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ORIGINAL ARTICLE

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Wearable vibrotactile systems for virtual contact and information display

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Abstract This paper presents a development history of a wearable, scalable vibrotactile stimulus delivery system. This history has followed a path from desktop-based, fully wired systems, through hybrid approaches consisting of a wireless connection from the host computer to a body-worn control box and wires to each tactor, to a completely wireless system employing Bluetooth technology to connect directly from the host to each individual tactor unit. Applications for such a system include delivering vibrotactile contact cues to users of virtual environments, providing directional cues in order to increase situational awareness in both real and virtual environments, and for general information display in wearable contexts. Through empirical study, we show that even a simple configuration, such as eight tactors arrayed around the torso, can be effective in increasing situational awareness in a building-clearing task, compared to users who perform the same task without the added cues.

Keywords Vibrotactile · Tactile · Wearable · Feedback · Human–computer interaction

1 Introduction

Over the past decade, we have seen a steady rise in the amount of information available to many types of *people* (e.g., old, young) in various *contexts* (e.g., work, home, school) while performing various *tasks* (e.g., shopping, traveling from one place to another, providing patient care). In addition to an increase in the *amount* of available information, we now receive information from multiple types of *sources*, and in more *formats*, than was previously the case. By way of example from a mobile-computing context, mobile-phone usage worldwide continues to increase, with many developing nations forgoing traditional land-line infrastructure in favor of more-reconfigurable wireless solutions. The typical functionality included in mobile devices also continues to increase, with most handsets worldwide including high-quality color displays, digital cameras, polyphonic audio support, and some form of Global Positioning System (GPS). From a software perspective, many handsets include some typical Personal Information Management (PIM) applications (i.e., scheduler, address book, memo-pad, etc.), E-mail, Web browsing, and Short Message System (SMS) capabilities. Many handsets have support for Java applications, and even 2D-barcode and optical character recognition from images taken using the built-in digital camera. The existence of GPS has spawned location-aware applications, such as restaurant guides and payment systems.

The preceding discussion gave only a cursory description of features currently available in one segment of the mobile-computing space. Other hybrid hardware devices combining motion sensors, media streaming, and support for general applications, provide other services, though the current user-base is much smaller than for mobile phones. One of the main difficulties in the design of mobile devices relates to the desire to reduce device

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size, while still providing usability. Display screens, though of high resolution, are physically constrained by device size. Thus, as the amount of information we want to display increases, contention for the already precious screen real-estate increases even further.

As computing resources and network bandwidth continue to increase for mobile devices, users will have to deal with an increasing amount of information. For the past several years, we have been working on developing technology and techniques for information display that offload work from the visual channel to the touch sense, in order to better utilize the human bandwidth capacity. Most computer-mediated information we receive today utilizes the visual and/or audio channels. As the amount of information needing to be digested increases, however, it can become difficult for users to keep up if we limit ourselves to these two channels, possibly leading to information loss, decreased efficiency, and increased distraction.

The largest organ in the human body is the skin, and its surface proves to be an interesting and expressive channel for conveying information. However, because of wide variations in the makeup of the sensory substrate depending on body location, selecting suitable locations for presenting stimuli for a given mix of user, context, and task must be done carefully. Due to the relatively high density of receptors in the distal finger-pad of humans, in addition to versatility and dexterity characteristics, most early work into providing touch stimuli has focused on this region of the body. More-recent work has begun to explore the effectiveness of the rest of the body for information display in virtual and real environments.

This paper describes the work we have been doing for the past several years designing, building, testing, and integrating scalable systems for delivering vibrotactile stimuli to the body at large. The goal of our work is to produce a highly reconfigurable, wearable system for delivering vibrotactile cues for use in the study of how these cues can be used in human–computer interaction. In addition, we place great importance on the ease with which application developers can integrate our technology into systems for deployment. In the following sections, we briefly describe characteristics of the spatial senses that should be taken into account when designing information displays, and then describe our work into the use of vibrotactile cues to display information in virtual environments.

2 Sensory characteristics and display technology for the spatial senses

In this section we provide brief descriptions of characteristics of the individual spatial senses that should be taken into account when designing displays. In addition, we present the current state of technology available to display information to each modality. We will not provide a detailed physiological description of the workings of each sense, as that has been adequately covered elsewhere.

2.1 Visual

The visual sensing system in humans is very well developed. The makeup of visual stimuli is well understood, and display technology can produce extremely expressive stimuli, whether iconic, textual, or graphical. However, one aspect that limits its general usage is the need for the user to attend to (i.e., look at) the visual stimulus. If the user is looking in a different direction, or is preoccupied with another visual task, stimuli can be missed. Contrast this with the audio channel, which can receive stimuli from any direction. Visual stimuli are generated by combinations of varying hue, saturation, and intensity. Both public (e.g., projection) and private (e.g., head mounted) displays exist, so many types of applications can be supported. There is a range of pathologies that can affect visual acuity. The more-common cases of near- and far-sightedness are routinely corrected optically. Aging can also degrade the visual sense.

2.2 Auditory

The sense of hearing is also very developed, and humans are sensitive to temporal, spatial, and waveform characteristics of audio signals. Audio cues are omni-directional in the sense that the listener does not need to be facing in a certain direction to attend to the sound. A sound signal is made up of waves of varying frequency and amplitude. This makes the general use of sound attractive for alerts (e.g., the telephone ringing), as well as for information display (e.g., flight arrival information at an airport). The makeup of sound waves is very well understood, and the technology for producing many audio effects is very advanced, both for private and public displays. In terms of hearing pathologies, total or partial hearing loss and amusia (tone deafness) are the most common. Partial hearing loss, due to accident or aging, can often be treated with hearing aids or cochlear implants. Sign languages and lip reading are often used to compensate for hearing loss. Aging often brings on hearing loss.

2.3 Cutaneous

The sense of touch is arguably the most complex of the three modalities. This is partially due to several types of sensations all being attributed to this single “sense”. Broadly speaking, our sense of touch can be divided into kinesthetic and cutaneous sub-senses. Kinesthetic stimulation maps roughly to forces being exerted on, and sensed by, mechanoreceptors in the joints, tendons, and muscles. For example, we feel the weight of a heavy object held in an upturned palm because the object weight exerts forces on the wrist, elbow, and shoulder joints, and we exert opposite forces to counter the weight. Proprioception, knowing where your limbs are without looking at them, is another example of a kinesthetic sense. Cutaneous stimuli, in contrast, are sensed through mechanoreceptors in the skin layers. There are several kinds of receptors, each allowing us to sense a different type of stimulus, such as thermal properties, vibration of varying frequencies, pressure, and pain. The sense of balance is also sometimes included as a cutaneous sense. The sense of touch is the only one where the entire system conducts both sensing and actuation, e.g., we maintain the equilibrium of an object held in our hands through a tight loop of sensing weight and exerting supportive forces.

The technologies for generating force-feedback (kinesthetic) stimuli are typically cumbersome, have limited range of motion, and are designed for special purpose applications. On the other hand, these devices can typically generate strong forces and arrest user motion in a realistic manner. Tactile (cutaneous) devices are designed to stimulate a local area of the skin. As with sound, a tactile stimulus is made up of a signal with varying frequency and amplitude. Much work has focused on the use of pin arrays for stimulating one of the most sensitive parts of the body, the distal finger pad of the index finger [1, 2]. More-recent work has focused on the use of large numbers of vibrating tactors distributed over a larger area of the body [3–6]. These devices cannot arrest the motion of the user, but can provide a means for displaying contact cues, as well as other types of information.

3 Development history of wearable cutaneous displays

For the past several years, we have been working to develop the necessary technologies and techniques for deploying wearable, scalable, systems for delivering vibrotactile cues. We have defined several desirable attributes of such a system that would allow researchers to better study the use of vibrotactile cues in human–computer interaction, and allow application developers to more-easily integrate such systems into their products. The first of these is ***expressiveness***, meaning that such a system should allow for *multiple* tactors (devices that provide some form of tactile sensation) to be controlled, with *multiple* levels of vibration (e.g., intensity, frequency), and with *dependable* timing, so that patters could be reliably displayed. Second, the system should impose ***limited cumber*** upon the user, meaning it should be easy to put on/take off the tactors and support hardware, and that movement should not be hindered by excessive cabling. Also, such a system should be ***easily scalable*** and ***reconfigurable***, and the ***mapping*** of input data to stimulus output should be straightforward. As is the case in most designs, decisions about the relative importance of these characteristics will depend on many factors, such the target application space (e.g., wearable, desktop, in-vehicle) or complexity of control and support apparatus (e.g., pneumatic, electrical, mechanical).

Several potential application domains have been identified, encompassing both virtual environments as well as the real world. Applications for virtual environments include providing force and torque information for molecular-docking tasks [7], creating a sense of motion using sensory saltation [8], and delivering cues when a user comes into contact with virtual objects [9], such as collision reaction vibrations in video games, rumble vibration for driving simulators, and high-frequency surface properties during active touching [10]. In terms of real-world applications, situation-awareness systems for pilots [5, 6] and road vehicle drivers [4], guidance systems for firefighters [11] or blind individuals [12], motion-following systems for sports and fitness, such as for learning Tai Chi [13] or improving a golf swing (Innovative Sports Training http://www.innsport.com/), and non-verbal communication [14] have been proposed.

Many technological approaches to providing high-fidelity haptic or tactile cues require a significant portion of the apparatus to be mounted on the floor [7] or fixed to a desk (PHANToM—www.sensable.com), while others place a substantial weight burden on the user for untethered operation (CyberGrasp—www.immersion.com). Several researchers have proposed the use of low-cost vibration motors as a means of providing vibrotactile cues in virtual environments [5, 6, 15–17]. In general, such systems trade high-fidelity and precise control for simplicity, modest power consumption, and reduced cumber on the user.

3.1 Scalable haptic feedback systems

The development of scalable haptic feedback systems has followed a path from fully wired systems to current systems, which have significantly reduced cumber. Early systems required tethering to a host computer for producing the haptic signals [5, 6, 15]. The advantages of this class of system include support for tactors that require substantial power or control circuitry, such as pneumatic actuators, and the ability to provide counterbalancing for exoskeleton-type or arm-linkage-type devices which can produce significant forces [7] (PHANToM, CyberGrasp). One example of this class of system uses a PC with analog-to-digital conversion hardware to feed a signal to motor driver hardware, which in turn drives the tactors (Fig. 1).

In order to reduce the complexity of full-body haptic feedback systems, several researchers began to experiment with the use of low-cost pager motors as a way of delivering vibrotactile stimuli [6, 16–18]. These systems use simple control boxes connected to a standard serial or parallel port to interface with the tactors. Van Erp and his group developed a 64-tactor wired system, and deployed the tactors in a regular-grid pattern around the torso.

Vibration intensity is controlled by varying the voltage delivered to each tactor, thereby causing them to

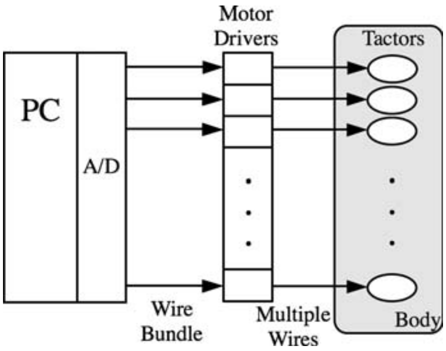


Fig. 1 Fully wired systems. The PC contains control software, and an analog-to-digital converter outputs stimulus signal to motor driving circuitry, which feeds power to the tactors over cables

spin faster or slower. Alternatively, the well-known approach of Pulse-Width Modulation (PWM) can be used to vary the ON-time of the motor, instead of the voltage (Fig. 2). If the period is too long, then strobing can occur, as the power is rapidly being turned ON and OFF by the PWM hardware. One of the advantages of using DC-motor-type tactors, however, is that the inertia of the spinning weight smoothes out discontinuities caused by this rapid power switching.

The main disadvantage of DC-motor-type approaches is the lack of a mechanism for arresting user movements. For example, when using exoskeleton-type devices, we can give a sense of the weight of virtual objects. With vibrotactile systems, we can map weight to some (arbitrary) vibration pattern, but gravitational forces cannot be properly simulated. Providing the ability to control the intensity of the vibration [16], as opposed to simply turning the motors on or off [6, 17], can provide added information (e.g., velocity, depth of penetration), but the stimulus will still only approximate the real sensation of touching.

Another problem with these DC-motor-type tactors is the lack of control over the actual stimulus that is output to the user. The mechanical performance of the motor is subject to dynamic changes in the environment. For example, the resonance frequency changes based on how rigidly the tactor is attached to the user, or other objects. Reorienting a spinning motor also produces changes in the vibration stimulus. We have tried several approaches to monitoring the momentary frequency of these tactors using a laser range finder and accelerometers. We have concluded that a number of hard-to-control parameters, including body location, method of attachment to the user, load placed on the tactor surface, orientation of the tactor, and individual manufacturing differences in tactors, precludes the use of static calibration data correction. Among these factors, the most significant is the location and method of attachment of the tactor to the subject. For example, if a tactor's attachment loosens during use, the frequency and amplitude of vibration of that tactor for a given input voltage may well change, affecting the quality and sensation magnitude of the stimulus. We have decided that a dynamic control approach, which constantly monitors the vibration frequency (and/or amplitude) and adjusts the voltage to maintain a desired value, will be necessary for studies where precise characterization of these parameters is required using DC-motor-type tactors [19].

In terms of tethering, many systems use AC power and control signals from a wired serial or parallel port (Fig. 3a). The technological solution to removing these two tethers is to use battery power in place of AC power, and wireless communication in place of serial/parallel control lines. To make the most efficient use of battery power, the selection of components on the controller, and the type of tactor, are key factors. We designed our own control box, called the TactaBox, selecting components that draw as little power as possible, while still allowing us to vary the intensity of the vibration using PWM. Several manufacturers now produce Bluetooth-serial-bridge solutions that are composed of a paired set of devices that conform to the hardware specs of RS-232 on one side, and use standard Bluetooth between them (Figs. 3b and 4). The main features of these devices are OS-independence, modest-power requirements, and a communication range of up to 100 m.

We have successfully used these serial-bridge devices in several applications, including vibrotactile armbands for sending simple signals to dismounted infantry during live-fire exercises on an obstacle course [11] (Fig. 5a), and an upper-body vibrotactile feedback system for training Marines in building clearing exercises in VR [20]. For these applications, the tactors are wired to the body-worn TactaBox, which uses the serial-bridge to

Fig. 2 Varying the output: the resulting output produced by halving the input voltage (**a**) can be achieved by halving the ON time (*duty cycle*) within a pulse period (**b**)

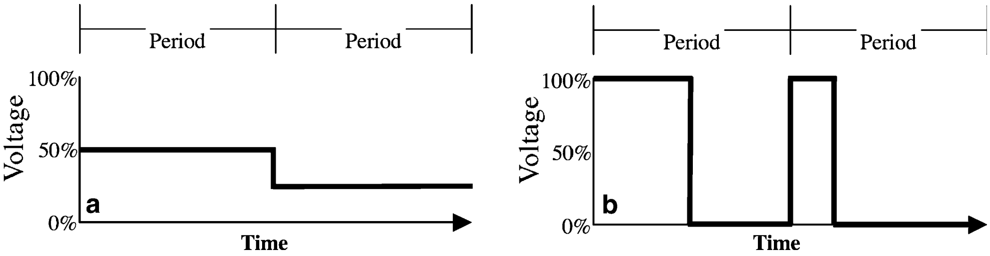
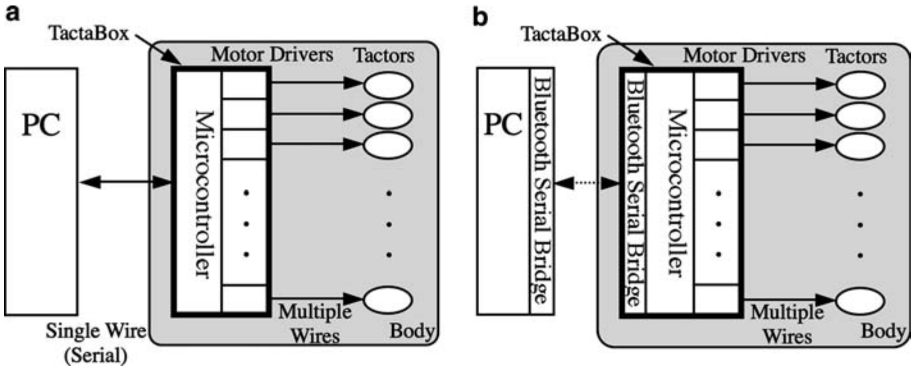


Fig. 3 **a** wired version of TactaBox, **b** wireless from host PC to TactaBox, wired to tactors



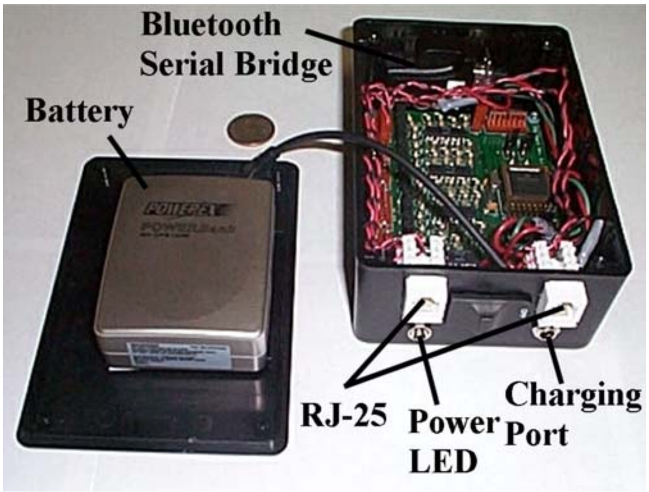


Fig. 4 Battery-powered TactaBox that can independently control 16 tactors using PWM (US quarter shown for scale)

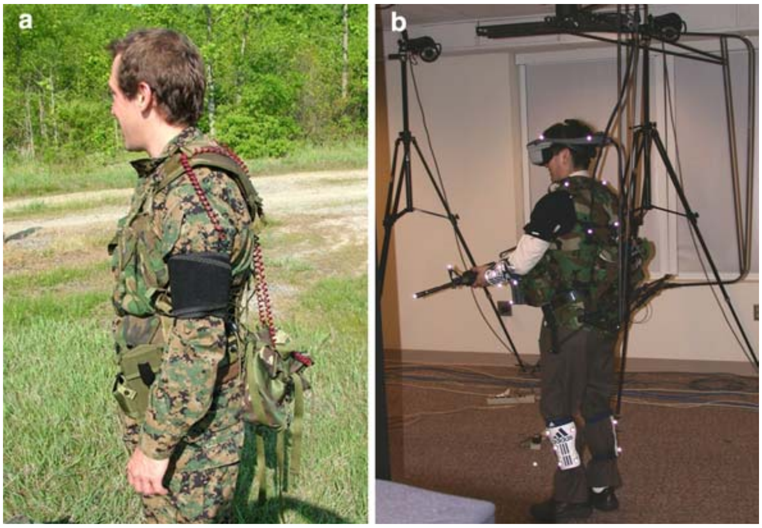
talk to the host computer. As the dismounted infantry VR system uses passive-optical tracking, the only remaining tether is the video cable for the stereo HMD (Fig. 5b).

The vibrotactile stimuli are delivered using tactors placed at 16 locations on the upper-body of the wearer. The tactors, ruggedized in house, are Tokyo Parts Industrial Co., Ltd., Model No. FM37E (Fig. 6a). They have an operating voltage range of 2.5–3.8 V at 40 mA, measure 2 cm (0.79″) in diameter, and 1.5 cm (0.59″) in height. They have a frequency of 142 Hz at 3.0 V, and have a vibration quantity of 0.85 G. We designed the shape of the tactor casing to be a disk with a cone on top that tapers to a near-point on the side that contacts the body (Fig. 6b). Several researchers have reported that maintaining good contact of the tactor with the body is a major problem in similar systems [5, 21], and this shape was chosen to mitigate this problem. Lightweight cable carries the power signal to the tactors, and connects to the TactaBox using friction-lock connectors inside the box.

3.2 Garment design, tactor placement, and wiring

One of the major issues to be dealt with in designing garments is the variation in size of potential wearers. We call our first attempt at designing and building such an upper-body garment the TactaVest (Fig. 7).

Fig. 5 Wireless vibrotactile cueing systems. **a** real-world obstacle course, **b** Fully immersive VR simulator with only a single cable (for video)



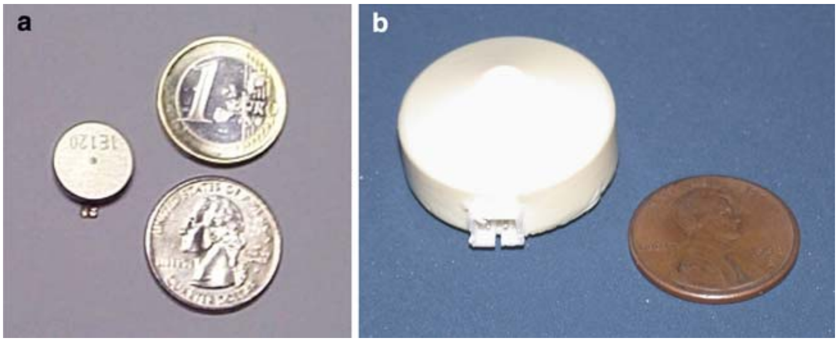


Fig. 6 **a** DC-motor type tactor, **b** Ruggedized version used in deployment

Fig. 7 The TactaVest (before wiring) is designed to hug the wearer through a large range of motion, while still granting adequate freedom of movement

Because tactor location is so important for most applications, the garment needs to keep each tactor fairly tight against the body, even during vigorous movement. In addition, the garment needs to fit different-sized users. We addressed these two, seemingly opposing requirements by making the garment out of five individual pieces of stretch neoprene (Fig. 8): two yoke-shaped pieces for the upper torso, two thin straps for the elbows, and a belt for the lower-torso/waist area.

Hook-and-loop fastener is used to secure the pieces in place, and during the donning procedure, each piece can be adjusted to correctly fit the user. Tactor mounting points are designated with a patch of loop-fabric sewn on the underside of the garment, allowing for fine adjustment of the tactor location. In order to reduce the amount the garment restricts the movement of the user, care was taken to minimize the amount of material used in the overall garment. The use of five distinct pieces of material also helps in this regard.

For wiring the 16 tactors in this system to the TactaBox, light-weight cabling, similar to that used for personal headphones, was mounted on the outside of the vest, with the tactors on the inside, in a branching structure using hook-and-loop swatches (Fig. 9). The use of lightweight cable, along with the garment's neoprene material, helps reduce the vibration propagation and localize the vibrations. Through the use of hook-and-loop fastener, the tactors and cables can be removed when the garment needs cleaning.

Similar to Yano et al. [14], we choose to mount the tactors at locations on the body with a high probability of contacting virtual objects. In addition, our application environment has users wearing a military tactical protective vest (a modern version of a flak jacket) during the simulation (Fig. 10), so care was taken to choose locations that would not be adversely affected by this and other gear worn during a typical session.

Fig. 8 The TactaVest is made up of five parts: two yoke-like shoulder pieces, two elbow bands, and a belt (not shown). The longer white hook-and-loop fastener pieces denote mounting points for the tactors

Fig. 9 TactaVest (*back*) shoulder wiring

3.2.1 Virtual-contact example

As an example of the effectiveness of our approach, one common problem encountered in head-mounted display virtual environments is the limited field of view available to the user. This can lead to confusion when the user bumps into a virtual object that is currently outside the field of view (Fig. 11). The collision detection system will typically stop the movement of the user, thereby enforcing physical constraints, and either an audio or visual cue will be given to indicate the contact. However, because the user does not see anything to impede progress, this situation can lead to confusion.

Fig. 10 TactaVest integrated within a VR simulation system

Although formal impact studies are still pending, after adding the TactaVest to this particular system, and triggering a vibrotactile cue to be delivered in the proximity of the contact, anecdotal evidence has shown that users experience less confusion compared to before the TactaVest was added, as the cue they are given better matches what they would expect in the real world. It should be noted that little extra computation is needed to decide where to deliver the cues, as the collision-detection system gives the location of contact as output, which we then take as input to a mapping function of collision location to tactor actuation.

3.2.2 Information-display example

In related work, we have also tested our TactaBox, along with the belt from the TactaVest, in an eight-tactor configuration [22] (Fig. 12a). It has been found that subjects can differentiate with 80% accuracy eight points equally distributed around the waist, with accuracy reaching 100% at the naval and spine [3]. Location discrimination accuracy falls off the further away from the mid-line the stimulus is presented [3, 23]. In our study, 28 subjects performed a building-clearing task, in an environment similar to a first-person shooter game (Fig. 12b). Each subject performed the task twice, once with a vibrotactile cue denoting areas of the space that they were exposed to, but had not yet viewed, and once without such cues.

Our main results showed a significantly lower percentage of time spent exposed when the vibrotactile cues were present, versus when they were absent (20.7% vs. 25.0%; F 6.54, η^2 0.20, *df* 1, 26; $p < 0.05$). Also, subjects cleared a larger percentage of the space when vibrotactile cues were present (90.0% vs. 97.5%; F 14.47, η^2 0.36, *df* 1, 26; $p < 0.01$) [22]. We are currently implementing the same setup to display sensor data on the torso of robot teleoperators. By offloading the visual channel, and providing a clearer mapping between the orientation of the sensor and the operator, we believe this system will be very effective.

3.3 Wireless tactors

A natural evolution of the system described above would attempt to increase the number of tactors, in order to cover a larger area of the body. With the current approach, however, adding more tactors means adding cables from each one to the TactaBox. This goes against the drive to reduce cumber, and limits the overall scalability of the system. One solution to this is to use additional TactaBoxes deployed at different locations on

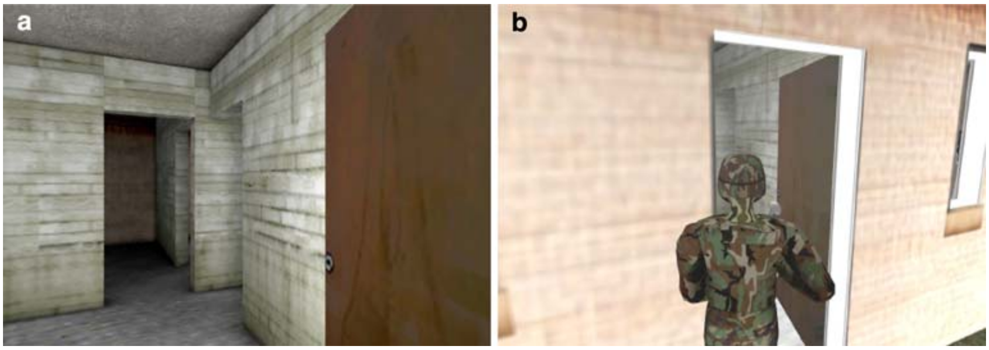


Fig. 11 **a** First-person and **b** over-the-shoulder views of a user stuck on a door frame

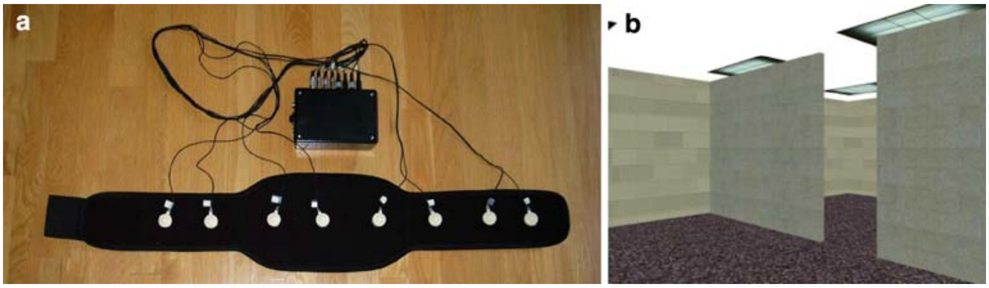


Fig. 12 **a** TactaBelt with eight tactors, **b** first-person view of the test environment

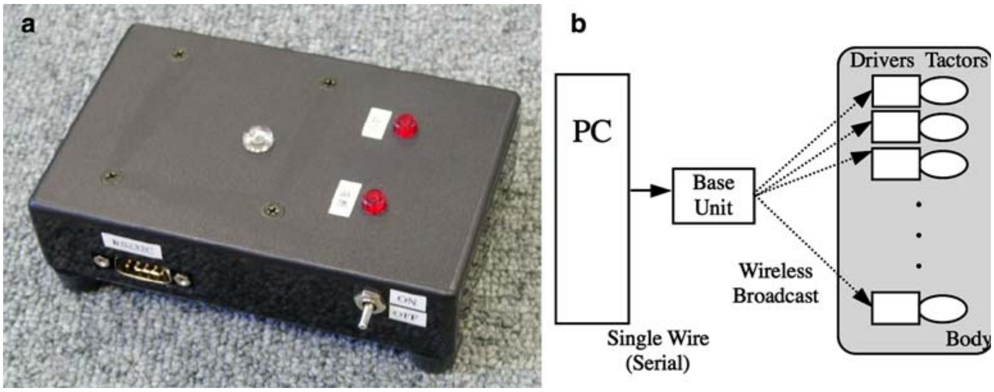


Fig. 13 **a** base unit of the wireless tactor system, **b** configuration of the wireless tactor system

the body (e.g., one on the torso for tactors on the upper body, one on the abdomen for tactors on the legs). While feasible, the added space and weight [each TactaBox with a battery weights approximately 0.45 kg (15.8 oz), and measures 15.2×10.1×5.1 cm^3 (6″×4″×2″)] still limits scalability. A better solution would be to use a wireless connection from the tactor to the control box. This would allow tactors to be easily mounted at any location on the person, as well as on hand-held props, and would mitigate the increased cumber incurred with the addition of more tactors.

In undertaking the design of wireless tactor units, we first concentrated on building a system that incorporated basic functionality, so as to better understand the nature of the problem. Once the prototype was working, we began to focus more on optimizing size and weight characteristics, as well as providing increased functionality.

The design goals of the wireless tactor unit are:

1. to include a vibration motor, a motor driving amplifier, a microcontroller, a wireless communication circuit module, an antenna, and a battery, in a compact chassis,
2. to make the tactor unit as small and light as possible, and
3. to allow the host to control multiple tactors simultaneously, so that various stimulus patterns using multiple tactors could be realized.

3.3.1 *First wireless tactor version*

The first attempt consisted of a host computer (PC) to send control commands, a wireless transmitter unit (base unit Fig. 13a), and multiple tactor units. One of the drawbacks of the use of wireless technologies is the

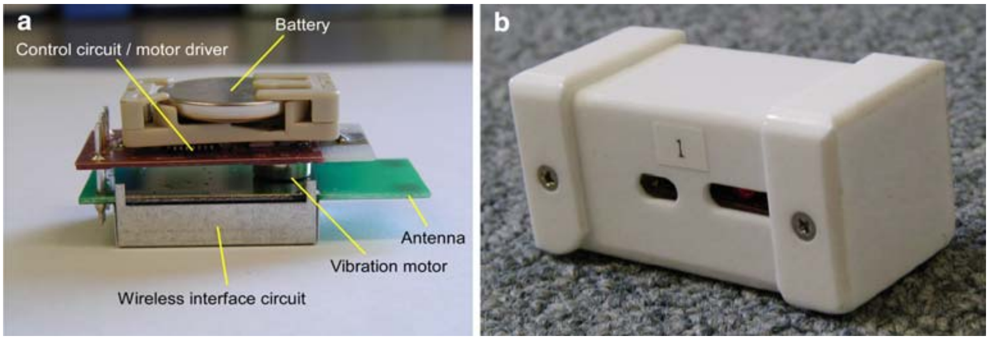


Fig. 14 A wireless tactor unit. **a** interior, **b** case

additional communications delay that is incurred. We are currently evaluating the size and variation in this delay. The base unit receives control commands from the host via a RS-232C serial communication channel, and broadcasts to all wireless tactor units (Fig. 13b).

Each tactor unit (Fig. 14a) is an all-in-one package consisting of a vibration motor, an amplifier circuit, a microcontroller (4-bit CPU: Mitsubishi Electric M34518M4), a wireless receiver circuit module, a chip antenna, and a coin-type lithium battery (CR2025). We use Fujikura FMIU-005 as the vibration motor, which measures 8.0 mm (0.31″) in diameter, 3.7 mm (0.15″) in thickness, weighs 0.95 g, and spins at 10,000 rpm at 3.0 V. The motor draws 24 mA of current at 3.0 V, and the vibration quantity is 10 m/s^2 for a 60 g chassis. The size of a tactor unit package (Fig. 14b) is 26 mm (1.0″)×26 mm (1.0″)×45 mm (1.8″) (H × W × D), and weighs 30 g including the battery. The battery lifetime is approximately 3 h when the vibration motor is always ON. As the time that the motor is switched ON is usually much less than this case, battery life is expected to exceed a whole day.

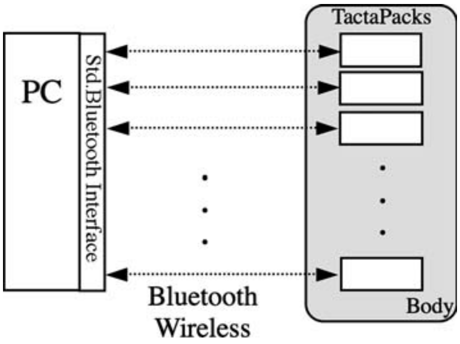


Fig. 15 The TactaPack uses a standard Bluetooth connection to exchange commands and data with the host

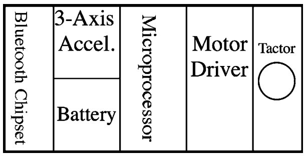


Fig. 16 The TactaPack contains a Bluetooth chipset, a three-axis accelerometer, a microprocessor, motor driver, and a vibrotactile tactor

We use a 315 MHz-band weak radio wave for communication between the base unit and the tactors. The effective range is 4 m, which is considered to be sufficient for coverage of the human body, assuming the base unit is well positioned within the workspace. Each tactor unit has a wireless receiver unit, but does not have a transmitter unit. This is because we wanted to make the tactor units as simple as possible. Each tactor unit has a unique ID, and the base unit sends a command that contains bits corresponding to ON/OFF for each tactor, allowing each tactor unit to find if it should activate itself or not. As the wireless communication is unidirectional, wireless tactor units may miss a control command if there is noise in the environment. However, by repeating commands, the tactor unit can recover the latest status.

3.3.2 Current wireless tactor version

There were several changes to this first attempt we wanted to make for future versions, including reducing the size, making the shape more appropriate for delivering feedback on the body, and adding bi-directional communication to get status from each unit. Most importantly, we wanted to have the ability to vary the vibration signal, instead of simply turning it ON and OFF, in order to support more-expressive cues. To this end, our current wireless tactor version takes advantage of recent reduction in size of support chipsets for both processing and wireless communication. Also, new innovations in battery technology are used to increase operating times. Finally, because we chose to use a more-powerful processor, we also included a three-axis accelerometer in the design.

As shown in Figs. 15 and 16, our latest version, called the TactaPack, uses a standard Bluetooth interface, as opposed to Bluetooth-serial-bridge devices, to control each unit. The microprocessor is a Renesas Technology H8/3687F running at 7.3728 MHz. The Version 1.2, class 2 Bluetooth chipset we are using is part number WML-C29 from Mitsumi. A three-axis accelerometer,

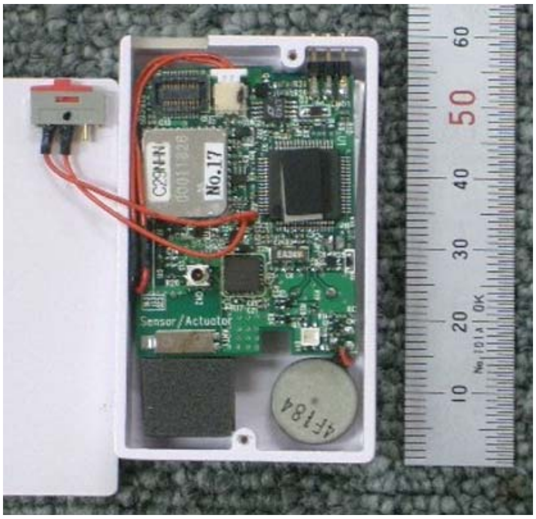


Fig. 17 The TactaPack interior (with mm ruler)

model number H48C from Hitachi Metals, is used as the sensor for this application. Each unit is powered by a rechargeable lithium-ion battery, part number IML-270530-2 from NEC Tokin, with a rating of 300 mAh. In our testing, we were able to stream data from the sensor over Bluetooth continuously for 8 h before the battery needed re-charging. In addition, we tested battery life when vibration was used, and were able to pulse the tactor ON and OFF in half-second intervals for 1 h and 20 min, while streaming sensor samples every 5 s. After this time, sensor return continued, but the battery could no longer support vibration. The physical, encased size of the current prototype is 58 mm (2.28″)×35 mm (1.38″)×13.5 mm (0.53″) (H × W × D), and weighs 24.6 g (Fig. 17). This low-profile design is more amenable to mounting on the body than our previous design, but further refinement is necessary.

In terms of interacting with the devices, an ASCII protocol allows for the host PC to collect data from the accelerometer and trigger vibration with varying intensity, depending on the application. The TactaPack has a local real-time clock in order to synchronize the acquired data. In general, the synchronization of distributed sensing data can be very important. However, data transmissions are sometimes interrupted and/or deferred due to radio conditions, especially in wireless networks. For the synchronization of the acquired sensing data, each TactaPack sends data with the local time stamp. In addition, a wake-up timer can be set to begin sensing at a specified time, relative to the on-board clock, and another can be set to vibrate at a certain time. If all TactaPacks are synchronized, they can be commanded to all vibrate at prespecified times, thereby providing support for fine-grained control, such as that required for producing apparent motion [24].

The target application for this project is the use of sensor/actuator devices for monitoring patient movements in physical therapy exercises following surgery, such as hip replacement. Using sensor data returned from the TactaPack, each unit can be instructed to vibrate when its movement violates a certain constraint in any of the three axes. Both maximum and minimum constraints could be defined for each of the three axes. For instance, if a patient moves their hip outwards, the sensor data can be used to trigger a vibration to occur, “nudging” the patient back into a safe range.

3.3.3 Wireless connectivity

To provide wireless network connectivity, we chose the Bluetooth standard for the following reasons. First, the use of Bluetooth is safe in many high-risk locations, such as hospitals. Some hospitals restrict the use of radio devices, such as mobile phones, because of the possibility they might interfere with other wireless equipment. However, because Bluetooth uses much less power than 802.11 b, which uses the same ISM band, it can be used in many hospitals.

Second, with our previous wireless system, tactors often missed broadcast commands. The transmission reliability provided by Bluetooth allows us to improve the delivery of commands, especially in environments where multiple devices must coexist. The Bluetooth specification includes support for simultaneous operation of multiple devices and covers many of the complex problems encountered in wireless networks, such as collisions and error detection/correction. So, we expect reliable connectivity even if multiple devices are worn on several parts of a body at the same time. Also, because the low-level network functionality can be offloaded to the Bluetooth chipset, the CPU can dedicate itself to processes related to sensing and actuation. Finally, Bluetooth provides sufficient bandwidth to transmit fine-grained sensor data, approximately 400 kbps in symmetric mode. Assuming that eight channels of 10-bit A/D data are acquired at 100 Hz and they are packed into 128 bits (with every 10-bits of data packed into 16 bits), the data rate is 12.8 kbps. Even if seven units are used simultaneously, requiring a bandwidth of 89.6 kbps, Bluetooth can successfully transmit the data, and still have a margin to transmit additional data. Moreover, Bluetooth is designed for short-range wireless networking, so the power consumption is relatively low, which is suitable for our use of the TactaPack.

The Bluetooth specification only allows each device to communicate with seven other active devices at a time. However, by using several Bluetooth controllers, we can support a much larger number of TactaPacks. And because Bluetooth control devices are fairly inexpensive (less than US$15), this provides cost-effective scalability.

4 Conclusions and future work

The results of our current work have been very encouraging for the future of unencumbered, full-body haptic feedback systems. We have followed the natural progression from a fully wired system to one that provides much more flexibility in terms of tactor placement, coverage, and ease of donning/doffing. Our first wireless system only allowed the tactor units to be switched ON and OFF, but this first prototype convinced us of the merit of the approach we are taking. The current system provides support for more-expressive vibrotactile stimuli to be output, and increases reliability through the use of Bluetooth.

We are now in the process of continuing to miniaturize the tactor units further, refining the shape, and are looking at how the overall mass of the tactor package affects the choice of the vibration motors we use. Because we still have some headroom in terms of processing power on the TactaPack, we are also looking at support for other sensors, such as microphones.

In terms of deploying the wireless tactor system, we have designed and built a second TactaVest that supports placing the tactors at any location on the torso, while still maintaining the flexible design that allows variations in user size to be accommodated. Finally, the wireless tactors have allowed us to expand the coverage of our vibration to the arms and legs, using similar wraps as we use in the TactaVest. These additions are currently being evaluated.

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