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A Vibrotactile Feedback User Interface for Haptic Teleoperation of Aerial Robots

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Abstract

Force feedback haptic teleoperation interfaces have recently been found to considerably improve operator performance in control of aerial robotic vehicles. Existing interfaces are based on kinesthetic principles and are limited in the information they can provide to the operator about the motion of the vehicle and the structure of the local environment. In this paper, we present a novel vibrotactile joystick interface for providing haptic feedback to communicate information about an UAV's flying environment to pilots and enable safe navigation through cluttered environments. Experiments on human perception of vibrotactile haptic cues were conducted to evaluate various vibrotactile stimuli and design an effective information modulation scheme. This modulation scheme was then utilised in user study experiments to assess the effectiveness of vibrotactile feedback in representing environments. The results demonstrated promising potential of the proposed vibrotactile joystick as an effective haptic interface to communicate environment information to pilots of aerial robots.

1 Introduction

Haptic feedback has been successfully adopted for teleoperation systems to promote human operators' performance in teleoperation tasks [Hannaford, 1989; Sheridan, 1989; 1993]. In contrast to the visual feedback of the conventional teleoperation system, which provides low resolution image and field of view from onboard camera [Aviles *et al.*, 1991], haptic feedback offers better perception of the remote environment and the dynamic states of the slave robot to the operator [Lawrence, 1993].

Haptic teleoperation of mobile robot systems was first considered in the late 1990s with the introduction of virtual environment impedance [Hong *et al.*, 1999]. Since then, several studies have been conducted to examine the effect of haptic feedback in aiding operators navigate mobile robots [Lee *et al.*, 2002]. A series of studies on obstacle avoidance of an UAV teleoperation system using haptic feedback was carried out in Delft university [Boschloo *et al.*, 2004; Lam *et al.*, 2006; 2009]. Optical flow based approaches have also been proposed for pilots to perceive the surrounding environment and achieve obstacle avoidance tasks. More recently, alternatives to the force-based obstacle avoidance approaches have been presented by Omari and Hou which haptically reproduce spatial information from the environment in the master joystick's workspace [Omari *et al.*, 2013; Hou and Mahony, 2013]. In addition to the feel of obstacle avoidance force or environment information, haptic feedback is also extended to provide pilots with the perception of the connectivity of multiple UAVs [Franchi *et al.*, 2012] and the dynamic states of the slave vehicle [Hou *et al.*, 2013]. Vibrotactile cues, distinct from kinesthetic cues, have also demonstrated promising potential to provide a pilot with addition perception of local flight environment in experimental studies undertaken in an airplane's cockpit environment [Raj *et al.*, 2000; Van Erp and Van Veen, 2004]. However, to the best of authors' knowledge, vibrotactile feedback has not yet been used in UAV teleoperation systems.

In this paper, we propose a novel vibrotactile haptic joystick interface to provide pilots with distinct haptic cues for warning of potential collisions and intuitive perception of the remote environment. Based on previous work on representing vehicle dynamic states in master haptic workspace, the proposed vibrotactile interface can be integrated into teleoperation system as a complementary sensory channel enabling multiple modalities, i.e. the vibrotactile cues augment environment information and kinesthetic cues associated with the vehicle states. A custom built joystick with an array of tactile actuators capable of providing vibrational feedback to users was designed and used in this paper to study the perception of the vibrotactile cues and its effects on pilots' environment awareness. Preliminary experiments on human perception of different tactile stimuli were carried out using vibration modulations of amplitude and frequency. Based on this, an 8-station vibrotactile joystick was built to represent directional information and a hybrid modulation scheme was designed to provide intensity information. The resulting user interface is capable of conveying 2D planar information about a robot's flying environment to pilots' fingertips. The effectiveness of the system was evaluated through user study experiments which indicated promise in the use of this haptic interface for environment representation.

The remainder of this paper has been structured as follows. A brief background of haptic science is discussed in Section 2, and followed by the tactile interface hardware design in Section 3. Experiments on human perception to different types of tactile cues guide the design of the modulation scheme discussed in Section 4. In Section 5, a set of user study experiments investigating how successfully people can perceive environments and the subsequent results are discussed. Section 7 concludes the paper.

2 Background

2.1 Haptic Science

Since the sense of touch was first proposed as a medium of communication by Geldard in the late 1950s, [Geldard, 1960] various psychophysics studies over the years have shown that the human haptic (touch-based) sense is one of the strongest in the body and is extremely viable information transfer [Loomis and Lederman, 1986]. In contrast to vision and hearing, it is also bi-directional in that it can support both perception from and response to the environment [Luk *et al.*, 2006]. The human haptic sense is divided into 3 sub-modalities; kinesthetic (force), vibrotactile (vibration) and thermal sensing (temperature).

The most commonly perceived is the kinesthetic sense which identifies forces, pressure and motion based stimuli from the environment. This is what humans feel when they simply touch, hold or drag objects [Smith, 1997]. The second type is the vibrotactile sense which recognizes vibration based stimuli in terms of frequency, amplitude and patterns. This is how humans can characterize the texture and roughness of a surface by rubbing across it [Biggs and Srinivasan, 2002]. The last submodality is that of thermal sensing using which humans perceive the temperature of the environment or an object. From user studies carried out in the late 1990s, [Biggs and Srinivasan, 2002] it was found that humans are capable of detecting static features with an indentation of 20μm while their tactile senses are most optimal when feeling vibrations at a frequency of 250Hz where an amplitude as small as 0.1μm can be distinguished. Apart from detecting such stimuli, humans can also respond to these stimuli within a reaction time of 70ms to 900ms using the same organs which have a capability of exerting forces up to 500N at resolutions lower than 0.5N highlighting their bi-directional capability [Jones and Sarter, 2008].

2.2 Tactile Modulation

A vibration cue can be characterized as a finite-time waveform signal that we shall term a *tacton*. While a vibration classically is an infinite time signal repeating endlessly, a tacton contains a finite packet of information lasting a finite period of time. A tacton has the same fundamental characteristics of a waveform; amplitude and frequency of vibration as well as a duty cycle if there are time periods with no vibration in between. These properties, when combined, contribute to a perceived intensity of a tacton. In order to use a tacton's intensity to represent the magnitude of a quantity, these properties can be modulated in various ways.

Frequency Scaling: A fundamental method to modulate tactile signals is to change their base carrier frequency by controlling the waveform frequency as a linear function of the magnitude being represented. The fact that humans have a vibration sensing range up to 1kHz with optimal perception at 250Hz means they perceive information through changing frequencies. Higher frequency vibration of an actuator at the same amplitude leads to higher linear velocity of the actuator during its vibration, and consequently higher energy impacts with the finger of the user when contact is made. Thus, higher frequency vibration is perceived as higher intensity actuation.

Amplitude Scaling: Similar to the case of frequency, changing the tactile waveform by controlling its amplitude as a linear function of the magnitude is possible. Higher amplitude vibration increases the energy of the contact of the vibrating actuator with a user's finger and is perceived by the user as a higher intensity actuation. It has been experimentally verified that humans cannot easily distinguish between changes in frequency or amplitude separately [Morley and Rowe, 1990]. That is, intuitively, a human is most sensitive to the energy of the impacts of the actuator with their finger than the amplitude or frequency of the actuator vibration. A consequence is that amplitude and frequency cannot be used as independent axes for modulating tactons to provide a user with information.

Amplitude Modulation: A more sophisticated approach to amplitude scaling is to use Amplitude Modulation (AM), that is, superimposing a sinusoid with a relatively low frequency modulation on top of the original sinusoid's high frequency carrier. This results in a complex signal with a different waveform shape, fre-

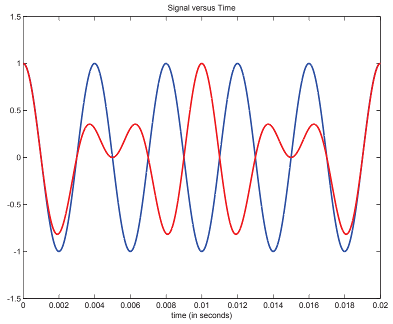

Figure 1: Pure (blue) and AM (red) sinusoidal tactons

quency and amplitude. Figure 1 is an illustration of a 250Hz sinusoid modulated with a 50Hz signal (red) in comparison to a pure 250Hz sinusoid (blue). Amplitude is remarkably effective in conveying information to a user and changes in Amplitude Modulation are perceived as changes in vibration roughness by humans [Brown *et al.*, 2005].

3 Tactile Joystick Hardware

To evaluate operators' perception of vibrotactile cues and validate the application of the tactile feedback interface, an end effector joystick was designed within the Computer Vision and Robotics Group at the Australian National University. The vibrotactile interface developed for the UAV teleoperation is a handheld joystick with an array of embedded piezoelectric bending actuators as shown in Figure 2. The user rests their fingertips on the surface of the actuators whose vibrations can be modulated and controlled as desired. The tactile array consists of 8 spatially distributed actuators corresponding to planar directions and each actuator's vibration represents the intensity of information. The piezoelectric actuators chosen have a resonant frequency of 275Hz close to humans' optimal sensation frequency of 250Hz and their vibration amplitude is sufficiently large, 315μm [PiezoSystems, 2013], to be easily perceived by the human operator.

4 Tactile Modulation Schemes

On our 2D tactile array, information containing both intensity magnitudes and directions can be represented so a modulation scheme for intensity and a mapping scheme for direction are necessary. In order to understand how humans perceive the different types of modulation and guide the design of information representation schemes, a set of user studies were carried out using our vibrotactile interface.

The subjects for these experiments were students from the Australian National University, belonging to an age group of 18 to 27 years. A mixed distribution of male and female subjects as well as right and left handed subjects were obtained. In general, the test subjects had general knowledge about tactile feedback, having used video-game joysticks, but none had prior experience with flying UAVs and had equal physical capability in using our interface. While the majority of students had an engineering background, some non-technical subjects were also sought. This meant our subjects were able to understand how information like direction and velocity would be useful to perceive but started with equal footing in the ability to use our vibrotactile interface.

Figure 2: Tactile Joystick Interface

4.1 Intensity Modulation

Through this experiment, the 3 different types of modulation discussed in Section 2.2 were compared for representing information changing both uniformly and randomly and the most suitable cues chosen for use in a modulation scheme. The 3 different modulations were tested across a range of intensity levels in order to identify how sensitive humans are in picking up changes of both uniform and random nature. In order to compare the 3 different types of modulation, a full factorial experimental study, using a cohort of 6 subjects, was used. Each subject was presented with a set of vibration signals at their fingertips. The vibration signals switched between the particular types of modulation signals with either uni-directional or randomized changes of intensities depending on the experiment. The range of frequency scaling tested was between 100Hz to 500Hz with unit steps of 100Hz while amplitude scaling ranged from 10% to 100% of peak amplitude at the resonant frequency of 275Hz with unit steps of 20%. The Amplitude Modulation frequency was changed within a range of 0Hz to 60Hz in unit steps of 20Hz while the carrier frequency was fixed at 275Hz, the resonant frequency of the hardware. In order to eliminate a conditioning and learning bias with the hardware, each subject was tested in a randomised order of modulations. Further, each subject also used ear-muffs during the experiment to block the audio they might sense due to the vibration of actuators in free air.

Table 1 shows the perception rate of humans in identifying uni-directional gradual changes in the vibration. The signals in this experimental set changed intensity in unit steps in either increasing or decreasing manner. It is observed from this data that amplitude scaling is the most perceptible medium for humans to sense gradual changes in the vibration intensity. However, the difference between frequency scaling and amplitude scaling is statistically negligible and both modulation schemes provide effective uni-directional stimulus.

Table 1: Perception rate of uni-directional changes

	Frequency Scaling	Amplitude Scaling	Amplitude Modulation
Range	100-500Hz	10-100%	0-60Hz
Change	±100Hz	±20%	±20Hz
Perception	90.6%	96.9%	79.7%
Uncertainty	±18.6%	±8.8%	±9.3%

Table 2 shows the perception rate of humans in identifying random changes with varying intensities in the vibration. This data suggests that Amplitude Modulation (AM) is the most effective modulation for humans to sense large random changes in the vibration intensity. It is interesting to note the important role the additional perceptual context of the "roughness" of the AM modulated signal plays in providing absolute information on a tactile stimulus. The relative intensity of the impacts in both frequency and amplitude scaling still provide reasonable absolute information on stimulus intensity in the particular experimental conditions. These two experiments also demonstrate a well known property of human perception that comparing relative intensity (ie. uni-directional changes) of a stimulus is easier than determining absolute intensities (ie. random changes).

Table 2: Perception rate of random changes

	Frequency Scaling	Amplitude Scaling	Amplitude Modulation
Perception	87.5%	80.6%	93.1%
Uncertainty	±18.9%	±11.5%	±8.3%

4.2 Design and Evaluation of a Modulation Scheme

Real-life data and information from UAV flight is likely to contain a mix of both random as well as gradual changes at different times and it is desirable that both types of information be represented effectively. Based on the outcomes of the experiment discussed in Section 4.1, we will propose a tacton that combines aspects of amplitude scaling and amplitude modulation. Frequency scaling has a very similar perceptual effect as amplitude scaling and is not considered. This has the additional advantage that the carrier frequency of the tacton can be tailored to the resonant frequency of the hardware, maximising the energy efficiency of the system.

We propose a hybrid amplitude scaling and amplitude modulation tacton signal as shown in Figure 3. By combining the two stimuli we believe we can encode ten separate levels of intensity rather than the five levels that were possible with a single tacton modulation described in Section 4.1. In practice, these ten levels of intensity will be mapped to information representation from the 2D environment of the robot as discussed in Section 5

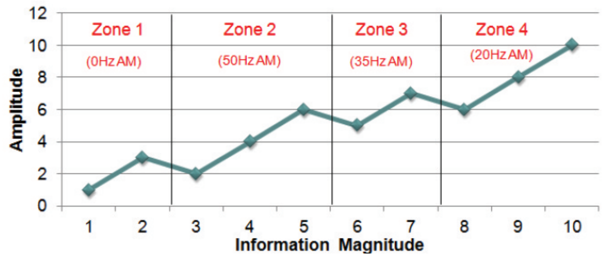

Figure 3: Hybrid Intensity Modulation Scheme: The bottom axis indicates intensity level of the signal that is desired to be represented to the user. The left axis indicates the magnitude of the amplitude scaling, while the four zones correspond to increasing perception of roughness (decreasing frequency of modulation signal) of the stimulus. Note that very low frequency amplitude modulation is perceived as no modulation, hence, the 0Hz modulation is perceived as the lowest roughness, while the next smoothest (least rough) stimulus has the modulation frequency of 50Hz, decreasing to 20Hz with increasing roughness.

In order to verify the performance of the hybrid modulation scheme a second comparison user experiment was performed. To provide a comparison, we implemented a simple amplitude scaling modulation scheme. The authors believe that there is already sufficient evidence to show that a frequency modulation scheme would not provide any additional resolution than is provided by amplitude scaling, and since there is a significant advantage associated with running the tactor hardware at its natural resonant frequency, this modulation was not considered in this experiment. A simple amplitude modulation scheme is incapable of representing all ten levels of signal intensity and was not included in this comparative experiment either.

In this experiment, subjects were given eleven different vibration signals over three minutes on their fingertips. These signals consisted of both gradual uni-directional as well as random changes in the nature of the signal to reflect realistic information. The subjects were asked to identify the number of total changes they perceived on their fingertips across the length of the test with each modulation scheme. The experimental results obtained were as shown in Table 3.

Table 3: Comparison of modulation scheme performance

	Amplitude Scaling	Hybrid Modulation
Success Rate (/10)	6.3	8.2
Standard Deviation	±3	±1.7

Using the 1-tailed student's T-test, it was inferred from the experiment that the hybrid modulation scheme is more effective than a single amplitude scaling scheme with a confidence interval of 93%. The average success rate using amplitude scaling was more than 1 standard deviation below that of the hybrid modulation indicating a significant performance difference. Hence, the hybrid modulation scheme is suitable for representing combinations of uniform and random information changes and this scheme is implemented in our vibrotactile interface.

4.3 Direction Mapping

While the intensity modulation scheme represents magnitude of information, a cylindrical tactile array can be used to represent directional information. A desirable characteristic of our joystick hardware is that it should be easily gripped by hand. The design of a cylindrical handle for the users' fingers to wrap around (Figure 2) allows the integration of cylindrical tactile array of tactors. The array of 8 tactors has been designed so that the 8 major directions in a compass can be represented if each tactor is mapped to a direction as shown in Figure 4. The number of tactors was physically limited by the hardware design and necessary size of the piezo actuators.

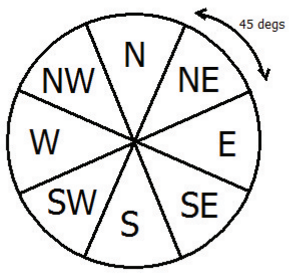

Figure 4: Physical mapping of directions across tactors

There were 2 potential mapping schemes proposed to represent directions across the tactile display. The simplest case was a direct mapping where each individual tactor corresponds to a particular direction. The second scheme was a Gaussian distribution mapping where a series of 3 tactors were used to represent a Gaussian vibration intensity distribution across them. The hope was that by using a distributed intensity profile across multiple tactors, we would be able to represent direction information with higher acuity than just the physical limitations of the hardware.

This user study experiment compared the two mapping schemes to identify which one could help users identify direction with higher accuracy and resolution. Each subject was given a sequence of stimuli randomly varying between any of 32 directions across a 360 degree range, all of the same intensity, and asked to identify their perceived direction in each mapping scheme. The order of mapping scheme was swapped with different subjects to eliminate the conditioning bias. After sensing the vibration, users had to point to a position on a compass which they felt was the perceived direction. In this experiment, users were also asked to state if they felt uncertain about a sensation so that their confidence could also be assessed. The results from this experiment were as shown in Table 4.

Table 4: Comparison of direction mapping performance

	Direct Mapping	Gaussian Distribution
Success Rate	93.4%	25.9%
Uncertainty	4.4%	28.6%

It was observed from the experiment that the direct mapping scheme was significantly better than the Gaussian Pulse mapping. The uncertainty level of the users was nearly seven times higher with the Gaussian mapping and the users' feedback attributed this to a reason that using multiple actuators to represent a direction was non-intuitive. Users found it difficult to judge the varying intensity distribution across the three tactors which led to confusion and a subsequent loss of directional perception. The conclusion is that the only eight directions can be effectively represented using the proposed modulation schemes that we have investigated. This will form the foundation of the experiments discussed later in the paper.

5 Rendering Environment Information

Following the establishment of information modulation schemes for the developed hardware, two user studies were undertaken to evaluate the relative performance of the tactile joystick in tactile rendering environment information. The first concerned the representation of vector information. The second experiment concerned the representation of local environment information, and the ability of the operator to distinguish in a natural manner between different local environments.

It was found during trial experiments that training the subjects with some tactile stimuli beforehand helped them learn to perceive information with more ease and success. Hence, prior to both experiments, a standardised set of training sequences were provided to subjects. For the vector perception experiment, users were given directions in Noth, East, South-West and North-West at maximum intensity. For the environment representation experiment, subjects were shown what a wall, square room, circular room and corridor would each feel like.

5.1 Perception of vector information

Vector quantities indicate direction along with a magnitude. Typical signals of interest for mobile robotics applications would be velocities, range and bearing to a target or an obstacle, etc.

We propose to encode vector information by mapping bearing to the closest tactor in the corresponding direction in cylindrical array and magnitude of the range is mapped, either linearly or on a logarithm scale, to the ten intensity levels we have proposed. The subjects in the user study were asked to identify both the direction and the intensity of vibration. Prior to commencing the test, the subjects are given a training set of vibrations on a single tactor for them to gain an intuition of what the different vibration intensity levels feel like. During the test, the subjects can feel a vibration for a period of 5 seconds following which they are asked to state their perceived direction from an 8-directional compass and whether the perceived magnitude falls under a Low, Medium or High zone. There are 32 such vibration sets in an experiment and from observing 12 user subjects, the results in Table 5 were obtained.

Table 5: Vector Perception Experimental Results

	Direction	Intensity Zone	Combined Vector
Success Rate	92.8%	70.3%	67.2%
Uncertainty	±7.3%	±11.2%	±11.8%

It was observed from the experiment that users were highly accurate in identifying the correct direction of information but found it tougher to judge the right intensity of the vibration.

5.2 Perception of 2D environments

Quantities that represent magnitudes in a particular direction can be represented using a single tactor (tactile actuator) by modulating the intensity of tacton. With the tactile array developed, it is possible to represent cylindrical field of information, at least to the resolution allowed by the hardware. In this case, a scalar intensity pertaining to each particular tactor's directional orientation is rendered, and all the 8 tactors will be active at all times. Examples of information that is of interest to mobile robotics applications include representing obstacle avoidance fields such as distance-to-environment or Time-To-Impact information.

In this experiment, scalar field data is used to communicate a potential field map of obstacles such that a representation of the 2-dimensional environment around a robot is rendered. Obstacles in a particular direction in the environment are assigned an intensity based on inverse range and mapped to the intensity of the corresponding tacton. That is close obstacles in the environment are mapped to high intensity levels while direction in which the environment is distant are mapped to low intensity. User study subjects were once again given a training set of information so that they could develop an intuition of how this mode feels like.

During the experiment, the subjects had ten seconds to perceive a given scalar field and were given a multiple-choice question where they had to identify what the scalar field looked most like. Sixteen such scalar fields were tested and some of the environments were as shown in the sample question in Figure 5. Based on the twelve users observed in this study, their success rate in identifying the correct 2D environment was measured to be 67.7% ± 11.8%.

Table 6: Environment Perception Experimental Results

	Success Rate	Uncertainty
Perception	67.7%	±11.8%

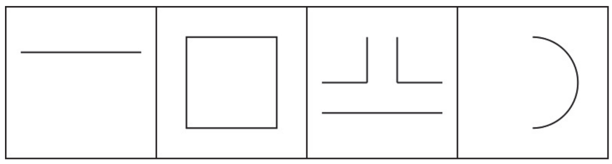

Figure 5: Sample 2D environments for user studies: From left to right, a flat wall ahead, a square room, a corridor with an opening, a curved wall on the side

6 Discussion

The goal of the user study experiments with the vibrotactile joystick was to ascertain how effective the interface could be in communicating information to help pilots navigate an aerial robot. The overall observation from both the vector and environment perception experiments is that users are able to perceive 2 out of

3 information signals (67%) accurately using the current interface. Identification of directions is strong with success rates in excess of 90% and errors in judgement mainly stem from perceiving the intensity of information incorrectly. These results point to the possibility that pilots can perceive coarse directional information without finer details about magnitudes. For example, with vector-guided navigation, pilots would be able to navigate their robot in the correct direction but may not be able to accurately judge their velocity in that direction.

Upon closer observation of the data from the 2D environment perception experiment, it was found that users were largely successful in identifying higher-level information about the flying environment using directional information in the scalar fields. This was seen in examples where users could easily distinguish between different environments like a room, narrow corridor or crossroad. It was further observed that users' major errors stemmed from situations where they had to identify finer-level information about the environment using the intensity information in the scalar fields. For example, users found it difficult to distinguish a square room from a circular room or identify a door in a corridor since these environments share similar directional information but the intensity information subtly changes. However, the initial success rate and the ability of users to identify high-level environmental information is an encouraging result considering this is the first time such an environment representation task has been attempted with vibrotactile feedback.

Moreover, it is evident that a training effect is present when the user learn how to use the vibrotactile interface over time. Hence, with sufficient training provided prior to using the interface, it can be expected that users' success rate in perceiving information will improve with time and experience.

A clear direction for improvement is in the intensity modulation scheme to help users identify finer-level information in the environment easier. User feedback from the experiments was that it was easier for them to compare the intensities of two tactons rather than being given an arbitrary tacton and being asked to evaluate its absolute intensity. This relates to the fact that humans tend to find comparison of information more intuitive than identification and explains how some users were confused between Medium and High intensity zones. It was also inferred from the experiments that if the intensity cues are starkly distinguishable, users would be able to identify the intensity level more confidently and perceive finer-level information about the 2D environments. A possible way to achieve this could be to reduce the number of intensity levels currently used from 10 to about 5 such that the modulation difference between each level is large enough to be quickly sensed.

In summary, the user study results indicate that it is possible to successfully represent and communicate an UAV's environment to pilots using vibrotactile feedback on their fingertips. Further work can improve the accuracy of finer-level information representation and there is significant promise for the use of haptic feedback for teleoperation of robots.

7 Conclusion and Future Work

In this paper, we have presented a vibrotactile feedback interface capable of communicating various types of information to pilots for teleoperation of aerial robotic systems. User studies provide strong support that the vibro-tactile interface developed is capable of rendering both directional information and distributed scalar fields that encode environment range information of aerial robots. Considering that the authors are unaware of any other system of similar capability the initial results are highly encouraging.

In order to evaluate the efficacy of the haptic interface, future work will involve further studies with subjects using the system to fly aerial robots and UAVs. Given the tactile stimuli have been tailored for representing information particular to flying vehicles, this would be a promising direction.

Acknowledgments

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