Augmenting spatial awareness with the Haptic Radar

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Abstract

We are developing a modular electronic device whose goal is to allow users to perceive and respond simultaneously to multiple spatial information sources using haptic stimulus. Each module of this wearable "haptic radar" acts as an artificial hair capable of sensing obstacles, measuring their range and transducing this information as a vibro-tactile cue on the skin directly beneath the module.

Our first prototype (a headband) provides the wearer with 360 degrees of spatial awareness thanks to height invisible, insect-like antennas. During a proof-of-principle experiment, a significant proportion (87%, p=$1.26 * 10^{-5}$*) of participants moved to avoid an unseen object approaching from behind without any previous training. Participants reported the system as more of a help, easy, and intuitive.*

Among the numerous applications of this interface are electronic travel aids and visual prosthetics for the blind, augmentation of spatial awareness in hazardous working environments, as well as enhanced obstacle awareness for motorcycle or car drivers (in this case the sensors may cover the surface of the car).

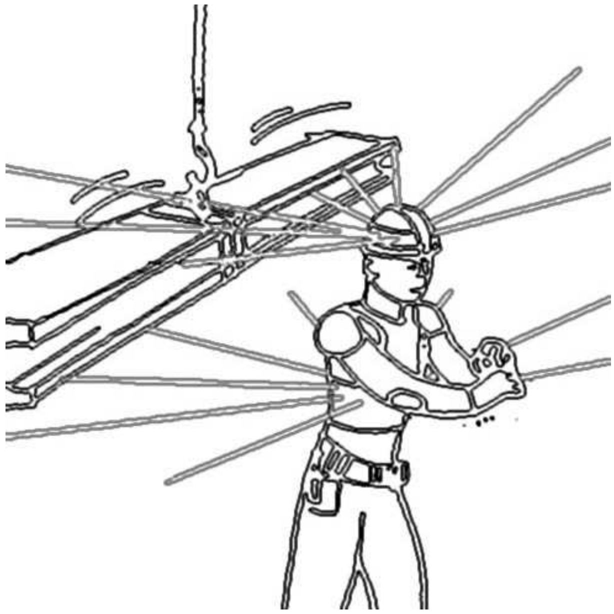

Figure 1. Augmented spatial awareness with an artificially extended skin.

1. Introduction

This project extends existing research on Electronic Travel Aids (ETAs) relying on tactile-visual sensory substitution (TVSS) for the visually impaired. Keeping things simple, we can say that two different paths have been explored in the past: one consist in extending the capabilities of the cane for the blind (using ultrasound or even laser rangefinders), and converting the sensed range-data to a convenient vibro-tactile cue on the hand wearing the device (see for example [18], [3]). The other approach uses the input from an imaging device to drive a two-dimensional haptic display (placed on the skin [9] or even on the tongue [2]). This approach benefits from the research on *reading aids* based on TVSS [16].

Each has its own advantages and disadvantages. For instance, the "image-mapped-to-the-skin" is very promising because it potentially provides the user with an extremely rich source of information. However, it may not be as efficient as it seems at first glance: although the brain has a certain degree of high-level cognitive cross-modal plasticity [14], people's withdrawal reflex reaction to a sudden skin stimuli will remain active. In other words, even a trained subject (able to "see with the skin") may not be capable of shutting down this somatic reflex arc. More importantly, since stereoscopic vision may be just impossible to achieve through this method, the approach does not provides any intuitive spatial (depth) cue.

On the other hand, the white-cane aid is extremely intuitive precisely because it is not really a sensorial-substitution approach: the cane only extends the reach of the user hand. But still, the traditional white cane (as well as more or less sophisticated ETAs based on the same "extension of the hand" paradigm such as the Laser Cane [3] or the MiniGuide ultrasonic aid [13]) only provides spatial awareness in the direction pointed by the device. The user must therefore actively scan the surrounding. This process is inherently sequential, and as a consequence global spatial awareness relies heavily on memory and on the user's ability to mentally reconstruct the surrounding, potentially overloading cognitive functions. The user must scan the environment as a sighted people would do with a flashlight in a dark room. The result is fragmented, poor spatial awareness with a very low temporal resolution or "tunnel vision". In certain cases this approach may be sufficient, for instance when tracking a signed path on the floor. Some researchers have proposed an interesting way to overcome this resource-consuming scanning by using an automated scanner and converting the temporal stream of range-data to a modulated audio wave [11], [4]. However, this is not an ideal solution, because (1) the user must be trained (a fair amount of time) to interpret sound-scape in order to "demultiplex" the temporal data into space cues, and (2) the device is (cognitively) obtrusive since it may distract people from naturally processing the audio input.

1.1. Spatially extended skin paradigm

The haptic-radar project intends filling the gap between the two different approaches described above, while trying to retain the most interesting aspects of each. This is realized thanks to the following paradigm:

- **Modularity (or parallelism)**. The system is composed of several identical modules, thus exploiting the input parallelism of the skin organ.

- **Range-to-tactile sensorial transduction**. Each module behaves as a "mini-cane" (or artificial hair or antenna) that translates depth-range information into a tactile cues right behind the sensor.

Actually, depending on the number and relative placement of the modules, this device can be seen as either an enhancement of the white cane approach (when just using a single module carried on the hand) or as a variation of the more classic "image on the skin" TVSS (when a large quantity of sensors are placed on the same skin region). It is a *variation* of the later approach, because instead of luminance-pixels what we have here are *depth*-pixels and besides the range data does not come from a unique 3D camera (or raster-scan laser rangefinder), but instead each measurement is independently performed at the module site. The user relies on spatial proprioception to give meaning to the tactile cues.

The proposed system is further enhanced with the following properties:

- **Module interaction and global stimulus**. Each module is able to produce a *local* stimulus directly related to the direction and proximity of the obstacle directly laying in its line of sight. However, modules can also communicate with their neighbors in a Manhattan grid network, enabling for the creation of more complex, post-processed *global* stimuli involving several modules at a time. The goal is to make the stimulation readily interpretable by either the user's low- or high-level cognitive functions, depending on the urgency of the situation;

- **Reconfigurability**. Finally, the system is physically reconfigurable: modules are placed at strategic positions on the body surface depending on the application targeted. The modules can densely cover precise skin regions, be distributed in a discrete manner, or span the entire body surface and function as a double skin with enhanced and tunable sensing capabilities.

The result is an artificial *spatially extended* skin provided with an elementary interconnection network and low-level parallel processing capabilities.

The driving intuition here is that tactile perception and spatial information are closely related in our cognitive system for evolutionary reasons: an analogy for our artificial sensory system in the animal world would be the cellular cilia, insect antennae, as well as the specialized sensory hairs of mammalian whiskers. There is evidence that insects can very rapidly use flagellar information to avoid collisions [6]. We then speculate that, at least for certain applications (such as clear path finding and collision avoidance), the utility and efficiency of this type of sensory substitution may be far greater than what what we can expect of more classical TVSS systems.

Optimal placement of the modules on the skin is of crucial importance. First, since each module is supposed to work as a miniature sensing cane, it is important that the module orientation remains consistent with its output. In the case of the ordinary cane for the blind, the user relies on body proprioception to learn about the hand/arm orientation; in the case of the proposed modular system, it is important that each module is placed in a meaningful, stable way over the body surface. One obvious way is to locate the modules on bands around the body, each module sustaining a more or less large "cone of awareness". However, other strategies are possible, for instance placing a very few modules all around the body at critical locations (places which may be fragile/delicate, such as the head or the joints - places where people would normally wear helmets and protections in dangerous situations).

Non-obtrusiveness is also of concern. The same question arises in classic visual-to-tactile systems, but there are quite a few skin regions (with more or less good spatial resolution sensitiveness) that can be readily used for our purposes. The skin of the head is a good choice because the skin does not moves a lot relatively to the skull - so that module stimulus gives the user a clear and consistent cue about the relative position of the object/obstacle.

2. Hardware Prototype (headband)

The prototype presented here is configured as a headband (Fig.2), which provides the wearer with 360 degrees of spatial awareness. Each module contains an infrared proximity sensor (SHARP GP2D12) with a maximum range of 80 cm (giving the user a relatively short sphere of awareness - everything at arm range). Vibro-tactile stimulation is achieved using cheap off-the-shelf miniature off-axis vibration motors, and tactile cues are created by simultaneously varying the amplitude and speed of the rotation, in direct proportion to the range-finder output.

An ATMEGA128 micro-controller addresses the modules sequentially, and information is read back on a PC for monitoring (using the Wiring/Processing environment [15]).The GP2D12 proximity sensors have a maximum sampling rate of about 5ms, so our interface is limited to a sampling rate of around 200Hz.

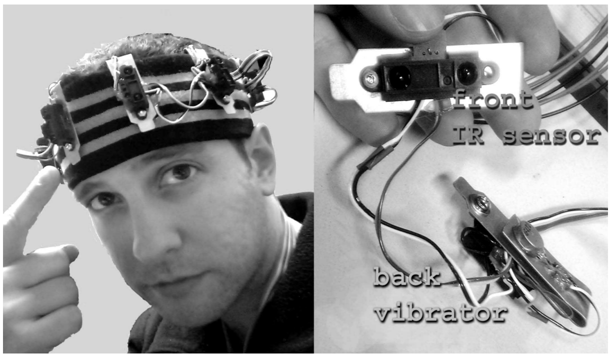

Figure 2. Headband haptic radar prototype

3. Proof-of-Principle Experiment

In a hazardous working environment such as a noisy construction site, one potential danger is being struck by an object that isn't seen or heard. Having constructed this prototype, we were interested in whether individuals could use it to avoid objects that they could not see.For a pilot experiment, we decided to roughly simulate this by measuring how well individuals avoided objects approaching from behind in a somewhat safer and more controlled environment. For that purpose, we reconfigured the system by arranging most of the headband modules towards the back of the head.

We hypothesized that participants using this Haptic Radar prototype could avoid an unseen object approaching from behind. The purpose of this proof-of-principle experiment was to asses the performance of haptic feedback provided on the skin directly beneath the range finding sensors. In this first experiment, we did not study if the stimulus provided by the system was more or less efficient at producing a startling reflex or a conscious response by the user.

Additionally, we wondered if participants who were not trained in how the Haptic Radar operates could intuitively avoid objects.

3.1. Participants

There were N=10 participants in our experiment. The participants were volunteers recruited from our laboratory. Participants were not randomly selected. However, the participants were not aware of the device and its purpose before the experiment.

The mean age of participants was 25.9 with a standard deviation of 4.51. With respect to gender 2 of 10 participants were female while 8 of 10 were male. All participants were Japanese individuals. All participants reported a college education. No reward was provided for participation. Instead we informally asked participants to help us with our research.

3.2. Apparatus

The experiment made use of a prototype system described above with 6 active modules at 30 degree increments roughly spanning 180 degrees along a flexible headband. The sensors were oriented along the back of the participant's head (situated in the region of the Parietal and Occipital skull bones). A simple Python program [1] was used to randomly determine which angles the stimulus would approach from. Two video cameras were used to film subject's responses to the stimulus.

A Styrofoam sphere approximately 12 centimeters in diameter impaled on a wooden rod approximately 1 meter long was used as the "unseen object." A blindfold (taken from an airline's complimentary flight kit) was used to ensure that participants would not be aware of the approaching stimulus. A 100 yen coin was used to randomly select task ordering. The experiment took place in a typical office equipped with a couch.

3.3. Design

The experiment consisted of two randomly ordered tasks. These tasks represented the independent variable. In the treatment task, participants used the Haptic Radar device. In contrast, during the control task the Haptic Radar device was switched off, but still worn.

As for the dependent variables we observed whether subjects moved or succeeded in avoiding the stimulus approaching from behind. Additionally, we collected Likert-scale questionnaire data regarding the system's usability and demographic data.

3.4. Procedure

Participants were first welcomed to the experiment. They were asked to seat themselves and make themselves comfortable. Participants were then told that "the purpose of the experiment will be to test a system for avoiding unseen objects." They were further told that their goal in the experiment "will be to avoid an object approaching from behind." Participants were verbally asked if they understood the instructions. If they did not, in some cases the instructions were informally translated into Japanese.

Figure 3. Avoiding an unseen object

Following this we flipped a coin to determine whether participants would perform the treatment or control task first. After noting the task ordering participants were handed a blindfold and asked to put it on. After the participant placed the blindfold over their eyes we would next place the Haptic Radar device on their head.

In the case that participants were assigned to perform the treatment task, we would then activate the Haptic Radar device. We then determined the ordering of the angles which the stimulus would be introduced from using a Python program. After noting the angles we moved the stimulus toward blindfolded participants' heads from each of the randomly-ordered angles (either 240, 270, and 300 degrees). The participants movement in response to the stimulus as well as their success in avoiding the stimulus was recorded.

In the case that participants were assigned to perform the control task the procedure was identical to the above, except that the Haptic Radar device was not activated. Having completed one task the process was repeated for the other condition.

Afterwards participants were asked to fill out a questionnaire. The questionnaire collected demographic information (age, gender, nationality, education) and asked participants on an 8-point Likert scale the following questions: "For avoiding the object the system is a: (Help...Hindrance)," "Using the system is: (Difficult...Easy)," "The system is: (Intuitive...Confusing)," "The system is: (Uncomfortable...Comfortable)." We also conducted very informal interviews to get a sense of participant's attitudes about the system and experience.

3.5. Results

In 26 out of 30 trails participants moved to avoid the object (Fig.3). A simple proportion test confirms that this is a significant proportion (p=$1.26 * 10^{-5}$). A Wilcox test comparing against a hypothetical even split of opinion found that participants viewed the system as more of a help (p=0.005), easy (p=0.005), and intuitive (p=0.005).

However opinions about the comfort of the system were more neutral with a mean of 5.2 and a standard deviation of 2.25 (where 1 is uncomfortable and 8 is comfortable). Although the majority (18 of 30) of trails resulted in the participant avoiding the object, this proportion is not significant.

3.6. Discussion

While the results are certainly promising it is healthy to view them with a certain degree of skepticism. Firstly, since the participants were non-randomly selected co-workers one might suspect an exaggerated desire not to provide negative feedback. Much of the questionnaire data should be viewed in this light.

It is also interesting to critically consider the effect of running an experiment with blindfolded participants. There is some evidence that visual processing dominates the processing of haptic data [8]. It would be interesting to compare the performance of participants when visual attention is occupied with the blindfolded participant's data.

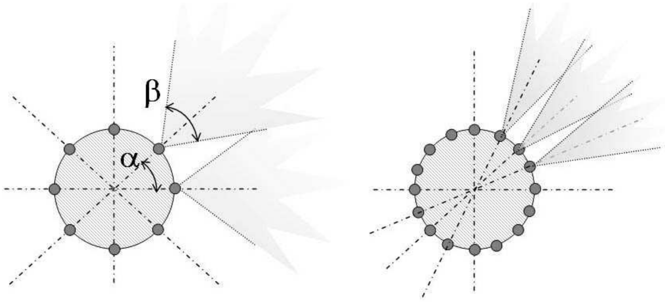

Figure 4. Reducing blind angles on the headband prototype

4. Conclusion

These results show that the Haptic Radar device can be successfully used to cause untrained users move in response to unseen objects approaching from behind. Video of Haptic Radar may be viewed at: http://www.k2.t.u-tokyo.ac.jp/fusion/HapticRadar/

5. Future Work

5.1. Hardware Improvements

We noticed that the current device suffers from blind angles between the modules, because the infrared sensors are too directive (small angular aperture β in Fig.4). This problem is easily overcome by increasing the number of modules around the headband (so as to decrease the angle α in Fig.4). However, if we want to keep a reduced number of modules, then ultrasound "PING" range detectors may be a more appropriate choice because each sensor will cover a larger field of view (roughly +/-20 deg). Eventually, combining extremely directive (infrared or even laser-based) sensors with ultrasound range-finders may be an ideal solution. A more thorough study of the ideal module density (taking into account the *successive spatial threshold* of the skin [17]) and ideal aperture of the cone of awareness for each module would be required to optimize the system depending on the application.

5.2. Place and nature of the skin stimulus

The nature of the stimulus is crucial to the correct production of an intuitive, easy to interpret spatial cue. It may be not enough to translate range data into intensity or frequency of the tactile stimulus, as done in the current experiment. As one participant pointed out in our questionnaire: "if the stimulus evolve in a continuous way, there is no startling effect and I don't feel the need to avoid the object". Inspired by the concept of tactile-icons or *tactons* [5], and the fact that the modules can communicate to each other, we are now thinking about the most efficient set of tactons capable of aptly representing structured and hierarchically ordered spatial information. For example, on the top of the hierarchy we would find a global stimulus relating to a measure of the crowdiness/emptiness of the surrounding (corresponding somehow to high-level cognitive states of claustrophobia/agoraphobia). This can be for instance a continuous, simultaneous low frequency buzzing of all the modules. Then, under such category we may place cues capable of generating a more region-specific yet fuzzy sense of presence (right/left, up/down) - and so on down to the finest spatial resolution possible (i.e the module cone of awareness). Compound tactons can be used to merge this information with data of a different nature, relating for instance to the obstacle's distance or looming speed, and even the obstacle's particular composition or proper rotating speed (it would be very useful to avoid small yet dangerous moving objects such as rotating wings of a fan for instance). Last, as pointed out in many works on ETAs, it is important not to overload the user with spatial information of objects too far away: a clear, startling stimulus may be produced by the device only when an obstacle comes closer to a (tuneable) safety radius.

To produce sufficiently complex tactile stimuli we need to replace the off-the-shelf motor vibrators (which have a large inertia, low response time, produce spurious noise and have relatively high power consumption) with more versatile actuators such as piezo-electric transducers or electrode arrays [12]. Another interesting thing to consider is the use of multi-point actuators attached to each module, indicating for instance the relative position of the object in a quadrant centered on the line of sight of the sensor. The actuator could even stretch the skin in the direction of the object motion, as if an invisible hair was being pulled by the object.

5.3. Miniaturization

In the near future, we may be able to create something like miniature MOEMS-based artificial hairs, and attach them directly to the skin or sew them to the clothes' fabric. The actual hair stem will be an invisible, unobtrusive, steerable laser beam that could even independently scan the surrounding to extract relevant information. Results in a similar direction have been already achieved in the framework of the smart laser scanner project in our own lab [7].

Eventually, this approach to range information can be applied to spaces at different scales and allow users to perceive other information such as texture, roughness, or temperature of objects far away. It is interesting to note here that a similar modular approach has been undertaken in the "SmartTouch" project [10] for augmentation of skin sensations through an artificial "optical skin receptor". Since the purpose is to *augment the touch*, the SmartTouch device is naturally shortsighted; instead, what we are proposing here is more akin to an artificial, *optical-based fur to augment global spatial awareness*. The Haptic Radar produce haptic sensation out of *range-measurements*. Both approaches are complimentary and in the future, the user should be able to tune her/his artificial hairs to the convenient detecting range.

5.4. Networked array of micro-modules

Interestingly, modules could be made to communicate with each other (even if they are situated in places far apart over the body surface) in other to create whole-body dynamic stimulus (such as waves on the skin to indicate the direction of the looming object), or even new haptic experiences such as "through the body" sensations by sequentially activating diametrally opposed actuators on the body (to represent directions, axis or edges of geometrical figures in augmented or virtual reality applications).

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