Sensory Augmentation with Distal Touch: The Tactile Helmet Project

Craig Bertram[1], Mathew H. Evans[1], Mahmood Javaid[2], Tom Stafford[1], Tony Prescott[1]

[1]Sheffield Centre for Robotics (ScentRo), University of Sheffield, UK

{c.bertram, mat.evans, t.stafford, t.j.prescott}@sheffield.ac.uk

[2]Wellcome Trust Biomedical Hub, Mood Disorders Centre, Department of Psychology, Univeristy of Exeter, UK

m.javaid@exeter.ac.uk

Abstract.

The Tactile Helmet is designed to augment a wearer's senses with long-range touch. Tactile specialist animals e.g. rats are capable of rapidly acquiring detailed environmental information from their whiskers using task-sensitive strategies. Providing similar information about the environment, in tactile form, to a human operator could prove invaluable for search and rescue, or partially-sighted people. Key aspects of the Tactile Helmet are sensory augmentation, and active sensing. A haptic display is used to provide users with ultrasonic range information. This can be interpreted in addition to visual or auditory information. Active sensing systems are “purposive, information-seeking sensory systems, involving task-specific control of sensory apparatus" [1]. The integration of an accelerometer allows the device to actively gate the delivery of sensory information to the user, depending on their movement. We describe the hardware, sensory transduction and characterisation of the Tactile Helmet device, outlining use cases and benefits of the system.

Keywords: Tactile devices and display, Human-computer interaction, Perception and psychophysics., Tactile and hand based interfaces, Mixed/augmented reality, Accessibility technologies, People with disabilities, Sensors and actuators, Sensor applications and deployments, Arduino.

1 Introduction

Touch is a richly informative sensory modality that can provide information about both the identity and location of objects. However, touch sensing is fundamentally local in humans, and distal environmental information must be gathered by other senses. In certain environments and situations a person’s ability to acquire information about the distal environment, and objects within it, using vision or audition may be impaired, such as when a fire-fighter is searching a smoke-filled building. Such environments are usually noisy, often dark, and visually confusing. In such cir-

adfa, p. 1, 2011.

cumstances a rescue worker's vision and hearing may already be stretched trying to make out shapes and structures through the smoke, or to listen out for the cries of trapped people above the background noise. The inspiration for this project comes from our past research on tactile sensing in rodents, whose facial whiskers give early and rapid warning of potential hazards or nearby objects of interest through a purely haptic channel, and the active direction and focusing of the whiskers to provide further information. We have recently shown that robots can be effectively controlled using information about their environment from arrays of whisker-like sensors [2]. Here we propose to use artificial distance detectors to provide people with a similar controllable sense of distal space.

Various technologies have been developed to provide information about the world to assist navigation and exploration, usually through sensory substitution. Sensory substitution involves presenting the characteristics of one sensory modality – the 'substituting modality' – in the form of another sensory modality – the 'substituted modality' Examples of sensory substitutions include presenting luminance (a characteristic of visual perception) in the form of a grid of vibrating tactile elements [3] or as a auditory landscape [4]. The translation from a characteristic of one modality to another in sensory substitution devices is usually fixed, and consequently the function of these devices is likewise inflexible. Another approach to assistive technology is sensory augmentation, where the device extends perceptual capabilities. This is contrasted with sensory substitution, where the sensory experience provided by the device is reducible to an existing modality [5]. As a sensory augmentation device is not designed to merely translate a scene, different patterns of activity can be used to communicate different types of information from moment to moment, allowing for greater functional flexibility compared to sensory substitution devices. In sensory augmentation, the aim is to reproduce the function of a sensory modality as a way of interacting with the world, rather than translate the form of one modality into the form of another [6]. Sensory augmentation can also include the creation of an additional 'sense' by presenting information about the aspects of the world that are outside human perceptual capabilities, such as a perception of magnetic north [7]. As this sense would be novel, its presentation cannot be a translation of its form into another sense and thus devices doing so cannot be considered to perform sensory substitution (although they might be more specifically called sensory enhancement devices [8]). Extra senses provided by sensory augmentation can be interpreted and used to guide behavior [8] and aid those with impaired senses, such as providing the visually impaired with spatial sensory information thus aiding movement [7].

The beneficiaries of sensory augmentation are not limited to the sensorily impaired. Personnel working in environments that temporarily restrict their sensory capabilities may also benefit from sensory assistance. Fire-fighters in smoke-filled buildings are often unable to visually locate important objects such as people, doorways, furniture, etc. Although details vary between countries, the universal best-practice method employed by fire-fighters traversing smoke-filled environments is primarily haptic, and involves maintaining contact with a wall or guide-rope and exploring the interior of the room by moving with an extended hand or tool (e.g. [9, 10]). This practice has been used for most of the past century and has not so far been supplanted by more technologically sophisticated approaches.

Attempts have been made to provide the kind of augmented spatial awareness that may be useful in such circumstances. For instance, the Haptic Radar [11], is a modular electronic device that allows users to perceive real-time spatial information from multiple sources using haptic stimuli. Each module of this wearable “haptic radar” acts as a narrow-field range detector capable of sensing obstacles, measuring their approximate distance from the user and transducing this information as a vibro-tactile cue on the skin directly beneath the module. The system has been shown to be effective and intuitive in allowing the wearer to avoid collisions, and the authors discuss the possibility of presenting multiple layers of information at multiple resolutions. However, the functioning of the system is insensitive to task or condition, and consequently there is a risk that the information is not specific or informative enough when it is needed or desired. At times, such a system could also overload the user with excessive or irrelevant information that could be distracting or make it harder to achieve goals. An ‘augmented white cane’ device has also been demonstrated recently [12]. Ultrasonic sensors and vibro-tactile elements were mounted on a hand-held device, allowing the user to infer the spatial configuration of an environment by sweeping the device like a search light. The downside to this approach is that the user only receives information from a small portion of the environment at any one time, and that it restricts the use of the user’s hand for other tasks. An objective of the Tactile Helmet project is to provide a system that overcomes these limitations of inflexibility and impracticality, or at least mitigates their worst effects, by providing a wearable assistive device capable of providing useful information through context sensitive function.

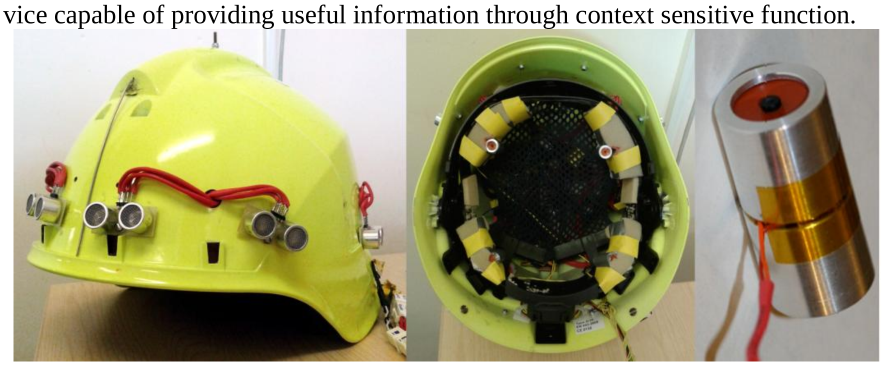

Fig. 1. The Tactile Helmet outside (left) showing the ultrasound sensors, inside (centre) showing actuators mounted around the headband, and a close-up of an actuator (right)

The Tactile Helmet device (shown in Figure 1) is a wearable sensory augmentation device, comprising an array of ultrasonic sensors mounted on the outside of a firefighter’s helmet to detect objects in the nearby environment, and a tactile display composed of actuators – vibro-tactile elements to physically engage the user’s head. The translation of information from the sensory array to the tactile display is controlled by a context sensitive algorithm. In the current implementation, the tactile display communicates object distance and warns the wearer of imminent collisions when moving. The function of the device is undergoing development: expanding its functioning, but with the aim of optimising the delivery of useful information to the wearer (see section 2.2).

In addition to drawing inspiration from the vibrissal system of rodents, who navigate extremely efficiently using distal tactile signals obtained through their whiskers, we consider that there are further good reasons to employ a head-mounted tactile display. First, experiments have demonstrated that while people find it difficult to process additional information through an already busy channel, such as sight or audition, they will often still have 'bandwidth' for information signals provided through the surface of the skin [13]. Second, there is also evidence that people may process touch stimuli preferentially (compared to signals in other modalities) when attention is divided [14]. Finally, we previously compared the sensitivity threshold and response times at five candidate locations: the hand, the outside of the thigh, the temples, the forehead and the back of the head [15]. We found comparable levels of sensitivity in the fingertips and temples, but quicker speed of response for stimulation sites on the head. In other words, the skin around the forehead and temples provides a sensitive and rapidly responsive site to transmit tactile information, which we take advantage of with the Tactile Helmet device.

A key component of the philosophy behind the Tactile Helmet device is the idea of active sensing, whereby the information presented to the user about an object is selected based on task-related demands. Previous approaches [3, 16] have proposed fixed-function devices, for example translating light levels and presenting them as 'haptic images' to the user, allowing the user to 'see' the environment through the sense of touch. In contrast, the display of the Tactile Helmet device could potentially communicate information about a range of properties: rate of change of position of the object with respect to the user; the physical attributes of the object; the time since first detection of the object by the sensory array; and the current situation or objectives of the user. Importantly, the Tactile Helmet device aims to communicate only the information most relevant to the present situation and will be flexibly controlled to do so. In this way the device should provide rich, task relevant information when it is most required without being unduly distracting.

This flexible approach to functionality will be achieved through another important feature of this device: the low bandwidth nature of the haptic display. In previous research, some laboratories have tested pixellated haptic displays, with many closely packed elements, in order to translate a visual scene into a tactile scene with reasonable resolution [16] – this is sensory substitution. In contrast, the present device uses only a handful of display elements, and seeks to use changes in activity (e.g. frequency or amplitude modulation of the tactile stimulation from the haptuators, or patterns of stimulation) to communicate information. This approach has two benefits – first, it can take advantage of hyperacuity to allow users to interpret simultaneous variable low-resolution stimulation at a higher perceived resolution. Second, as the system is not designed solely to translate a scene different patterns of activity can be used to communicate different types of information from moment to moment. This flexibility of function is a strong benefit of sensory augmentation over substitution devices. The possibility also exists that several overlapping channels of activity could be presented simultaneously, although more complex signals would necessarily require more time to master, and potentially take more cognitive load to process.

The remainder of this paper describes the hardware and software components of the Tactile Helmet device, before characterising the sensory field of the system and detailing some preliminary experimental work designed to explore the utility of the device in an exploration task. Finally, we will consider some future directions for the project, including improvements and experimental evaluations.

2 Methods

2.1 Hardware Overview

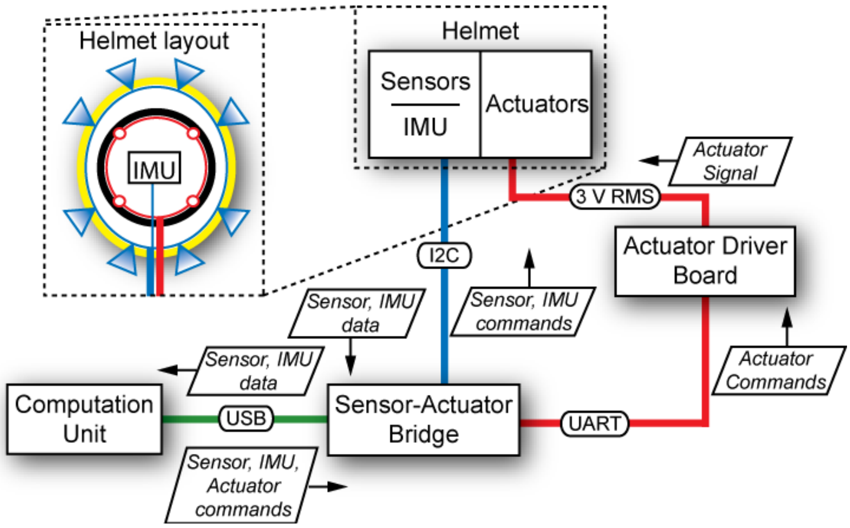

Fig. 2. Main: A diagram of the control process of the current embodiment of the Tactile Helmet device. Dashed inset: A schematic representation of the current embodiment of the helmet, corresponding to the dashed region 'Helmet' in the main figure. The helmet (yellow ellipse) is fitted with eight ultrasound sensors (gradated blue triangles) and an IMU, connected to a shared I2C bus (connection shown in blue) – the Sensor-Actuator Bridge (main figure). Inside the helmet is an adjustable headband (black circle) fitted with four actuators (small red circles) connected to the Actuator Driver Board (main figure), which is in turn is connected to the Sensor-Actuator Bridge (connection shown in red). The Sensor-Actuator Bridge then connects to the Computation Unit (connection shown in green).

Figure 2 shows the configuration of present embodiment of the complete unit, divided into two main parts: computational and control aspects (main figure) and transducers and environmental sensors fitted to a firefighter's helmet (figure inset). The helmet shell is fitted with an array of eight Sensors – a ring of ultrasonic range finding sensors[1], which scan the local environment of the wearer, and communicate information

[1] Eight Devantech SRF08, frequency: 40 kHz, range: up to 6 m; robot-electronics.co.uk

about the environment through four Actuators[2]. Transformation of the ultrasound sensor signal to the actuator output is governed by measurements from an intertial management unit (IMU[3]). The transformation is performed by the Computation Unit (a small netbook running Matlab in a Windows 7 environment). The computation unit also controls the system as a whole – reading sensor data, executing algorithms, sending actuation commands to the actuators. Sensor and IMU data is sent to the computation unit via a Sensor-Actuator Bridge[4] on an I2C bus (4-line serial bus with 7-bit addressing). The bridge also acts as an interface between the control unit and the Actuator Driver Boards (in-house design including PIC microcontroller (dsPIC30F2011), amplifier, and other necessary circuitry). The PIC receives the actuation commands via a UART bus, interprets the commands, prepares the output waveform and drives the amplifiers. The amplifiers then send their output to the actuators. All sensors, and the IMU, are connected to the Sensor-Actuator Bridge via the above mentioned I2C bus (a single four-core umbilical). Power to the amplifiers is provided from a 12V battery via separate cabling. From the amplifiers, the actuator signal travels on separate lines for each actuator.

2.2 Context sensitive sensory transformation algorithms

The helmet is able to perform context sensitive selection of one of two general modes of function dependent on acceleration measurements from the IMU. At walking speeds or higher, the helmet functions in ‘explore’ mode as a unidirectional proximity warning system. The signal amplitude of each of the four actuators is calculated from the pairwise average of the signal from two adjacent sensors to the actuator, which was initially scaled according to a cubic function (see Equation 1):

$$a = \left(1 - \frac{x}{m}\right)^3 \tag{1}$$

Where a is the amplitude of the signal sent to the actuator, x is the pairwise average of the distance measurement from the two sensors adjacent to the actuator, and m is the maximum distance to which the sensors are set to measure, which we chose to be 200 cm. Following pilot testing, the transformation was changed to a piecewise function where $a = 1$ if $x < 100$, and according to an adjusted version of Equation 1 function (see Equation 2) if $x \geq 100$.

$$a = 2\left(1 - \frac{x}{m}\right)^3 \tag{2}$$

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2 TactileLabs Haptuators, model TL002-14-A, frequency range: 50-500 Hz, peak voltage: 3.0 V, acceleration at 3.0V, 125 Hz, 15 g load: 3.0 G; tactilelabs.com

3 9-dof SensorStick; sparkfun.com

4 Arduino Mega (arduino.cc) board with an ATmega microcontroller running at 16MHz

The intention of the cubic scaling was to account for the Weber-Fenchner law, whereby as stimulus intensity increases, a greater absolute increase in stimulus intensity is necessary to produce the same increase in perceived intensity [17, 18]. Further, frequency of stimulation follows a stepwise function such that objects closer than 50 cm trigger a shift to a lower frequency (80 Hz) 'warning' signal to indicate immanent collision from the normal stimulation frequency (150 Hz).

At slower speeds, the helmet currently gates the activity of the actuators such that they are not active when the user is still. An alternative mode for this situation is being developed, where the helmet will switch to a forward focused 'scanning' mode, intended to provide more detailed spatial information about the area on which the user is focusing. The rear two actuators continue to function as collision sensors according to equation 1, but the front two actuators respond such that $a = 0$ if $x \geq 100$ and calculated according to equation 3 if $x < 100$, to produce fine resolution of distance at shorter ranges (note that the warning signal is not present for these actuators in this mode).

$$a = \left(1 - \frac{x}{0.5m}\right)^3 \tag{3}$$

Further, the frequency of the signal now also varies to indicate the difference between the signals of the two sensors to which it responds, with lower frequencies indicating a relatively smaller signal, and thus an object relatively closer to the more lateral sensor, and higher frequencies indicating the same for the medial sensor, thus providing the user with more spatial information. This IMU-based switching between exploration and scanning encourages the wearer to actively engage in their environment which may result in the user acquiring richer environmental information, analogous to exploration in active touch sensing [1].

3 Device characterization

A protocol was developed to measure the sensory range and extent of the helmet device to determine whether there are any significant blind spots or overlaps between sensors. The helmet was placed on a level surface atop a tripod, with the sensors 1m from the ground. A modification was made to sensing code such that the computation unit (the netbook) would output a sound if a particular sensor detected an object within its range. At approximately regular angular intervals around each sensor, a rubber balloon inflated to around 15 cm in diameter and held at 1 m off the ground was incrementally moved away from the helmet until it was out of range. By recording the closest locations that did not elicit a sound from the netbook at steps of 10 degrees, it was possible to map out the extent of each sensor. The process was repeated with the balloon at heights of 145, 135, 80 and 60 cm to get an estimate of the vertical extent of the range of the sensor. Figure 3 displays a map of sensitivity of the helmet based on this signal characterization, where the shape represents the area where the balloon would be detected, and is constructed from averaging across four sensors and orienting it according the location of the sensors on the helmet.

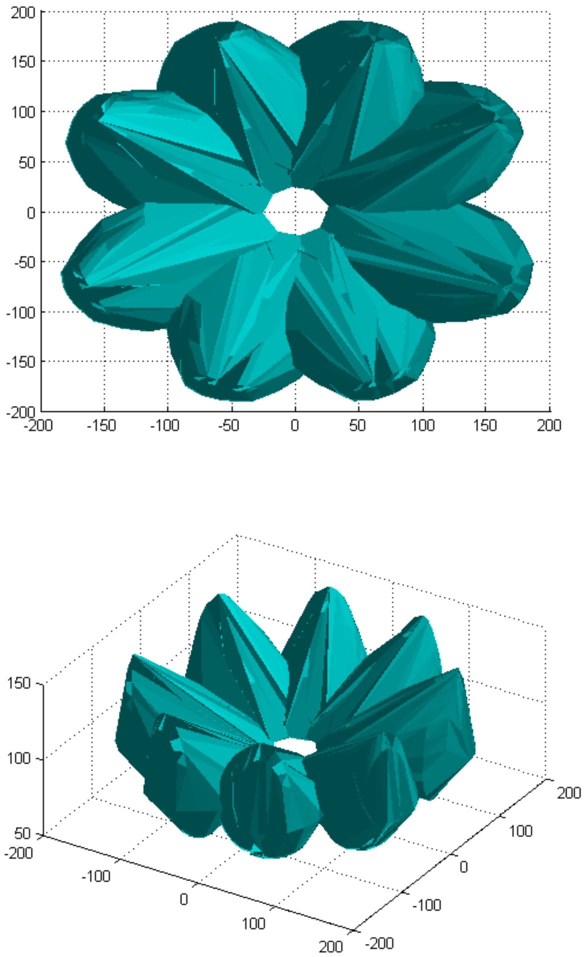

Fig. 3. Sensory extent of the Tactile Helmet device. (above) From above, showing the horizontal extent of the sensory field. Sensors overlap to ensure that there are no blind spots. (below) From the side, showing the vertical extent of the sensory field

4 Preliminary Experiments

After construction and characterisation of the helmet, a preliminary experiment was conducted to determine whether the distal spatial information could be successfully interpreted and used. A 4 m long corridor was constructed with exits on the left and right side 1 m before the end. Participants were tested in both “helmet on” condition, where the helmet worked as described above, and “helmet off” condition, where the actuators were disabled. On each trial a randomly selected exit was narrowed so that it was too small to exit through. Participants were blindfolded instructed to navigate along the corridor “using all means available to them” (including their hands in both conditions) until they found the exits, to determine which of the exits was passable, and to exit the corridor. Participants were able to navigate and successfully locate the exit with little contact or collision with the wall. Video inspection of the trials suggests that, although participants used their hands in both conditions, they were relying on their hands much less in the helmet on condition than when no information was available from the helmet Some preliminary data from the experiment is shown in Figure 4. Although participants were slower to complete the task in the helmet on condition, experience with the helmet was limited, and performance is likely to improve with practice. Within each condition, performance increased (i.e. time to exit through a gap decreased) across trials, suggesting a learning effect.

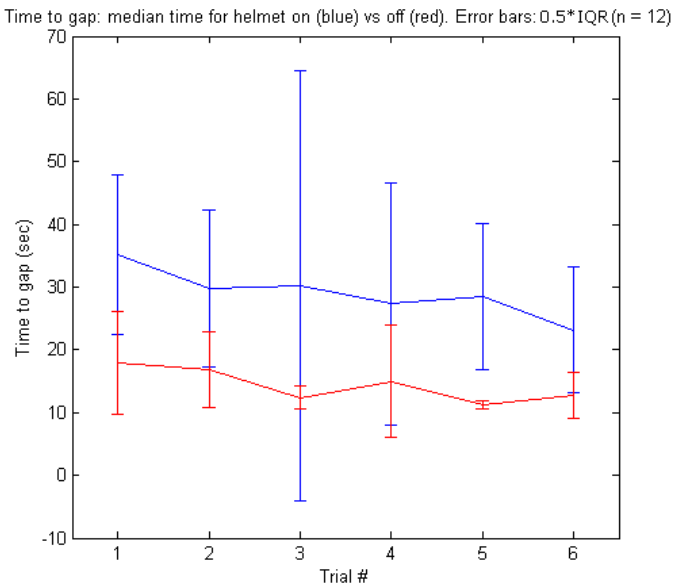

Fig. 4. Time taken for participants to navigate along a corridor, find, and then exit through a gap.

5 Conclusion

This paper presents a proof of concept of the Tactile Helmet device. The device is contrasted with previous devices in several ways: it provides sensory augmentation, rather than sensory substitution by providing the functionality of a novel sense of distal spatial awareness rather than translating the form of existing distal senses; it makes use of the spare ‘bandwidth’ of tactile stimulation to convey information, which may be of particular use in confusing visual and auditory environments such as those which may be encountered by fire-fighters; it is head mounted, which provides a balance of sensitivity and response time to tactile stimulation whilst also leaving the hands-free for other tasks including direct haptic exploration of surfaces; and finally the device is developed within a philosophy of active sensing, where the behaviour of the system changes depending on the task and the behaviour of the user. Preliminary experiments have demonstrated that the helmet can be used in the absence of vision to assist users in navigating along and exiting a constructed corridor.

The on-going goal of the project is to work towards an ideal transformation of the distance information provided by the sensors – more generally into a sense of space, but more specifically into a task related account of the environment, and objects and affordances within it. As 'ideal' is probably best defined as most useful for a user, this transformation would likely be high bandwidth, highly specific, low latency, and low in intrusiveness. At present, the device represents a first step towards these goals.

Initial psychophysics experiments [15] suggested that the best option for scaling for the transformation of distance to vibro-tactile haptuator signal was a hyperbolic function, as this would counteract the effects of the Weber-Fechner law. However, when this signal was used in pilot navigational tasks, participants found that stimulus amplitude at long distances was too low, and too hard to detect to be of use. As a compromise, scaling for distances outside of arms range was selected for the navigation experiments described here. Further psychophysics experiments will provide information for improving the scaling further.

The intrusiveness of the transformation is minimised by controlling the flow of information according to thresholds of rotational and/or linear acceleration. However, this is currently quite imprecise due to the nature of the IMU and also quite coarse – the device is switched on or off, or between states depending on a fixed acceleration threshold. Future implementations could use the IMU more intelligently, for example by dynamically compensating for the potential risk of increased speed by providing more intense stimulation or initiating stimulation sooner in a proportional manner.

The bandwidth and specificity have only been briefly touched on with the current incarnation of the device. The function of the helmet is basic, and consequently the function hasn't been tailored to one or more specific functions or to make use of a high bandwidth signal. The near-term goal of the project, however, is to develop a 'language' of signals that is able to communicate information with more depth than simply scaling as a function of range, while potentially communicating information about several aspects of the environment simultaneously. This could include 'special case' signals to indicate the presence of particular salient features in the world, for example trip or collision hazards, or task affordances. As with the general functioning of the helmet, the detection of particular special cases could be tailored to particular situations or tasks.

A long-term goal is to develop a system to coordinate information between multiple helmets about the environment and other users, which could be used to aid navigation and provide additional support. This could take the form of constructing a map of a building by synthesising information from multiple helmets as users move through it,, or providing information about the location and status of other device users, both to each other, and to a centralised command unit that could support coordinated tracking.

The current direction of development for the Tactile Helmet device has been as a navigation aid to fire-fighters and other emergency personnel. However, as noted earlier, sensory substitution and augmentation devices have also shown potential for use in aiding those with restricted senses, such as providing the visually impaired. For this kind of day-to-day usage, developing a lightweight version of the Tactile Helmet device is a priority. This could be achieved by replacing the safety helmet that the device is currently mounted in with a lightweight cap or headband. Further, once a set of functions has been settled upon, the computer notebook and related hardware that is required to run flexible calculation software could be replaced with a self-contained piece of specifically constructed hardware, which would also reduce weight.

Finally, as well as a technological development, the Tactile Helmet device also represents an opportunity to investigate the nature of sensory perception and the integration of additional senses provided by sensory augmentation. A ‘ladder of integration’ has been proposed [15], which suggests that a series of tests could be used to determine the extent to which an extra sense provided by sensory augmentation has become integrated into a users ‘cognitive core’. The Tactile Helmet device already satisfies the lower steps of the ladder – the stimulation provided by the device is detectable and users can respond to it i.e. use it to navigate. There is also evidence that it reaches the middle steps – users of the device are able to use the device to explore their environment without instruction, and participants in preliminary experiments made spontaneous statements about the nature of the task that framed the sensation from the device in distal terms, e.g. a participant who felt “a wall had appeared from nowhere”, rather than reporting a sudden onset of tactile stimulation. Further experimentation could explore the nature of perception of the device, how perception and performance of tasks using the device change over time, and whether a change in the nature of the percept is related to changes in task performance. After satisfying the middle steps, investigating whether the perception provided by the device is subject to sensory illusions would indicate whether the novel, artificial sense has been truly integrated; an effective combination of man, machine, and code. Although this kind of work is removed from the practical applications of the technology, it has the possibility to be greatly informative. A sensory augmentation device that is interpreted in an integrated, heuristic manner would have a smaller cognitive load than one that required attention and intentional processing. Implementing a framework to measure this aspect of using a sensory augmentation device, rather than focusing on performance rates could help improve product development for the field as a whole.

Acknowledgements This research was funded by an EPSRC HEIF Proof-of-Concept award, and an EPSRC/UoS KTA, “A wearable active sensing device using tactile displays”.

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