Implementing Effective Tactile Symbology for Orientation and Navigation

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Abstract. The sense of touch is an effective, but underutilized, human communication channel. In this paper we describe our research efforts towards optimizing a minimal tactile array for personal navigation and route guidance. There are several aspects to this problem. From an information transfer viewpoint, the question of tactor array size, dimension, location and display symbology requires careful consideration. Effective tactile display symbology involves providing information in an intuitive manner without adding to the cognitive loading of the user. Tactile information may be presented through spatial, temporal and signal variables. We have recently developed new wearable tactors that offer wide sensory capabilities to provide different "feeling" stimuli. These actuators are non-linear in that the salient characteristics for perception are linked to a complex drive stimulus. We have therefore developed a tactor activation design approach termed "TActions" (Tactile Actions) where patterns or sequence of individual tactile stimuli, each of which has its own characteristics and properties, are used to create tactile display symbology that a user can naturally associate with a particular function. These components provide display design frame work which we have used to demonstrate orientation and navigation.

Keywords: Tactile display, navigation, tactor.

1 Introduction

The sense of touch offers a relatively untapped and intuitive channel for communication and orientation. It is intrinsically linked with the neuro-motor channel, both at the reflex and higher cognitive regions, which make it naturally suited to localization tasks. Tactile arrays can be an effective communication modality even under situations where the conventional communication channels such as visual, audio and even the vestibular system become disorientated [1]. Further, according to multiple resource theory [2], parsing information across the input modalities can potentially alleviate sensory bottlenecks. Tactile displays offer additional advantages in that they are potentially covert, omnipresent and are omni-directional (the user does not need to be looking in a specific place to receive tactile feedback and it may be applied at almost any place on the body – in effect, act as "eye's in the back of the head").

Research [3] has also demonstrated that under appropriate conditions, tactile cueing yields significantly faster and more accurate performance than comparable visual or spatial auditory cues. This finding is relatively stable across a variety of

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body orientations, even when limited spatial translation is required and under physiological stress [4]. However, there are a number of critical human factor issues and hardware system limitations that must be considered in the design of practical tactile cueing systems. Our focus has been on optimizing wearable tactor actuator components [5] and tactile symbology for tactile cueing. In this paper we describe how new tactile hardware and systems constructs can be applied in personal navigation and route guidance.

2 Background to Navigation and Orientation

The informational requirements associated with navigation and orientation will depend on the environment, task and application. In complex environments, these requirements may require aspects of motion (velocity), position and orientation with respect to a frame of reference. It is very difficult to convey large amounts of information simultaneously and the tactile channel is particularly limited. Effective tactile displays should ideally provide navigation and orientation information intuitively without adding to the cognitive loading of the user. This usually requires careful bounding of the display (limiting the dimensional variables), designing specific tactile symbology and careful tactor array implementation.

Attentive observers are able to perform complex spatial translation and orientation mapping during navigation tasks, but this is usually less effective in dual task conditions or if the user is under stress (such as that encountered in many military applications). Therefore displays that are implicitly aligned with a world coordinate axis are preferred. The torso is usually aligned with the direction of intended motion and is also well suited to the presentation of multidimensional spatial concepts such as elevation and azimuth (with respect to body coordinates). This can be particularly useful in aviation, as demonstrated by the tactile situational awareness system (TSAS) [6] where 3-D orientation variables are needed. For navigation and orientation in many ground based tasks the plane of interest can be restricted to only the azimuth, greatly simplifying the array.

The simplest informational requirements for completing a navigation task are the direction to and distance from the waypoint, and this can be presented on a torso worn tactor array [7]. Directional information is naturally mapped to an appropriate sector on the torso and studies [8] have shown that an array of 8 tactors represents a reasonable compromise between resolution and accuracy. Typically sensor systems calculate and map the target waypoint location (with respect to the body axes) to the corresponding sector on the tactile belt. The user then turns to align to the waypoint, and the tactile cue moves to the front tactor to confirm the correct heading and orientation. Some information regarding the distance from the way point can be conveyed by modulating the pulse rate of the tactors (modulating faster when one is in close proximity to the target). Although tactile navigation has been shown to be useful [9], it is desirable to extend the capabilities of tactile displays beyond simple directional cueing and improve the overall effectiveness.

3 Tactile Array Displays

3.1 The Perception of Tactile Stimuli

There is a difference between feeling a stimulus, and being able to assign meaning to that sensation. The extension of tactile orientation cues to more advanced symbology is limited by the relatively narrow tactile channel bandwidth of the body [10]. Our model for the perception of tactile stimuli is shown in Figure 1.

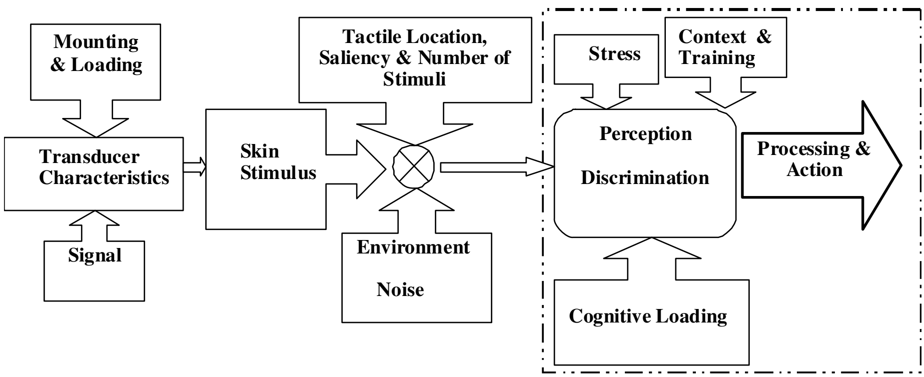

Fig. 1. Model for the perception of tactile stimuli – the transfer function of the transducer, environment, tactile stimuli, user workload, loading and task context all play a significant role in the tactile perception process

Actuators, especially light weight wearable transducers, are prone to loading and are seldom able to present wide-bandwidth vibratory signals when loaded against the skin. Therefore the first limitation in the tactile perception system is the vibrotactile actuator itself - the signal will be modified by the transfer function of the transducer. Perception of vibrotactile stimuli depend on body location, actuation area and the characteristics of the stimulus [11]. It is also known that attention influences sensory performance [12] and that distraction such as noise, masking from other vibratory sources and resource competition also potentially influence perception. Clearly ideal tactile display constructs should offer reliable and intuitively discernable cues within the intended application and environment.

3.2 Wearable Vibrotactile Transducers

Wearable vibrotactile transducers fall into two broad categories depending on their design and inertial reference [5]. The first is that of inertial shakers: A typical example would be the widely used eccentric mass motor or pager motor. The second category is that of a linear actuator which drives a contactor or moving element against the skin. In the inertial shaker, the rotation of the motor causes the housing to vibrate, stimulating the adjacent skin. However, this approach can be rendered ineffective through any additional mass loading, for example due to mounting.

Linear actuators such as Engineering Acoustics Inc's (EAI) C-2, C-3 and EMR tactors are shown in Figure 2. These tactors are configured such that when an electrical signal is applied, the "contactor" oscillates perpendicular to the skin, while the surrounding skin area is "shielded" with a passive housing. These linear actuator tactors provide a strong, point-like sensation that is easily felt and localized. In wearable systems, the overall mass of the actuator should be minimized. However, from a linear actuator transduction viewpoint, the mass of the housing is a "reaction mass" against which the contactor operates while displacing the skin load. Thus there is a careful tradeoff between contactor and housing dimensions and the actuator (housing and contactor) mass ratio's.

Fig. 2. The EAI C-2, C-3 and EMR vibrotactor transducers (left to right respectively)

Non-spatial tactile symbology includes modulating the operating frequency, amplitude, waveform, or temporal properties of a vibration signal. The skin comprises of a number of different types of mechanoreceptors that are sensitive to different frequency ranges and rates of adaptation [13]. Pacinian (PC) receptors have high vibration sensitivities and are perceived with a high degree of "urgency" and saliency. We have previously used mechanical resonances to improve vibrational performance in a linear motor design (C-2 and C-3 shown in Figure 2) optimized to the PC range (250 Hz). The EMR is a new motor based design with an operating frequency around 60-160 Hz. This design is able to produce a wide range of perceivable tactile features ranging from a strong "alert" (similar to the sensation of a C-3 or C-2), to a "soft" pressure pulse or "nudge". Control of the sensation parameters is via a complex mapping of the motor's drive voltage. Our explanation for this effect is that we believe that the vast majority of perceivable features (in short tactile pulses) are contained in the rise time, peak displacement amplitude, frequency and pulse envelope. Rapid turn-on pulse characteristics will result in a relatively broad Fourier spectrum, which will (depending on the pulse amplitudes and durations) excite PC type receptors as well as other mechanoreceptors, resulting in an "urgent" stimulus. Lower frequency stimuli produce sensations that are typically regarded as being less urgent provided the tactor turn-on characteristics are smooth or "gradual". Lower frequency vibration is part of the haptic environment and may therefore be regarded as being more "natural" but also more prone to being masked by environmental noise. Therefore we have designed the EMR to be capable of producing substantial peak displacements of up to 1.2 mm p-p (as measured against a phantom with the mechanical impedance of skin). In contrast, the C-2 (operating at 250 Hz) would typically only be driven to peak displacements of about 0.5 mm p-p owing to the relatively high PC channel displacement sensitivity.

3.3 Design Tools for Tactor Symbology

Structured tactile patterns can be used as messages where information is encoded into the signal by manipulating parameters of the vibration [14]. There are several signal parameters that can be modulated [15]. We have developed a tactor activation design abstraction approach and software tool termed "TActions" (tactile Actions). TActions are patterns or sequences of individual tactile stimuli (each of which has its own characteristics and properties). TActions can also have spatial relationships which can be easily assigned to reference a particular tactor in the array. TActions allow designers to easily create extremely complex patterns (with spatial and sequential pattern features).

Our software tool has two components; a design environment "TAction Writer" and a TAction management layer. The design environment provides a graphical environment for creating various tactor array geometries or "layouts" and an editing / configuration tool for designing multidimensional tactile patterns. The patterns can be created and saved as "TActions" which can also be reused. TActions can be assigned to application specific events or message contexts, providing a basis for developing common tactile symbology. Our overall design goal is that tactor display designers can use TAction library components and develop their own symbology that users can naturally associate with a particular function.

4 Orientation and Navigation Symbology

New capabilities in vibrotactile actuators and design tools facilitate more complex tactile symbology in orientation and navigation. For example, in navigation way-finding tasks a TAction can be used to indicate that the waypoint target has been reached, or in other implementations indicate the potential for different route options, i.e. convey a predetermined context sensitive message. Tactile messages require some aspects of training and must be carefully designed with properties that are clearly distinct so that they can be reliably separated from other messages and directional cueing information. Changing the tactile salient features together with time varying spatial and rhythmic pattern implementations has been previously found to be intuitive in conveying military hand signals [16]. Thus this extends the capabilities of tactile displays beyond simple directional cueing to one of mission support, improving overall effectiveness.

It is instructive (especially for emerging hand held navigation applications) to also consider approaches for minimizing the tactile display array size. Generally orientation requires a tactile display with a complete spatial representation to be effective while navigation only requires the presentation of spatial directional course cues. Therefore tactile displays can be reduced in application specific implementations.

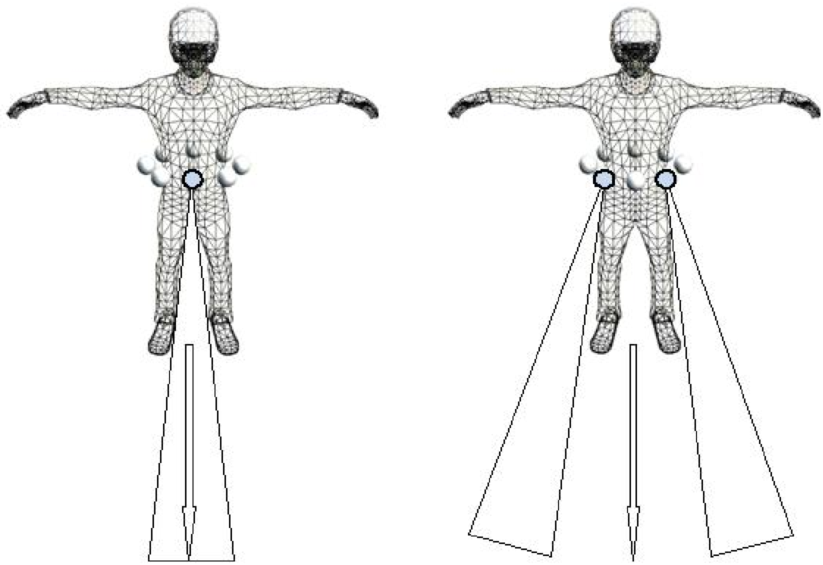

Fig. 3. Two distinct directional cueing for navigation modes that are possible with a torso worn tactile array; move to cue (left) and move away from cue (right). The arrow depicts the correct heading to the waypoint while the shaded circles represent an example of active tactors for each mode – as the user's orientation deviates from the heading either a new tactor sector is activated (move to cue), or a left or right error is activated (move away from cue).

Tactile spatial direction course cues can be either directional (move towards the cue) or, we can represent the information as an "error" (move away from the cue) as shown in Figure 3. In each case the tactor cue can be given proportional to the deviation from the course line (depending on the tactile symbology chosen). Both constructs have natural analogies; moving towards a cue is similar to tapping on a shoulder, while move away from a cue is similar to bumping into a real physical corridor barrier. Each approach has similar minimum array requirements but very different operating modalities; a directional course cue can be designed to be continuous i.e. the tactor pulse pattern is continuously firing, while a deviation cue is only presented if the course deviates beyond a threshold. The effectiveness of each implementation depends on training, multisensory display modalities and the confidence in the navigation system – continuous cues are beneficial in that there is a constant representation that the system is operating but there is also a risk for elements of change blindness [17].

Generally systems that are visually intensive (such as aviation) are better suited to navigation constructs that are error threshold based (move away from cue). This approach also allows multiple layers of information, such as threat or orientation, to be potentially represented on the tactile display (using the advanced tactor capabilities described previously). For example threats may be represented as a high priority, high frequency, high amplitude, pulse train stimulus. This is distinct from the navigation cues which may be lower priority, low frequency, slow rise time, high amplitude pulse train stimuli. Although these modes must be prioritized so as to prevent any simultaneous tactor mode displays, we successfully implemented this in TSAS (operators are able to easily act on the correct cue). Various solutions, including a hierarchy for the presentation of information such as threat, alerts, target, range, heading and navigation have been implemented using this approach.

Dismounted warfighter navigation applications are, in contrast, better suited to navigation constructs that are directional (move towards cue). With appropriate training, it is possible that a minimum of only three tactors are needed (center, left and right) for navigation – the navigation objective is to orientate and move such that the center tactor is activated. The salient characteristics ("urgency" and pulse repetition rate) can be modulated based on waypoint proximity. However, the restricted dimensions of the array and continuous navigation information will restrict the type and saliency of TAction message constructs.

5 Conclusions

Tactile displays present an intriguing and natural pathway for representing orientation and navigational information. However, there are several compromises in the system design and display interaction that must be carefully implemented (based on the specific requirements of a particular application). We have presented a simple model for understanding the effects of human factor and hardware on the perception of tactile cues. Our current research efforts are focused on optimizing tactor navigation systems that use each of the described tactile display modes. We have built a new range of tactile hardware and implemented software development tools that greatly increase the overall capability of system. In this work, we have illustrated how these capabilities can be used to design minimized tactile arrays for navigation. Future research will integrate multisensory information (especially visual) with tactile augmentation, and quantify the impact of different tactor array dimensions, and natural tactile symbology on task performance.

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