion that is obvious for replication. For example, several vibrotactile systems provide heading information through the waist [15], [21], [52], while others target finger-pads, backs of fingers, arms, torso and feet [22], [25]. Such systems also provide different types of navigation instructions, such as proportional stimulus to obstacle proximity or discrete turn-by-turn commands. To physically recreate one (or two) of these systems would not provide fair representation of an entire field of prototypes.

2 RELATED WORK

When GPS localization was first deployed in the early 1990s, technology to assist blind travelers had been already been under exploration for some time [23], [53], [54]. While GPS is now a reliable and established platform, technical solutions to aid VI pedestrians remain on the developmental periphery. Literature provides almost five decades of haptic systems for this purpose, yet only a minute fraction, (such as the *Ultracane* http://www.ultracane.com*)*, have ever entered commercial production. For more elaborate technologies, this may be due to difficulties of fabricating a complex product for the relatively limited market while maintaining reasonable consumer costs and reliability.

In this section we shall review related approaches to navigation assistance devices. Note that our work focuses on guidance to a destination (as is the role of GPS), rather than around local obstacles (as in [55]), and this review will largely reflect this. Note that with the appropriate sensing method the Animotus would also be able to provide guidance around obstacles.

McCarthy and Wright state that design of an interface should not be based purely on function, but should also consider history of practice, user values, user goals and social embedding of the activity [56]. Indeed, these factors were considered in this review and Animotus design.

2.1 Sensory Substitution Systems

Audio is an obvious method of communicating data to VI persons, yet rather than rely on synthesized speech, audio sensory substitution approaches hope to cognitively integrate artificial sensory data into the user's perceptual system. Beep sounds of different frequencies were generated by an obstacle detecting belt in [11] while stereophonic audio cues were the navigational feedback method of [12]. Other approaches have tried to communicate the output of a visual camera feed into alternate sensory channels via modulated audio tones [13], large numbers of vibrotactors [23] or electrostatic actuators pressed against the torso [53]. Despite lengthy training times (over a hundred hours in some cases) the mapping of relatively simplistic obstacle location to alternative channels led to overwhelming cognitive loading [12], [14] and 'unsustainable' levels of concentration [53]. Reducing the complexity of environmental data prior to presentation can reduce this cognitive dominance. Karcher et al. proposed the benefits of a device for blind travelers that could provide spatial information without drawing on attentional resources [15]. In the resulting *FeelSpace* belt (further discussed in Section 2.3) only compass heading is communicated via sensory substitution [15], [21], [52]. Such a *reduced-data* approach to navigation may be considered in the use of a guide dog. A trained dog is an intelligent agent that processes huge amounts of environmental data in real-time to safely lead their owner through the world. This guidance is via the simple interface of forces and torques exerted via a harness handle.

2.2 Robotic, Wearable, and Handheld Systems

A number of mobile robotic solutions to guide VI pedestrian have been proposed (e.g., [12], [14], [54], [57]). These devices are essentially programmable alternatives to guide dogs. Such systems are often large, cumbersome and could be costly to commercially produce and maintain.

Wearable guidance assistance solutions have been frequently proposed [25], [53], [58], though a number of these devices are also quite ungainly and liable to attract unwanted attention to the user. In [59] VI guide dog owners expressed 'considerable concern' about how their dog made them more conspicuous and generated frequent unwanted attention from dog-loving members of the public, effectively interrupting their intended activities. It is likely, that prominent technical robotic/wearable systems may lead to similar scenarios. For example, prominent instrumented & actuated helmets [13], [24], [60], waistcoats [13], [53], abdominal belts [12], [14], [15] and devices that protrude from the mouth [25], [61] may lead to social discomfort for the wearer, as their personal appearance is compromised to others by strange and obvious technology [17], [19]. Even the constant buzzing sound of the FeelSpace vibrotactors ([15], [21], [52]) may lead to perceived or actual social acceptance issues in certain situations [1]. Additionally, the simple requirement to put on or take off a jacket or sweater will compromise many of these wearable systems, or require them to be removed, adjusted and replaced, leading to questions of practicality.

Though such wearable and robotic systems have shown promise in the cited work, it is likely that the practical considerations described above have limited their success outside of the laboratory. In contrast, the wide adoption of the mobile phone and folding guide cane illustrates the benefit and appeal of lightweight, handheld technology that may be conveniently picked up when needed and stowed when not in use. To pick up a cell-phone when leaving the home or office is now typical daily behavior. Indeed, this has been a major inspiration of the handheld Animotus.

Some haptic interfaces have been integrated into the handles of guide canes, augmenting a commonly held VI device with additional obstacle [28], [29], [30], [31], [32] or guidance information [62]. For now, the Animotus is considered as a 'general purpose' interface for sighted, VI and HI users and so has not been integrated into a VI specific tool.

2.3 Haptic Navigation Interfaces

Haptics has often been considered for VI interfaces. Most common to this application is the use of vibrotactile feedback, which has been implemented in numerous prototypes for almost 50 years (e.g., [13], [15], [21]–[32]). According to [40], vibration has dominated haptic guidance research, primarily due to ease of technical integration and effectiveness at eliciting user response. Generally, the most common application of vibrotactile feedback is mobile phone event notification, the success of which has been attributed to the 'firm fit with the usability constraints of signifying alerts' [44]. By definition, an alert interrupts an individual's concentration in order to provide important information. While an alert is appropriate for signaling infrequent hazards (e.g., head level obstacles for VI pedestrians [29], [30], [31]), it has been argued that such sensations may not be suitable to conveyance of all types of data [40], [45], [46]. This is particularly true for navigational guidance, which typically requires frequent information updates over extended periods of time, in the presence of hazards such as traffic.

The previously mentioned *FeelSpace* belt is a notable example of a vibrotactile navigation device. The belt features a ring of vibrotactile actuators worn on the user's waist [15], [21], [52]. Persistent vibration of the north facing actuator facilitated sensory augmentation and was reported, after several weeks, to reduce walking path length in familiar environments and increase feelings of security for a blind individual [15]. However, other study participants reported the constant vibration stimulus as "annoying" and impairing concentration [21].

Zheng et al. argued that if a stimulus treats all data as urgent then a user may be distracted from genuinely more important tasks [46]. In [45] seated posture guidance from a vibrotactile system impaired typing performance more than a pressure based system. Zheng et al. argue that designers should consider a haptic stimuli's place in a user's *attention spectrum*, to prevent such distraction.

There exists a wealth of alternative haptic sensations that may be used to elicit ungrounded stimulus more appropriate to guidance [40]. Skin stretch has been used to convey direction on the finger pad [63]. Spinning flywheels [64], miniature mass-spring-dampers [65], actuated surfaces [66] and moving weights [62] have all generated ungrounded directional force effects. Wrist worn tapping, stroking, squeezing and twisting interfaces were used for pronation/supination guidance in [40]. 'Pull-Navi', pulls the ears of a user for guidance [60]. Few interfaces however, target shape perception.

2.4 Shape-Changing Interfaces

The appreciation of shape and volume within the hand is a fundamental haptic ability [41], [42], [67] which we (the authors) consider to be more naturally encountered and unobtrusive than stimulus generated by vibrotactors. Such stimulus properties may mean that shape interfaces may fall within a more appropriate region of the *attention spectrum* [45] for particular applications.

Several past shape-changing systems provide visual-only representation of concepts and data [34], [68]. Some devices are primarily input tools, with the user physically modifying the shape of the object (via pulling, squeezing etc.) to change its functionality or ergonomics [36], [69], [70], [71]. A number of actuated systems are able to drive their own bodies, or portions of their bodies, into alternative forms in order to communicate visual or haptic concepts [34], [72]. It is notable that in tactile shape displays [73], [74], the volume of the drive mechanism often greatly exceeds the workspace of the active surface.

A notable example of ungrounded haptic shape-changing is the actuation of a mobile phone back plate in order to facilitate body tapering or thickness change [1], [37], [38]. While [37] concerns static perceptual trials of the 2 DOF device (the Animotus has also been evaluated by such methods [75]), a 1 DOF version of this system was evaluated via simulated navigation [1]. Here, participants rotated an office chair, but did not walk anywhere, in response to device heading feedback. Another mobile interface, *Bendi*, was developed to augment (non-navigational) communication via visual and tactile feedback [76].

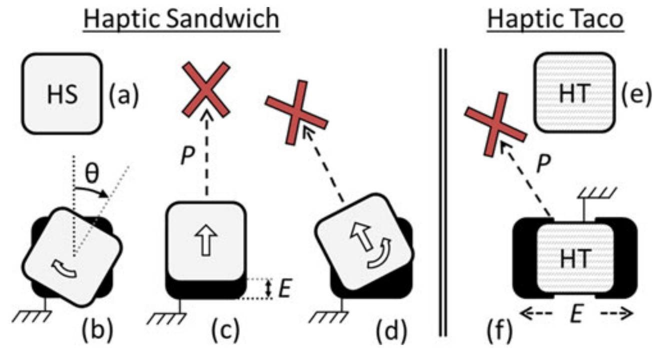

Fig. 4. Haptic Sandwich (a-d) and Haptic Taco (e-f) navigation concept. The sandwich rotates and extends based on heading (θ) and proximity (P) to a target, the Taco expands bi-laterally based only on proximity to a target.

3 DEVICE DESIGN AND PRIOR EVALUATION

In this section we shall describe the design of the Animotus and Haptic Taco. An overview of prior evaluation of these devices will also be given. Note that these devices are intended for use by both blind and sighted individuals, leading to several 'inclusive' design considerations (such as tactile orientation features and absence of pinching areas).

3.1 Animotus/Haptic Sandwich

The Animotus was developed through multiple diverse prototypes and focus sessions with sighted and VI members of the Flatland project [47]. The device is approximately cube shaped with rounded vertices for additional comfort when grasped (as shown in Fig. 1). The top half of the device is able to independently rotate (±30 degree) and translate (up to 12.5 mm) relative to the bottom half. This allows the Animotus to simultaneously indicate direction (heading) and distance (proximity) to a navigational target (Fig. 2). Such a target may be destination in open space, or a waypoint (such as a location on a corridor or city block). To achieve the proposed user interface concept, the device was designed to achieve articulation while being grasped in an adult hand, allowing natural shape perception to take place [41], [42], [67].

Fig. 4 provides some examples of how device articulation relates to target position. In (a) the device is at the 'home' position. There is no extension and the rotation angle is zero. The overall shape resembles a cube to indicate that the user is at their destination or no guidance is currently being provided.

In (b) the top half of the device rotates to indicate that the user should turn by θ degrees to face the navigational target. This DOF will rotate to point directly at a target within the mechanical bounds of ±30 degree, allowing *fine* heading feedback to the user. If the heading to the target is outside of the range of ±30 degree (for example, if the user needs to turn 60 degree to face the target) then the rotational DOF will remain at either +30 or -30 degrees, providing *gross* heading feedback. Such gross feedback informs the user to keep turning clockwise or counterclockwise (whichever is closest to the target heading) until they are in the range of fine feedback. The gross heading will change sign when the error passes 180 degree.

The extension of the linear actuator (Fig. 4c) projects the top half of the cube forward by an amount *(E)* proportional to the proximity to a target *(P)*. The maximum value of *P* to produce saturation (P_{max}) may be set dynamically. In this work, where the study was conducted in a limited $5\ m \times 5\ m$ area, the device extension saturates ($E = 12.5\,mm$) when $P_{max} = 6\ m$. In the $16\ m \times 7\ m$ Flatland environment, which was prone to greater localization error and contained other people, P_{max} was set (via trial and error) to 7.12 m. In larger environments (e.g., outdoor urban spaces) intermediate waypoints will be used between distant targets, with the automatic spacing of these waypoints set by an experimentally determined, optimal P_{max}. This quantity has yet to be established, but is likely to be around 3-15 m and may be dependent on dynamic environmental factors, such as local complexity of a route or proximity to predictable hazards, such as traffic or rush hour pedestrian density.

In (d) the device simultaneously extends and rotates to indicate a target that is some distance away and to the left of the user. These motions are also presented in the 3D renderings of Fig. 2 via the same alphabetical key.

An embossed triangle on the top of the Animotus is a tactile feature to allow a user to identify the top and front of the device when it is picked up, without the need for visual identification. A 3 mm groove that traverses the front face of the device is another tactile feature that aids device orientation and heading perception, by aligning across the top and bottom sections when the heading error is 0 degree. In our previous work, a haptic interface with a hand-strap [49] led to complaints from users that they were unable to use that hand for other tasks. As such, straps were not featured in the Animotus, with the tactile landmarks instead providing easy hand alignment cues. In Flatland, participants stored the Animotus in pockets when not in use [47], similar to a mobile phone.

The Animotus has dimensions $60 \times 60 \times 40$ mm $(\mathrm{L} \times \mathrm{W} \times \mathrm{H})$ when at the 'home pose'. The dimensions were chosen to allow users with shorter fingers to enclose important features of the device body in their grasp [75]. A major observation of a previous device, the *Haptic Lotus* [49], was that many individuals would tightly grip the interface, overpowering the actuation mechanism and significantly reducing the effectiveness of the provided haptic sensations. The form and force capabilities of the Animotus have been designed to avoid this issue. By using miniature, high-power servos (HiTec HS-82MG) in horizontal configurations with integrated gear transmissions (Fig. 5), it was possible to reduce height requirements while increasing actuator torque and force output. The battery life of the current device is between 2-4 hours, depending on usage.

To achieve the linear, extension DOF, a 32 pitch rack gear is 3D printed into the top part of the device. This engages with an acetyl spur gear (13 teeth, OD = 12.06 mm) directly mounted on the servo output spline. The sides of the rack gear act as linear guide rails with the central plate. The body of the servo (mounted onto the central plate) aligns and holds together these guide rails and the top half of the device. A top plate with the raised triangle feature covers the mechanism. In the bottom half of the device a second servo motor engages a larger acetyl spur gear (22 teeth, OD = 19.22 mm) with a 32 pitch crown gear, printed onto the underside of the central plate. Guide rails and a central bolt enable rotation of the central plate, relative to the bottom section. A bottom plate covers the mechanism and secures the servo in place. The transmission affords ±30

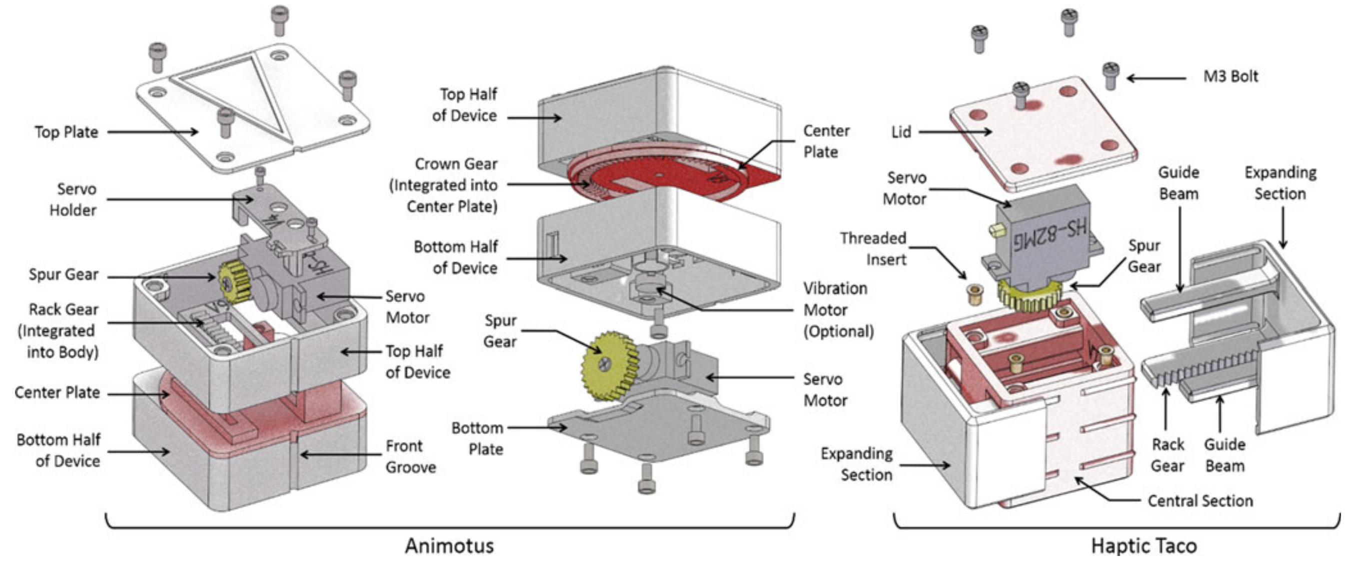

Fig. 5. Assembly views of the Animotus and Haptic Taco. The left image shows the upper half of the Animotus, illustrating the linear extension mechanism. The middle image is an exploded view of the lower half of the Animotus, illustrating the crown gear rotating mechanism.

degree of rotation via a 1:3 gear reduction from the servo output (±90 degree). The force / torque exertion capability have been measured as 25 N for the linear DOF and 1 Nm for the rotational DOF. It takes approximately 20 minutes to assemble an Animotus from component parts, using only a screwdriver and hex key.

Power and control are currently provided externally, via a 100 gram microcontroller / battery combination attached to the device via a cable. However, space has been left inside the upper and lower sections to integrate miniaturized versions of these components in future generations of the device. A housing feature in the base can accommodate an optional vibration motor (shown in Fig. 5) for alert provision. This was not used in the presented work.

The device was originally named the 'Haptic Sandwich' due to construction analogies with a sandwich. It has matching square top and bottom sections (the 'bread') which sandwich the actuators and transmission (the 'filling'). During the Flatland immersive theatre production, it was re-named The Animotus, for plot reasons [47]. The device weighs 100 grams, including actuators.

3.2 Haptic Taco

The Haptic Taco (Fig. 3) was developed to test the concept of proximity-only navigation guidance via an bi-directional expanding mechanism that causes two equal 'shells' to move away from the central section of the device (Figs. 4e and 4f). This articulation generates a sensation of variable volume. The Taco has a similar closed form to the Animotus. The mechanism relies on a single acetyl spur gear (22 teeth, $\mathrm{OD} = 19.22$ mm) and a dual rack and pinion mechanism (Fig. 6). Each rack is integrated into one of the two rigid shells. Linear guides prevent twisting and jamming of parts during expansion / contraction (Fig. 5). Again, the device makes use of a HS-82MG servo motor.

The Taco weighs 100 g and measures $60\,\mathrm{mm} \times 60\,\mathrm{mm} \times 47\,\mathrm{mm} (\mathrm{L} \times \mathrm{W} \times \mathrm{H})$ when in its home/fully contracted pose. When fully extended the length (L) value increases from 60 mm to 90 mm (50 percent volume increase). Force exertion capability is 4.5 N per armature. The device name originates from '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 device. This contour improves the impression of the device modifying its volume, rather than the 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 sections pinching the user's skin.

To navigate in 2D space with the provided 1D feedback, participants are required to make use of exploratory tactics and/or interpret particular stimulus response. For example, Fig. 7 illustrates the response of a proximity based feedback as a user walks past, but does not intersect, a navigational target. Though the device will contract and expand relative to decreasing and then increasing proximity, it will not reach the minimum contraction (or 'home pose') associated with reaching a target. In practice, users are able to detect increases in device size and quickly modify their path. The target may then be approached in a steepest-descent fashion.

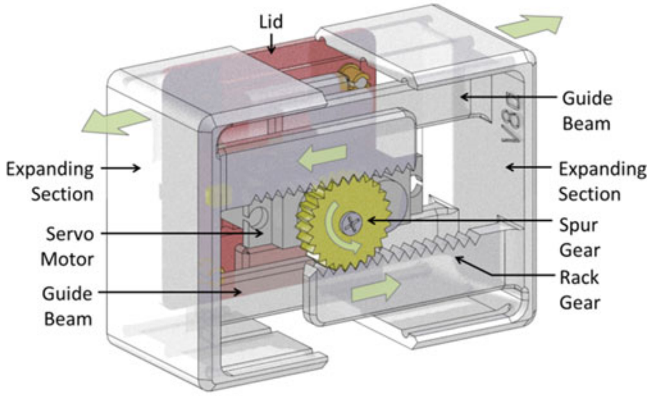

Fig. 6. Haptic Taco mechanism, a dual rack and pinion provides increased volumetric expansion. The central section has been removed in this image.

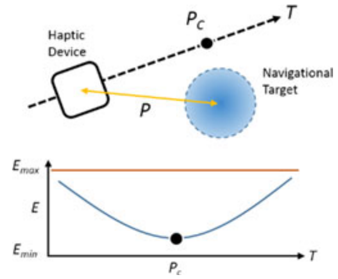

Fig. 7. The response of proximity (P) based feedback, when a user's straight line path (T) does not intersect a target. E represents extension magnitude. PC is the closest point on T.

3.3 Previous Evaluation

In prior evaluation of the Animotus, the ability of seated participants to evaluate assumed poses of a prototype device was evaluated [75]. Results were encouraging with 80 percent of responses having no errors, 17.5 percent having the minimal possible error and only 1 percent of errors involving misinterpretation of both heading and proximity DOF. A pilot navigational study confirmed that pose recognition translated to embodied navigation.

An earlier version of the Animotus with additional tactile 'ridge' features was used in [75]. These were determined to be distracting and uncomfortable by VI members of the Flatland team. A pilot study ($n = 3$, *unpublished*) comparing navigation ability between ridged and smooth devices found no significant differences ($p < 0.05$) for motion efficiency, though all participants preferred the 'smooth' device.

Evaluation of the Animotus in the in-the-wild Flatland environment was carried out with sighted ($n = 79$) and VI ($n = 15$) participants in [47]. Performance between VI and sighted participants was comparable. In addition average walking pace when using the Animotus was only 0.28 m/s less than the typical human walking speed of 1.4 m/s [77]. These positive results were despite minimal familiarization with the device, involving no practice targets. Many audience members instilled characterful/personality traits into the device, describing it with terms such as "a companion" and "like a pet".

4 EXPERIMENTAL TESTING

The goal of the experiments presented here was to further evaluate the capabilities of the shape-changing interface for navigation while also considering the roles of the heading and proximity related components of the Animotus. The Haptic Taco provided an additional point of comparison for volumetric shape-changing systems.

The devices were evaluated via an indoor navigation experiment in which the visually obscured haptic interfaces assisted sighted participants in locating sequences of ten invisible circular targets in a 5.1 × 5.3 m space, cleared of obstacles. The experimental protocol was approved by the Yale Human Subjects Committee (ref #1408014462). Unlike in [1], navigation was not simulated, and users had to physically walk to reach targets.

4.1 Localization and Guidance System

To enable navigational guidance, a closed loop localization and feedback system was established using a *Ubisense* Real Time Localization System (RTLS) and an *X-OSC* wireless microcontroller [78]. The Ubisense system relies on Ultra-Wide Band (UWB) radio signals from four wall mounted *Ubisensors* to locate small (38 mm×38 mm×16 mm) battery powered *Ubitags*. Although 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 results by avoiding signal occlusion from the user's body (Figs. 8 and 9). Data recorded from static Ubitags illustrated position fluctuations by up to 0.32 m. To account for this uncertainty, the navigational targets used in the study were established as circular areas with a 0.4 m radius. User position data was moving-average filtered in real time to reduce the influence of localization jitter on actuator motion.

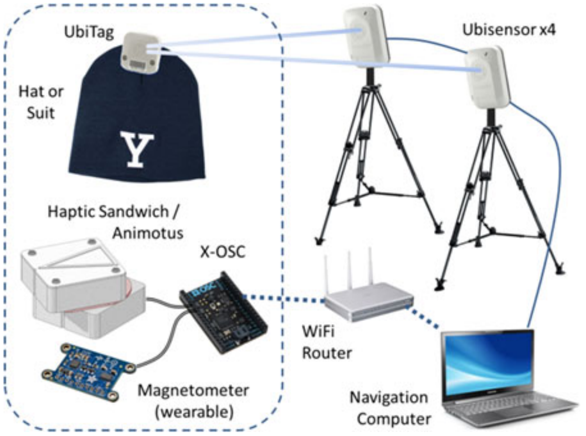

Fig. 8. The localization system used for the study.

The localization system reported the 2D Cartesian location of the participant to a PC running custom navigation software, written in *Processing* (*www.processing.org*). A wrist worn tilt-compensated magnetometer (an 'Adafruit 9DOF' IMU) communicated user heading to the same system.

Though it would have been preferable to place the magnetometer on the haptic devices, rather than the participant's wrist, electromagnetic interference from the device actuators prevented this. Though such external sensor placement introduces some potential for orientation mismatch between the device and user, the tilt compensation aspect of the IMU, combined with supinated holding pose of the wrist meant that only radial/ulnar deviation of the wrist can translate into mismatched headings between the device and user. To avoid this, participants were instructed

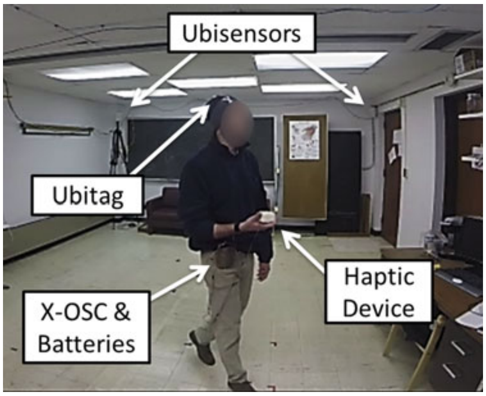

Fig. 9. Navigation experiment environment. The Haptic device is uncovered (as shown) during the familiarization process.

to keep the base of the device in line with their forearm during the study. This constraint appeared to cause no mobility or discomfort issues. Note that initial attempts to strap or mount the sensor to the back of the user's hand interfered with grasping ability and/or comfort.

The navigation software calculated proximity and heading error to the current target. Corresponding servo signals were then determined and transmitted to the X-OSC. The system updated at 100 Hz.

The X-OSC and a LiPo battery pack (combined weight of 110 g) were carried in a belt pouch by participants and connected to each device's actuators through cables. The experimental equipment setup is shown in Figs. 8 and 9.

4.2 Experimental Method

Participants, none of whom were VI, used feedback from the haptic devices to locate sequentially presented navigational targets in the workspace. The haptic devices were visually obscured with black fabric during the study, draped over the devices and user's hand and held in place with a clip. It was confirmed that device motion could not be determined through the fabric.

As this study focused on general navigation ability for different device conditions, 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 was to prevent the accidental 'finding' of targets by users who may momentarily pass through them 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.

Four device conditions were presented, the order of which was randomized and balanced between participants. The conditions were:

1. *Taco* - Haptic Taco (volumetric proximity feedback)
2. *Extension (1E)* - Animotus with extension based proximity feedback only
3. *Rotation (1R)* - Animotus with rotation based rotation feedback only
4. *Rotation and Extension (2D)* – Animotus with both extension and rotation DOF active.

Four different sets of navigational targets were utilized with a different set used for each condition, per participant. The order of these sets were randomized between participants. All sets involved ten targets in pre-defined, distributed locations. Prior to using each device, participants underwent a familiarization process that took 5-12 minutes. This began with demonstration of the range of motion & haptic sensations of the device condition, while held by the participant. Following this, participants were requested to locate three 'training targets' in the workspace, which were not part of the experimental sets. The device was not visually obscured during familiarization.

4.3 Evaluation Metrics

User motion was evaluated by three metrics:

1. Motion Path Efficiency *(ME)*
2. Average Velocity *(AV)*
3. Time Facing Targets *(TF)*

The time taken to find targets was not considered as an appropriate evaluation metric for this study, due to the differences in distance between targets in addition to difference in walking speed between participants. Motion path efficiency *(ME)* was used instead to determine a measure of directness of a user's walking path between each consecutive target, via the measure

$$ME\ (\%) = \frac{E_P}{U_P}, \tag{1}$$

where E_P is the euclidean distance between the start and end of the motion (the optimal path), U_P is the distance covered by the user's path and *ME* is the resulting path efficiency ratio. E_P considers the circular nature of the targets and measures distance from the start of the user's motion to the target's boundary. The start of motion is determined by the user's position when a new target is presented. A 50 percent *ME* ratio would indicate that the user had travelled twice as far as the straight line path between targets. Distances between successive circular target boundaries ranged from 1.32 m to 3.6 m. User path length (U_P) was calculated as the sum of euclidean distances between successive positions (X_i, Y_i) and (X_{i+1}, Y_{i+1}) in the position log, as follows:

$$U_P = \sum_{i=0}^{n} \sqrt{|X_i - X_{i+1}|^2 + |Y_i - Y_{i+1}|^2}. \tag{2}$$

During the study it was noticed that some participants spent noticeable amounts of time stationary or moving forwards and backwards in certain device conditions. Measuring average velocity (*AV*) for each path provided a measure of these factors irrespective of walking speed or target spacing. This was calculated as $AV = E_P/T_{P,}$ where T_P is the time between a user starting motion and finding a target.

Time Facing Targets *(TF)* illustrates the proportion of the trial when a user was facing the target (±10 degree). This was in response to observations of some participants who performed more sidestepping and backwards motions with certain conditions, as part of exploratory motions. *TF* was calculated as the proportion of the trial where the error between participant heading and error heading were less than ±10 degree.

5 RESULTS

13 participants (ages 23-38, seven male) took part in the experiments and were each paid $20. All participants completed the four conditions (see Section 4.2), with 10 targets (leading to nine motion paths) in each case. Note that the same pair of targets is never encountered by the same participant twice, even across conditions. This led to $13 \times 4 \times 9 = 468$ motion paths in total. Example motion paths between three targets for participant 'P12', are given in Fig. 10.

5.1 Numerical Results and Observations

Individual participant means, standard deviation and overall mean per device condition are displayed as bar plots in Fig. 11 for ME, AV and TF. In Fig. 12, combined participant results are displayed as boxplots.

Repeated measures ANOVA analysis was performed across device conditions (in MATLAB 2015b via the *ranova*

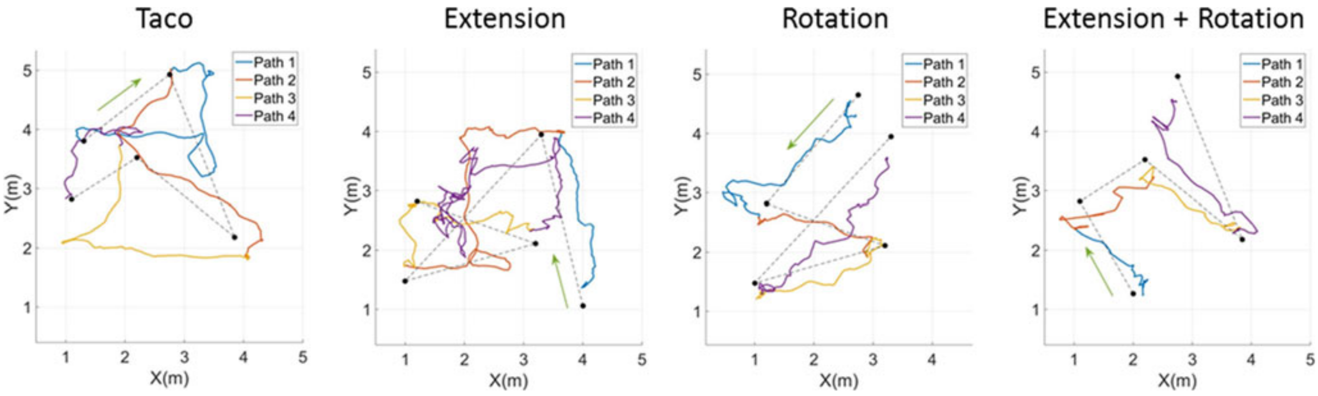

Fig. 10. Sample motion paths between five targets, for participant P12, for each of the four device conditions. Initial direction of travel (from the first target) is indicated by the arrow. Note that each target has a 0.4 m radius (not shown).

command, where participant/path combinations are predictor variables and response variables are the metric under observation for each device condition). The repeated measures ANOVA illustrated significant differences in all metrics. These were ME $(F(3,464) = 22.414, p = 3.612 \times 10^{-13})$,

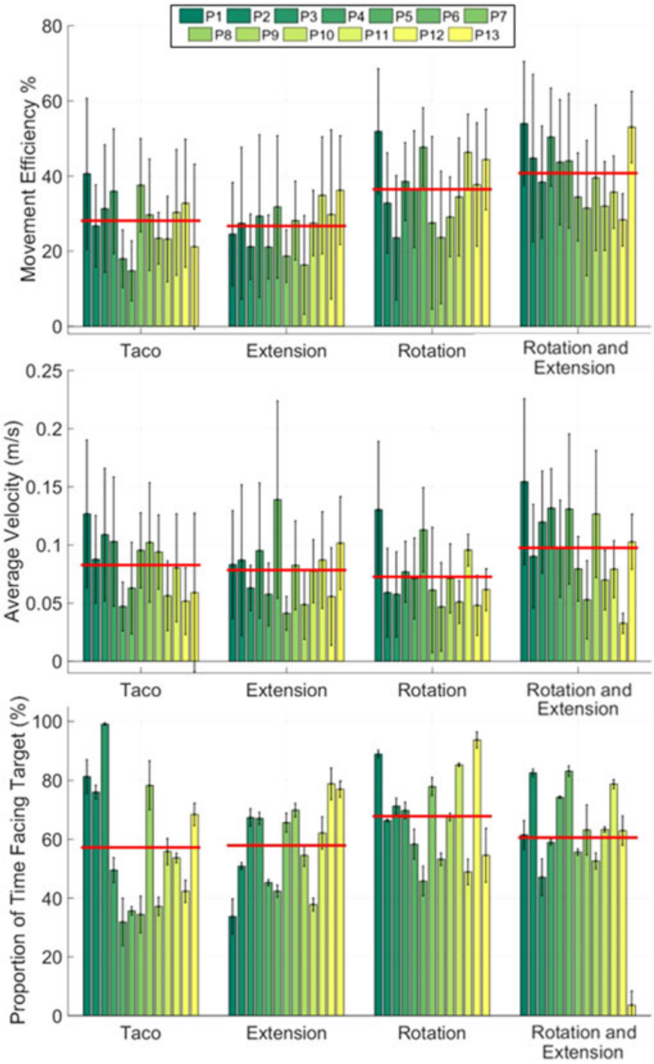

Fig. 11. Individual user (P1 – P13) mean results for (a) ME, (b) AV, and (c) TF. Error bars illustrate standard deviation, solid lines show mean across all users for a given condition.

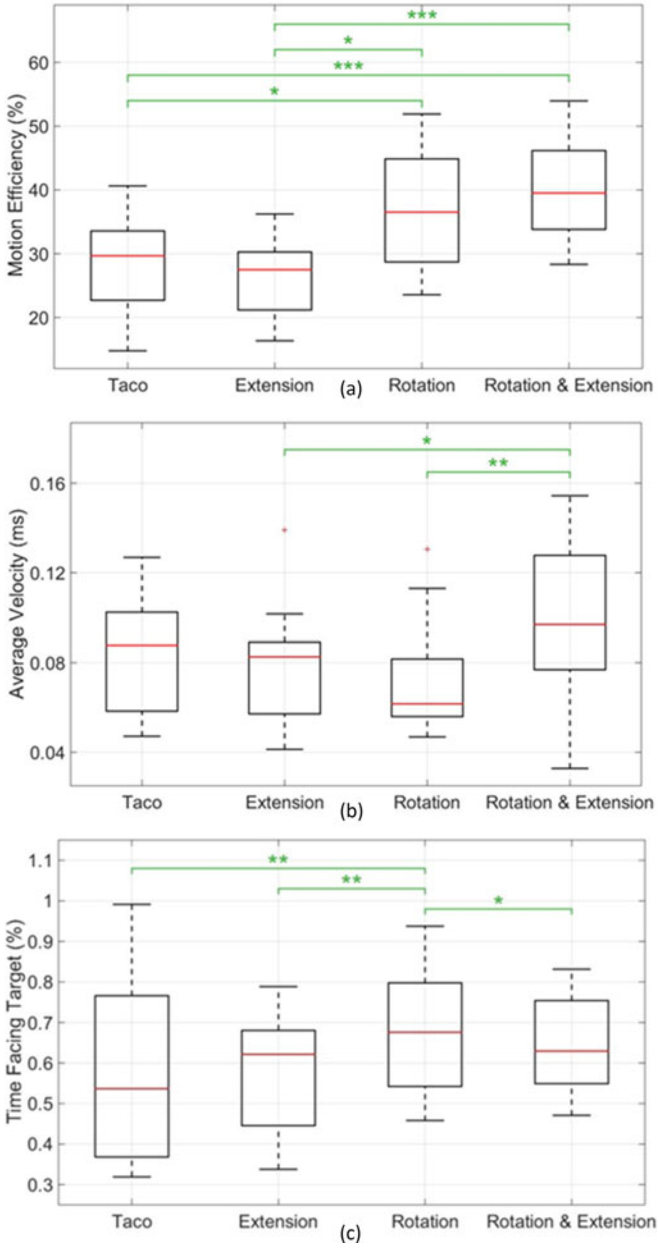

Fig. 12. Boxplots of all user results for (a) motion efficiency, (b) average velocity, and (c) proportion of time facing target. Red lines indicate median results. Stars represent differences of statistical significance after Bonferroni correction, where: * represents $\mathrm{p} < 5 \times 10^{-3}$, ** represents $\mathrm{p} < 1 \times 10^{-5}$ and, *** represents $\mathrm{p} < 1 \times 10^{-8}$.

$AV(F(3,464) = 7.185, p = 1.118 \times 10^{-5})$ and $\mathrm{TF}(F(3,464) = 7.11, p = 1.235 \times 10^{-4})$.

Further analysis between conditions via paired t-test (via the MATLAB command *ttest2*) with Bonferroni correction ($\alpha = 0.05/6$ comparisons) identified differences of statistical significance ($p < 0.05$), these are shown by stars in Fig. 12, where more stars indicate higher significance (a numerical key is given in the caption).

Regarding *ME* there are no significant differences between the Taco and 1E conditions. The ME of those conditions are significantly lower (worse) than ME in the 2D and 1R conditions, implying that indication of heading plays a significant role in improving motion efficiency. 2D is extremely significantly different to 1E and Taco, while 1R has less significant difference. Mean and median efficiency of the 2D case is higher than other conditions.

Regarding *AV*, the 2D solution led to statistically faster walking times than the 1E and 1R conditions, even though it also had the greatest distribution of walking speeds among participants. It was observed during trials that although individuals in the 1R scenario would often follow relatively straight lines towards the targets, they would frequently stop prematurely or overshoot the boundaries of the target. Effectively the lack of proximity information prevented participants from knowing the location of the target and therefore when to stop walking. This impaired their overall average velocity. Several heading-only devices presented in literature would no doubt suffer from this issues [1], [39], [51]. Despite the need for exploration in the Taco and 1E cases (which led to lower ME), mean and median AV is higher than the rotational cases. Both phenomenon may be observed in the motion plots of Fig. 10. It should be noted that AV was much lower in this study than that previously recorded during use of the device in Flatland [47]. It is likely that this was influenced by the more precise and lab-based nature of the task combined with the smaller, illuminated environment, clearly enclosed by walls.

In terms of *TF*, the rotation only (1R) result was significantly higher than all other conditions, indicating that participants interpreted the rotational DOF well, in order to face the target. Somewhat surprisingly, the 2D case was not significantly higher than either of the proximity based cases, but significantly lower (by a lesser degree with lower variance) than 1R. It is possible that the inclusion of proximity information detracts from user attention to rotational feedback. Many users were observed to sidestep or walk backwards when using the proximity based (1E or Taco) methods to locate targets. This was irrespective of the unilateral or Bi-lateral conditions, as reflected by the lack of significance between these results.

5.2 Qualitative Results

Following the study, participants were asked for comments about the different devices. Six participants said they preferred the Animotus (with both DOF active) to the Taco. Four participants preferred the Taco. The remaining three participants did not state a preference.

Of the four participants who preferred the Taco (P4, P5, P10 and 12), three performed better with the Animotus, showing higher ME, AV and TF scores. P12 demonstrated better ME and AV scores with the Taco.

Average scores (indicated in brackets) from a scaled response questionnaire (1 = strongly disagree, 5 = strongly agree) indicate that participants found the shape-changing devices easy to follow (4.2) and disagreed that they were confusing (1.64). The extension / expansion DOF of the devices was deemed slightly easier to understand than rotation (4.1 vs 3.9). Participants disagreed that they got mentally (2.09) and physically (1.91) tired as the experiment progressed. Participants enjoyed using the devices (4.55), found them interesting (4.82) and thought they could use them for more complex navigation (4.36).

5.3 Influence of Hand Size on Performance

There was concern that user's with smaller hands may not be able to perceive instructions communicated by the shape-changing devices. In order to test this, the hand sizes of study participants were measured and correlated with measured ME performance.

A hand size metric (HSM) was determined via the average of three measurements, intended to give an indication of the ability of a participant to enclose the device in one hand. These measurements were 1. Palm width (between the distal heads of metacarpals), 2. Length of the middle finger and 3. Length of the hand (from the tip of the middle finger to wrist). This gave a range of HSM between 9.83 mm to 13 mm (mean 11.41 mm). Based on this metric, participant average *ME* data was split into three groups, small ($< 11\,\mathrm{mm}, \mathrm{n} = 4, 4$ females), medium (11-12 mm, $\mathrm{n} = 4, 2$ females) and large ($> 12\,\mathrm{mm}, \mathrm{n} = 5, 0$ females). One-way ANOVA was used to compare average ME value per participant with between the three hand size groups for each device condition. This produced the following results: $TacoF(2,10) = 0.21, p = 0.81)), 1E(F(2,10) = 0.21, p = 0.82)$, $1R(F(2,10) = 0.77, p = 0.14), 2DF(2,10) = 2.42, p = 0.14)$. In all cases the comparison was not statistically significant, though hand size did have more of an effect on the 2 DOF Animotus condition (2D) than the single DOF conditions.

6 DISCUSSION

The study has revealed that the articulated components of the Animotus have different roles in providing navigation assistance. Heading feedback appears to contribute to motion efficiency, guiding people in straight(er) lines towards targets. Proximity feedback appears valuable for increasing walking speed by letting participants know at what point they should slow down and stop.

Navigation with proximity-only or heading-only feedback has been shown as possible, though issues of not knowing when to stop walking (1R), or the necessity to explore an environment (1E & Taco) limit practical appeal. Clearly, the 2D sandwich has demonstrated good all-round performance, though the higher TF value of the 1R condition implies perhaps some distraction between DOF.

7 CONCLUSION

This work has provided an in-depth analysis of navigation using a novel shape-changing haptic interface, the Animotus. The contribution of individual elements of the device to navigation have illustrated that both heading and proximity information are used by participants to influence their motion trajectory. This, combined with positive quantitative reactions from participants is encouraging for the use of such technology in practical scenarios. Future work will seek to investigate the cognitive aspect of this novel feedback mechanism.

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