

# The Perceptual Effects of Altered Gravity on Tactile Displays

Topic area: Life Sciences

*A proposal for the Fall 2000 NASA Reduced Gravity Student Flight Opportunities Program*



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**Haptic  
Interface  
Research  
Laboratory**

## **Abstract**

Spatial disorientation (SD), the incorrect perception of attitude, altitude, or motion of one's own body, aircraft, or spacecraft, is a major problem facing military aviators and NASA astronauts. This problem costs the Department of Defense \$300 million per year in lost aircraft and can cause astronauts to have motion sickness during shuttle missions. This project examines possible ways of increasing situational awareness. Specifically, it will examine how vibrotactile intensity is perceived in altered gravity environments. The experiment will build upon a previous experiment flown in August 1999. Results of this project should be of interest throughout the aerospace community. Tactile displays could provide better orientation awareness for astronauts during EVAs (Extra-Vehicular Activities), navigational cues to Special Forces operators during HALO (High-Altitude Low-Opening) parachute insertions, and silent communication for military units on the ground and in the water. Additionally, tactile technology could be used for navigational assistance for the blind by using a Global Positioning System (GPS) and an electronic map stored on a wearable computer.

**Table of Contents**

**ABSTRACT .....2**

**BACKGROUND AND MOTIVATION .....5**

    HISTORY OF SPATIAL DISORIENTATION.....6

    SENSORY SALTATION .....8

    CURRENT RESEARCH.....10

*Massachusetts Institute of Technology* .....10

*NAMRL*.....11

*Princeton University*.....12

    APPLICATIONS.....13

**TEST OBJECTIVES.....13**

**TEST DESCRIPTION .....14**

    PREFLIGHT TESTING PROCEDURES .....14

    IN FLIGHT TESTING PROCEDURES .....14

    IN FLIGHT TEST CASE EXAMPLE .....15

**EQUIPMENT DESCRIPTION.....15**

    OVERVIEW .....15

    CONTROL BOX .....16

    SIGNAL GENERATION AND WAVEFORM SAMPLING.....16

    TACTOR DRIVER CIRCUIT.....17

    TACTILE DISPLAY .....17

**STRUCTURAL LOAD ANALYSIS .....18**

    ASSUMPTIONS .....18

    ANALYSIS.....18

    CONCLUSION .....20

**ELECTRICAL LOAD ANALYSIS .....20**

**PRESSURE VESSEL CERTIFICATION.....20**

**IN-FLIGHT TEST PROCEDURES (CHECK LIST).....20**

    INITIAL SETUP .....20

    TESTING .....20

    TEST CONCLUSION .....21

**PARABOLA REQUIREMENTS, NUMBER, AND SEQUENCING .....21**

**TEST SUPPORT REQUIREMENTS, GROUND AND FLIGHT .....21**

**DATA ACQUISITION SYSTEM .....21**

**TEST OPERATING LIMITS .....22**

**PROPOSED MANIFEST FOR EACH FLIGHT .....22**

**PHOTOGRAPHIC REQUIREMENTS .....22**

**HAZARD ANALYSIS.....22**

**SAFETY CERTIFICATION.....23**

**OUTREACH PROGRAM.....23**

    ELEMENTARY SCHOOL.....23

    MIDDLE SCHOOL.....23

    HIGH SCHOOL.....23

    UNDERGRADUATE.....24

    MUSEUMS.....24

**PARTICIPANT INFORMATION FORMS.....24**

**OFFICIAL VERIFICATIONS.....25**

**HUMAN RESEARCH CONSENT FORMS.....25**

**PUBLICITY.....25**

**ADDITIONAL SUPPORT.....25**

**REFERENCES.....27**

**APPENDIX A.....29**

**APPENDIX B.....30**

**APPENDIX C.....31**

**APPENDIX D.....32**

**ABOUT US.....33**

    RYAN CASTEEL.....33

    RYAN TRAYLOR.....33

    ADRIAN LIM.....33

    DANIEL HROMIS.....33

    LAUREN NAESSENS.....33

**ACADEMIC ADVISOR PROFILE.....34**

## Background and Motivation

Spatial disorientation (SD) is the incorrect perception of attitude, altitude, or motion of one's own aircraft relative to the earth or other significant objects. It is a tri-service aviation problem that annually costs the Department of Defense in excess of \$300 million in lost aircraft. Spatial disorientation is the number one cause of pilot related mishaps in the Navy and the Air Force. The typical SD mishap occurs when the visual system is compromised by temporary distractions, increased workload, reduced visibility, and most commonly, g-lock, which occurs when the pilot undergoes a high-g maneuver and temporarily blacks out behind the stick [16]. Frequently, after pilots recover from the distraction, they rely on instinct rather than the instrument panel to fly the aircraft. Often, the orientation of the aircraft as perceived by the pilot is much different than the actual orientation of the aircraft and disaster strikes.

Last summer, our Purdue University Electrical Engineering Flight Team proposed a solution to spatial disorientation using a tactile feedback system to enhance spatial awareness. The system utilized a phenomenon called sensory saltation to stimulate the feeling of someone drawing directional lines on the user's back. Specifically, the project examined how the sense of touch can be engaged in a natural and intuitive manner to allow for correct perception of position, motion and acceleration of one's body in altered gravity environments. The system consisted of a 3x3 array of tactors sewn into a vest. The goal of the experiment was to examine how accurately the users (those wearing the vest) perceived four different directional signals (left, right, up, down) based on sensory saltation.

The results of the previous flight were inconclusive. Data was collected on forty-one (41) parabolas during two flights. During the periods of microgravity, the signals felt considerably weaker to the two test subjects as compared to the sensations felt during normal 1-g conditions. User success rate at determining the correct *direction* of the signal sent was approximately 44% in zero gravity, as compared to a success rate of nearly 100% in a normal 1-g environment [24].

The low user success rate may be due to a number of factors. Firstly, the dynamics of the tactors might have changed during the periods of microgravity. Secondly, perceptual threshold for tactual events might have increased during periods of microgravity, thereby requiring more intense signals to be delivered, especially since the system was tested on the back. Thirdly, the test subjects might have been distracted by the novel experience of *flying* in microgravity, and therefore were unable to devote the cognitive attention required to perceive the vibrotactile patterns on their backs. Finally, the sensory saltation illusion might have manifested itself differently in microgravity.

This project is specifically designed to address the first two issues, the dynamics of the tactors and the perceived intensity of the tactors in altered gravity environments. To investigate whether the tactors are able to deliver the same vibrational amplitude in microgravity as in a 1-g environment, new data collection circuitry has been designed and constructed. Data from accelerometers placed on the tactors will record the vibrational amplitude patterns while aboard the KC-135. To investigate whether perceptual threshold is altered in microgravity, a new psychophysical procedure has been developed that allows us to collect data on the perceived magnitude of vibration using the method of magnitude estimation. This study is important

because very little work has been conducted to examine whether tactual perception is altered in microgravity. During typical testing periods, pilots wearing tactile devices *expect* to be disoriented—they have experienced disorientation before. However, pilots or astronauts that experience spatial disorientation may panic because of the possible risk of death, and as a result, they may perceive factor intensity differently. The KC-135 provides an ideal environment for testing this phenomenon, especially for first-time flyers.

To show the growing importance of solving the problem of spatial disorientation, a detailed history of spatial disorientation is followed by a discussion of sensory saltation, current research, and the applications that can result from this project.

### ***History of Spatial Disorientation***

Spatial disorientation and situational awareness (SA) issues were recognized when man began flying more sophisticated aircraft, particularly during the Vietnam War. Early solutions to the SA/SD problem focused on better visual displays. Early medical research proved that SA and SD were directly influenced by the interrelationships of vision, vestibular (inner ear), and somatosensory (skin, joint, muscle) sensors [15].

Spatial disorientation occurs due to the incorrect perception of attitude, altitude, or motion of one's own body, aircraft, or spacecraft. The human vestibular system and somatosensory system work reliably while on earth, yet these internal systems can be rendered unreliable quite easily once in flight. Because human balance and orientation systems evolved in a 1-g environment, moderate aircraft maneuvers can stimulate these systems to provide a false orientation [2].

The three basic types of spatial disorientation are unrecognized SD, recognized SD, and incapacitating/uncontrollable SD. Unrecognized spatial disorientation is the most dangerous and causes the most fatalities. Because the pilot is unaware of his disorientation, he cannot correctly control the aircraft. Recognized spatial disorientation happens when a pilot believes he is receiving incorrect readings from his flight instruments. In this situation, the pilot does not always realize he is experiencing SD, but knows he has a problem controlling his aircraft. This results in fatalities less often than the first type because the pilot is more aware of his incorrect perceptions. Incapacitating or uncontrollable spatial disorientation is the least common type, and in this case, the pilot knows he is experiencing SD but is unable to do anything about it [2].

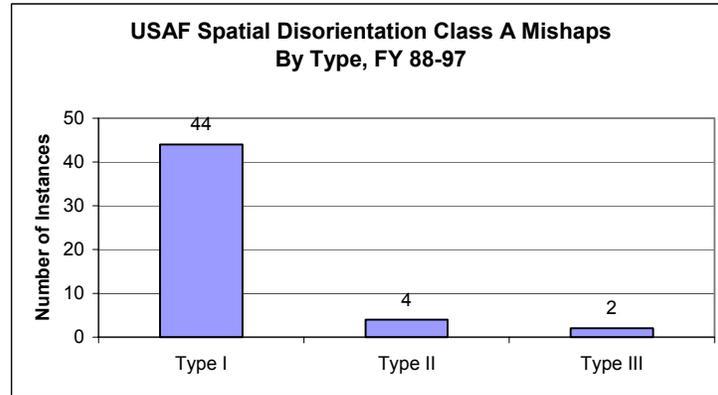


Figure 1 Number of incidents of each type from 1988 – 1997 [2].

As aviation technology advanced, spatial disorientation became more of a problem. The Navy reported that from 1980-89, disorientation was listed as the definite cause of accidents that resulted in the loss of 38 lives and 32 aircraft. During Desert Storm, 50 % of the single pilot aircraft mishaps and helicopter non-combat mishaps were due to spatial disorientation [13]. From 1988 to 1997, the Air Force reported 50 Class A mishaps directly attributable to spatial disorientation [2]. General Rufus DeHart, a Command Surgeon in the USAF Tactical Air Command (TAC), has reported that "the most significant human-factors (HF) problem facing the TAC today is spatial disorientation (SD), followed by high-G loss of consciousness. Of all HF mishaps, 30% in the F-16 and 19% in the F-15 and F-4 are due to SD [1]."

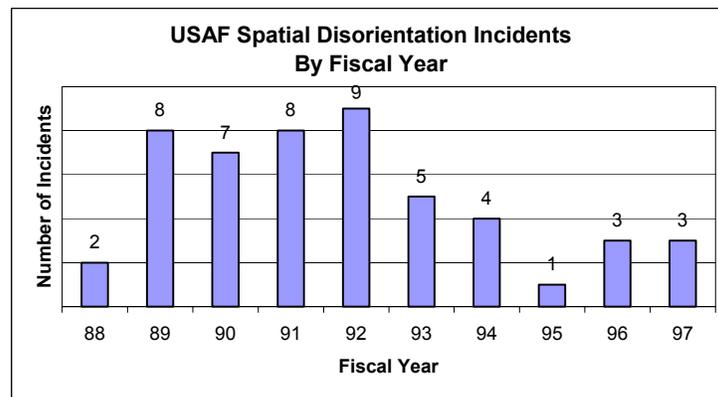


Figure 2. Number of Spatial Disorientation Incidents From 1988 – 1997 [15].

Spatial disorientation is a world wide problem. Currently, the U.S. military loses roughly 20 aircraft and 20 officers per year as a result of spatial disorientation mishaps, resulting in a loss of over \$3,000,000 each year. Additionally, the Federal Aviation Administration reports that SD is a cause or factor in 16% of fatal general aviation accidents. Other countries have had similar problems. The Royal Air Force reports that 15% of its helicopter accidents and 33% of its helicopter fatalities result from SD. The Dutch military has lost nearly 10 aircraft in the last 10 years from SD-related mishaps. Canada has lost six CF-18's because of spatial disorientation [15].

Spatial disorientation has been a continuing problem for NASA as well. During the days of the Mercury, Gemini, and Apollo missions, space sickness was not a major issue since astronauts were relatively immobile in these smaller spacecraft. However, aboard the larger Skylab and Shuttle, astronauts began to leave their seats to perform experiments inside and to conduct EVAs outside. These activities occurred in visually unfamiliar environments and astronauts began to experience conflicting cues from their eyes and ears while working “upside down,” viewing another crew member upside down, and assuming that the floor was beneath their feet. Dr. Charles Oman of MIT’s Man-Vehicle Laboratory explains that “in the spacecraft, the walls, ceiling, and floors frequently exchanged subjective identities [21].”

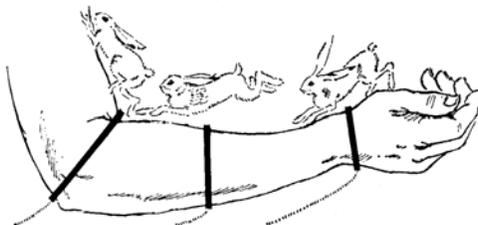
Space sickness quickly became a well-publicized problem as astronauts continued to report occasional disorientation in zero-gravity [21]. The multi-institutional Neurovestibular Adaptation Integrated Research Team explains that “the human balance system has evolved to take advantage of Earth's gravity cues coming from the vestibular organs of the inner ear. When the downward reference provided by gravity is missing, about two thirds of astronauts and cosmonauts experience disorientation and space motion sickness [18]. “

The role of vision with respect to orientation in zero gravity continues to be a major concern for NASA astronauts. Visual orientation also caused problems for astronauts and cosmonauts aboard MIR as they traversed its perpendicularly connected modules. As absolute visual frames of reference changed from module to module, astronauts found that it took a while to visualize the three-dimensional relationship among the modules and to move about in a natural and instinctive manner [21].

One method used to solve the problem of spatial disorientation has been sensory saltation, which is exactly what our team tested aboard the KC-135A in August 1999.

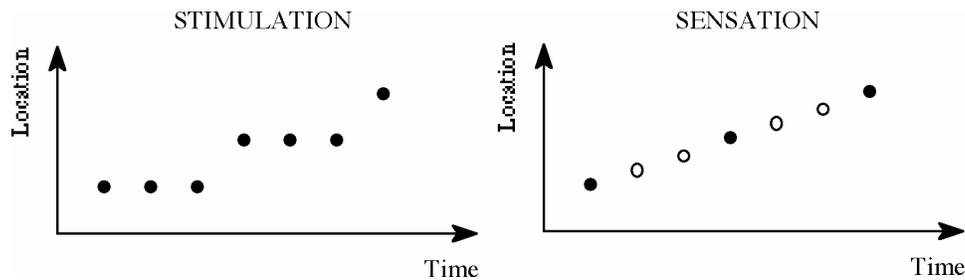
### ***Sensory Saltation***

The "sensory saltation" phenomenon was discovered in the 1970's in the Cutaneous Research Laboratory at Princeton University. In an initial setup that led to the discovery of this phenomenon, three mechanical stimulators were placed with equal distance on the forearm [Figure 3].



**Figure 3. A Norwegian artist's interpretation of the "sensory saltation" phenomenon [10].**

Three brief pulses were delivered to the first stimulator closest to the wrist, followed by three more at the middle stimulator, followed by another three at the stimulator farthest from the wrist. Instead of feeling the successive taps localized at the three stimulator sites, the observer is under the impression that the pulses seem to be distributed with more or less uniform spacing from the site of the first stimulator to that of the third. The *perceived* taps in-between actual stimulators are *perceptual illusions* (see open circles in Figure 4). The sensation is characteristically described as if a tiny rabbit was hopping up the arm from wrist to elbow; hence the nickname “cutaneous rabbit.” The word “saltation” is Latin for “jumping.”



**Figure 4. Stimulation vs. Sensation. Open circles indicate the perceived "phantom" location [25].**

Sensory saltation has many unique features that make it ideal for use in a situation-awareness display. Sensory saltation presents directional information that is highly intuitive [24], meaning untrained users can easily interpret the information. The illusion of saltation is easily induced through simple hardware configurations and therefore less stimulators are needed. Through extensive research, it has been found that the sensation caused by sensory saltation is identical to that caused by a veridical<sup>1</sup> sensation. This not only allows for a simplification of hardware but cuts the cost of the hardware as well. The sensory saltation phenomenon is obtainable at many body sites, and therefore is flexible. One of the major advantages of using sensory saltation is the finely defined directional lines that are generated to the user [5]. Also, saltation can be extended to applications involving vision or audition.

The idea of replacing vision or audition with the sense of touch (i.e., sensory substitution) is not new. Numerous devices have been developed for persons with visual or auditory impairments (e.g., the Optacon, a reading-aid for the blind, and Tactaid VII, a hearing aid for the deaf). It is conceivable that such devices can be employed under conditions where visual/auditory sensory channels are overloaded or information received via visual/auditory channels are distorted. However, devices like the Optacon require extensive user training and high level of concentration during its use. In addition, it requires the use of the fingertip, which would interfere with many manual tasks. In contrast, the tactual display system we proposed to use had many advantages. It used parts of the body not usually engaged by other tasks (i.e., the back). It

<sup>1</sup> Veridical refers to the mode that requires all elements (7) that make up a line of stimulators be activated, whereas in saltation, only elements 1,4, and 7 would be activated [4].

required no user training. It delivered directional information that is easy to interpret (i.e., in the coordinate frame of the user's body) [25].

The Reduced Gravity Student Flight Opportunities Program provided a unique opportunity for us to observe whether this illusion is robust under altered gravity conditions, thus gaining some insight into whether this sensory illusion interacts with the visual system, other components of the tactual system (e.g., kinesthesia), and the vestibular sensory system. Although the current project will not specifically examine the sensory saltation phenomenon, it is still our goal to develop an intuitive situation-awareness display using this sensory illusion. As such, we have examined some of the other important research involving spatial disorientation.

### ***Current Research***

Examining current research is key to understanding how the problem of spatial disorientation could be solved. Three current approaches to solving the problem are 1) visual orientation cues by MIT's Man-Vehicle Laboratory under Dr. Charles Oman; 2) the TSAS system by the Naval Aeromedical Research Laboratory under Dr. Angus Rupert; and 3) sensory saltation and other methods of tactile pattern perception at Princeton University's Cutaneous Research Laboratory under Dr. Roger Cholewiak.

### **Massachusetts Institute of Technology**

At the Man-Vehicle Laboratory (MVL), Dr. Charles Oman works on how space travel affects human balance and orientation and examines visual reorientation illusions (VRIs) in zero gravity. After first learning about VRIs aboard the KC-135, Dr. Oman and several colleagues began to train the astronauts to be ready in orbit. After flying experiments aboard several Spacelab missions during the past 15 years, Dr. Oman concluded, "crewmembers became more dependent on visual and tactile cues to their self-rotation [20]." Aboard STS-90, Neurolab's experiments used virtual reality (NASA's Virtual Environment Generator, or VEG) to see how the balance between vestibular and visual cues shifts toward the visual system. A key issue is how astronauts use pressure cues, vestibular organs of the inner ear, and vision to perceive objects and orientations in the absence of a gravitational force:

**Or is this the floor?**



**Is this the floor?**

**Figure 5**

The MVL wants to determine whether astronauts are able to develop a more robust orientation ability through visionary cues or whether human evolution and lifetime experience in 1-g has limited our learning ability. Results are used to reduce space motion sickness on shuttle flights [19].

Examination of visual cues in zero gravity is critical research. However, developing a *system* based on visual or audio displays as a means of reorientation could result in information overload for the user. Jennifer Rochlis of MIT explains that “the burden on the visual system to perform primary tasks as well as compensate for other sensory channels not operating at their full potential, motivates the use of the skin receptors for the display to complement the visual system [23].”

## **NAMRL**

The Naval Aeromedical Research Laboratory (NAMRL) seeks to solve the military aspect of the problem using its Tactile Situation Awareness System (TSAS), which is a display that takes data from the aircraft’s avionics and relays this information to the pilot via columns of tactors integrated into a flight vest. Unlike Dr. Oman’s research, TSAS is non-visual. Additionally, TSAS does not rely on sensory saltation, but instead relies on dozens of tactors to expensively convey the same information. Using TSAS, pilots experience an increase in spatial awareness due to improved control of aircraft during challenging flight conditions. The TSAS system can reduce pilot workload and thus has the potential to increase mission effectiveness [15].

Although TSAS has the capability of providing a wide variety of flight parameter information to the pilot (attitude, altitude, velocity, acceleration), it has weaknesses. According to NAMRL, “TSAS is a serial system that requires compatibility between all components (sensor, processor, and tactors) to function properly. It was found that presenting two or more different types of information simultaneously and in close proximity makes the system non-intuitive and difficult to use. This is due in part to limitation of current tactor technology [17].” Additionally, the TSAS

requires all factors to be functioning properly whereas a system using saltation will still function properly if intermediate stimulators fail [5].

These limitations are part of what our team wants to examine aboard the KC-135. A version of NAMRL's TSAS system was successfully tested by the MIT NORTHSTAR team in March 2000 for the Reduced Gravity Program. However, NORTHSTAR test subjects were stationary since they were testing the system only for pilots, not astronauts. Although factor intensity was perceived equally on the ground and in zero gravity, the test subjects were much better oriented aboard the KC-135 than the typical fighter pilot or astronaut experiencing spatial disorientation [11].

Additionally, work has been done by Jennifer Rochlis on NAMRL's Tactor Locator System (TLS), a display used to convey intuitive information about position via a vibrotactile stimulus applied to the subject's torso region. Although the on-ground research is proven to be successful, it is too early to judge the overall effectiveness of the system because the two most important tests involving the system have yet to be performed: testing aboard the KC-135A and testing in NASA's neutral buoyancy tank while wearing a pressurized EVA suit [23].

### **Princeton University**

Since the original discovery of sensory saltation, the Cutaneous Laboratory under Dr. Roger Cholewiak continues to conduct exciting research. Currently concentrating on the individual differences in vibrotactile pattern perception, the laboratory hopes to determine whether an individual can accurately process tactile pattern sequences using devices based on the individual's sensory, perceptual, or cognitive abilities [22].

Meanwhile, research on linear tactile sensations has concentrated on user quality judgement. In terms of stimulus parameters, Dr. Cholewiak has tested saltatory and veridical modes on the forearm, back, abdomen, leg, and fingertip, and has found that each location perceives a different amount of spatial detail. Changes in temporal parameters have been examined. These include burst duration (BD), which is how long a tactor vibrates, and interburst interval (IBI), or the amount of time in between successive burst durations. Spatial parameters were also examined and results showed the ideal distance between tactors was no more than 10-cm [4, 5].

In terms of judged qualities, the Cutaneous Laboratory has tested perceived length, smoothness, spatial distribution, straightness, and temporal regularity of the linear tactile sensations. Results showed that users judged the sensations as having greater length but more temporal irregularity and less straightness as the BD increases. Furthermore, the shorter the IBI, the more smooth the stimulus and the more equal the spatial distribution of perceived vibrations [5]. However, it was found that the BD and IBI could not both be adjusted to maximize all five judged qualities at once. The results of this research should have a major impact on the development of tactile display systems [4].

The discussion on several areas of spatial disorientation research is to emphasize that testing factor *intensity* in zero-gravity has never been done and that this proposed research should be of interest to wide variety of researchers in the aerospace community, rather than just those involved with sensory saltation. Additionally, factor-producing companies such as Transdimension and Audiological Engineering should be able to use our results when considering how to design better products for the future.

### ***Applications***

Tactile technology can be expanded beyond solving SA/SD problems into areas such as navigation, communication, alarms and indicators, and training and simulation.

Tactile technology can be used to reduce mission failure, aircraft loss and pilot loss due to pilot disorientation, and to enhance pilot performance by simplifying the flight task. Currently the only accurate sensory information available to pilots concerning their attitude and motion is visual interpretation of instruments or outside reference to the horizon. By integrating the tactile directional display with existing systems, pilots can be steered in the right direction when they fall off course. Ideally, the pilot could maneuver the aircraft using tactile displays in the complete absence of visual cues.

Tactile technology utilizing sensory saltation can enhance EVA safety and effectiveness. Having a correct perception of their own position and motion will allow astronauts to work even more productively and confidently in space. A tactile feedback system could help astronauts navigate easily both inside and outside the International Space Station.

For military Special Operations, tactile displays provide the advantages of low signature, a silent form of communication, reduction of information overload, a backup to other senses, a good representation of 3-D space, and the utilization of an otherwise unused sense. For example, if a team is attacking a target at night, the platoon leader can give silent commands for attack strategy: a pulse going around the operator's back could mean to "surround the building." Also, if a team is performing a High-Altitude Low-Opening parachute insertion in the pitch black of night, a system integrated with a Global Positioning System could allow all operators to easily find the on-ground rendezvous point [16].

Application of a tactile system for the blind is evident. Combined with GPS, the system could help guide the user through unfamiliar territory, and perhaps one day to even drive a car. Even for the non-blind, a wearable tactile display could guide the user through an unfamiliar building to find a room or help a tourist navigate through an unfamiliar city [25].

### **Test Objectives**

The goals of the proposed experiment are 1) to determine if a hardware component of the previous experiment caused the low user success rate and 2) to compare the intensity perception of vibrotactile signals in zero-g , one-g, and two-g environments.

## Test Description

### *Preflight Testing Procedures*

Extensive testing will take place on the ground prior to the flight of the experiment in the KC-135. Since the experiment involves making individual judgements concerning the intensity of a perceived signal, data will be collected on the ground to characterize the response of each subject. The first step is to determine the detection threshold of the subject. This measurement is the smallest amplitude of the signal that can be perceived by the subject. The detection threshold can then be used as a base measurement that other signal intensities can be compared against. The intensity of each vibration can be related to the amplitude of the tactor as  $10\log_2(A/A_{th})$  dB SL, where  $A$  is the driving amplitude,  $A_{th}$  is the detection threshold, and dB SL is the sensation level measured in dB.

The next step is to determine a range of signals that will be tested aboard the flight. Two main points must be considered, 1) the vibrational dynamic range and 2) choosing the intensities and number of test signals such that results are statistically relevant. Vibrations begin to feel uncomfortable and even painful at intensities exceeding approximately 50 to 55 dB SL [26]. Thus, the upper limit of signals that will be tested is set at 50 dB SL. At least ten trials per tested intensity should be run throughout the experiment to be statistically relevant. Assuming the subject will be able to take data from at least two random signals per period of altered gravity, and assuming a total of 30 parabolas per flight, a minimum of 60 test points can be generated. Thus, choosing five different intensities evenly distributed between the range of 0-50 dB SL seems to be an appropriate choice. Therefore, five signal intensities of 10, 20, 30, 40 and 50 dB SL will be used for this experiment. Many trials of every signal will be conducted on each subject while on the ground. One of the signals will be randomly selected and presented to the subject. The subject will be asked to indicate the perceived intensity of the signal with a number between 1 and 100 (i.e. magnitude estimation). The results will be analyzed by plotting the normalized magnitude estimates as a function of signal intensity in dB SL. The data points will then be fitted by a logarithmic function.

By extensively testing the hardware and psychophysical procedures on ground, we hope to fix any problems that might surface before we carry out the experiments aboard the KC-135.

### *In Flight Testing Procedures*

The test subject will be prompted to begin a preprogrammed signal by pressing a key on the keypad. After this key is pressed, the subject is able to stop the signal at any time by pressing another key. The signal will then be delivered to the subject by the tactor positioned on his/her back. Upon completion of the presented signal, the subject is asked to enter the perceived intensity of the signal into the system. This scenario is repeated twice in both 0-g and 2-g portions of the parabola. The results will be recorded in the system's memory and analyzed post-flight using magnitude estimation plots. The magnitude estimation graph obtained from each subject in 1-g will be compared to the graphs created from data points in 0-g as well as 2-g.

All three graphs for the subject can then be evaluated in order to discover any correlation between perceived intensity and altered gravity environments.

***In Flight Test Case Example***

Just before the KC-135 begins the parabolas, the test subject puts on the control box containing the supporting electronics and positions the tactor on his/her back. The electronics are then turned on and any outreach materials are setup. At the commencement of the testing, the subject presses the “start signal” key. The subject then enters the perceived intensity as a number between 1 and 100 into the data recorder via the keypad. This routine is repeated twice in both 0-g and 2-g. Finally, all outreach activities are performed in the time remaining. Upon completion of the test, all outreach materials are stowed away. The electronics are powered down and the subject removes the electronic testing equipment. The team then prepares for landing.

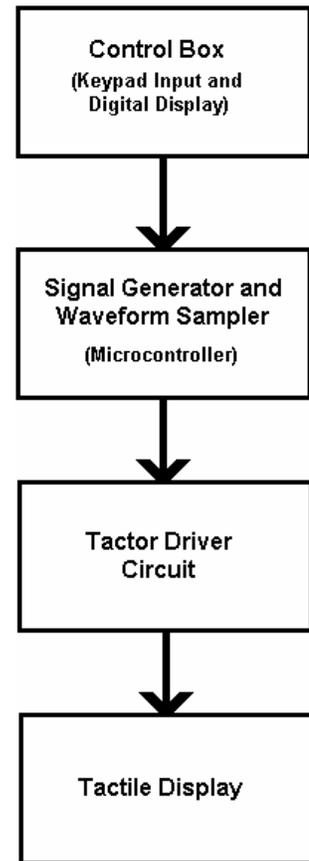
**Equipment Description**

***Overview***

The hardware used to drive the tactor and to measure signal intensity can be described by four functional blocks. These blocks include the control box, signal generator and waveform sampler, tactor driver circuit, and tactile display as shown in Figure 6. The control box utilizes a keypad and an electronic display to aid user interaction with the system. A microcontroller is used to control the intensity of the signal supplied to the tactor and to measure the displacement of the vibrating tactor in real-time. The tactor driver circuit supplies a 220 Hz sinusoidal signal and acts as a power amplifier to produce oscillations at the natural frequency of the vibrators. Finally, the tactile display is implemented with a single tactor located on the user’s back. All of this hardware is enclosed in a box of length 11.02 inches, width of 7.87 inches, and depth of 2.95 inches (see Figure 7).



**Figure 7 Hardware Enclosure Box.**



**Figure 6 Functional Flowchart (Drawn by Ryan Traylor.**

### ***Control Box***

The control box consists of a keypad, encoding circuitry, and a digital readout, which instructs the user throughout the experiment. Using the keypad, users are able to prompt the system for a new preprogrammed signal and then input the perceived intensity. The keypad is interfaced to the microcontroller with encoding hardware provided by a 74C922J integrated circuit. The binary output from this chip is of a form that can be read and interpreted by the microcontroller used for signal generation.

### ***Signal Generation and Waveform Sampling***

The next functional block contains a microcontroller which directs information to and from the user, controls the intensity of the signal sent to the tactors, and records the displacement of the tactors in real-time. The microcontroller chosen for this task is the Motorola 68HC912BC32 16-bit microcontroller equipped with flash memory (Motorola Inc., IL). The 68HC912BC32 (HC12) is an ideal choice because it is compatible with a vast array of peripheral devices and is very well documented [12]. Before flight, the HC12 will be preprogrammed with a set of random signal intensities, which will be presented to the tactors during the flight. The user will test two signals of random intensity in both the 0g and 2g portions of each parabola. A button will be pressed on the keypad to initiate and terminate a vibration to the tactor. Upon termination of the signal, a perceived intensity of that signal will be entered into the system and stored for later retrieval. After entering the perceived signal strength, the user is able to prompt the system for another signal. This same scenario will be replayed twice in both the 0g and 2g portions of each parabola.

On each trial, the HC12 pulls the preprogrammed signal intensity from memory and sends a corresponding signal to the tactor driver circuit indicating how strong it should actuate the tactor. The HC12 will also be able to record the displacement of the tactor in real-time with the aid of an accelerometer fixed to the tactor's surface. As the tactor oscillates back and forth, the accelerometer will be displaced in the same manner. The signal output by the accelerometer reflects the acceleration of the tactor at certain instants in time. However, the actual position of the tactor is of interest in this experiment. Since the movement of the tactor is sinusoidal due to the sinusoidal driving voltage, the signal viewed from the accelerometer will be sinusoidal in nature. Noting that position is two integrations of acceleration with respect to time and  $\int(\int \sin(t) dt) dt = -\sin(t)$ , the tactor's position function is just a constant multiple of its acceleration function. The microcontroller is not able to record the continuous waveform output by the accelerometer, so samples must be taken and later pieced together in the form of a discrete function.

One major source of error can occur when sampling a continuous signal. If the microcontroller does not sample at a high enough rate, higher frequency components of the signal are aliased and the reconstructed waveform is distorted. Preliminary tests were carried out on the tactors to be used in this experiment and through Fourier transform techniques, a sampling rate was found that eliminates any problems associated with aliasing. The discrete data points collected by the

HC12 will be stored in RAM and used post-flight to reconstruct the continuous waveform for further analysis.

### *Tactor Driver Circuit*

The HC12 is not capable of supplying the current and voltages required to directly drive a tactor. Thus, an intermediate device was designed to translate the control signals from the HC12 and then to output the appropriate driving signal necessary to actuate the tactor. The driver's main function is to supply an amplified oscillating signal to a tactor when prompted by the HC12 to do so. The circuit consists mainly of a power supply, a 220 Hz oscillator, and a 16-Watt bridge amplifier. When the driver circuit receives an enable signal from the microcontroller, it responds by supplying an amplified 220 Hz oscillating signal to the tactor. The amplitude of this oscillating signal is governed by the voltage level on a control line generated by the HC12. A schematic of the bridge amplifier is shown in Figure 8.

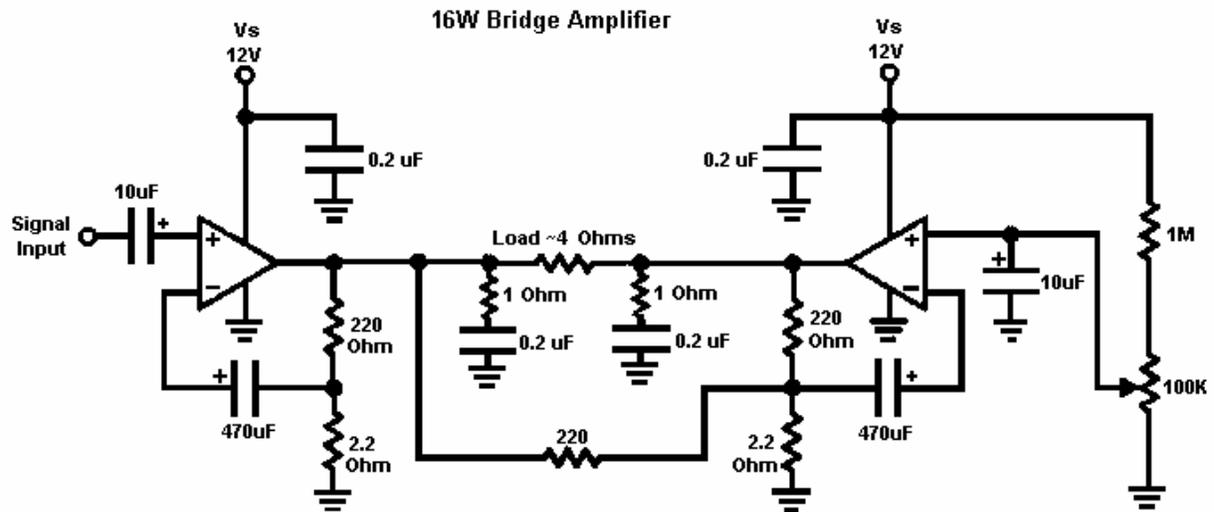


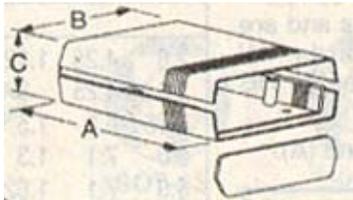
Figure 8 A schematic for the 16W Bridge Amplifier [14]

### *Tactile Display*

The tactile display consists of a single tactor placed on the user's back. The tactor is made of a flat speaker, four centimeters in diameter, designed to resonate around 220 Hz (Audiological Engineering Corp., MA). The sensation delivered by the tactor is similar in nature to the vibrations felt from a commercially available massage chair.

## Structural Load Analysis

The device is designed to be contained inside a backpack. In this case, since the device is not restrained such as bolted to the ground of the airplane, its only loading will be its own weight, which is approximately 6.5 pounds. The device is approximately stress- and strain-free during the micro-gravity period. However, as soon as the airplane starts to accelerate upward, the device will experience a large deceleration, which causes a loading onto the surface of the plastic casing. For a 9-g safety factor, ten times the loading is used for analysis. The following calculation and explanation summarize the stress states and the safety of the proposed device.



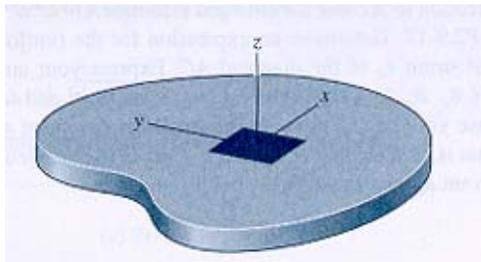
A= 11.02 in  
B= 7.87 in  
C= 2.95 in

**Figure 9: Dimensions of the Flame Retardant Plastic Cases and Aluminum panel [7]**

### *Assumptions*

1. The contribution of thermal expansion to the stress analyses is negligible.
2. The thickness is uniform throughout the ABS Flame Retardant Plastic Instrument Cases.
3. All screws are significantly stronger than the casing they are securing and will not deform.
4. The forces exerted by the entire device are evenly distributed to the 2 belts that support the backpack.
5. The mass of backpack is negligible.
6. The loading on the plastic casing is uniformly distributed throughout the surface area.

### *Analysis*



**Figure 10: A small portion of the thin plastic plate experiencing uniform stress [6].**

By assumption (6), the worse internal loading of the plastic casing is the loading on the smaller surface area (B×C).

$$\text{Stress} = \sigma$$

$$\text{Strain} = \varepsilon$$

$$\sigma = \frac{10 \times 6.5 \text{ lbf}}{7.87 \text{ in} \times 2.95 \text{ in}} = 2.8 \text{ psi}$$

The followings are generalized Hooke's Law for isotropic materials:

$$\text{Modulus of Elasticity} = E$$

$$\text{Poisson's Ratio} = \nu$$

$$\text{Shear Modulus} = G = E / 2(1+\nu)$$

$$\sigma_x = [E / (1+\nu)(1-2\nu)][(1-\nu)\varepsilon_x + \nu(\varepsilon_y + \varepsilon_z) - (1+\nu)(\alpha\Delta T)]$$

$$\sigma_y = [E / (1+\nu)(1-2\nu)][(1-\nu)\varepsilon_y + \nu(\varepsilon_x + \varepsilon_z) - (1+\nu)(\alpha\Delta T)]$$

$$\sigma_z = [E / (1+\nu)(1-2\nu)][(1-\nu)\varepsilon_z + \nu(\varepsilon_x + \varepsilon_y) - (1+\nu)(\alpha\Delta T)]$$

Since the loading is only on the surface,  $\sigma_x$  and  $\sigma_y$  does not apply to the system.

$$\varepsilon_x = 1/E [ \sigma_x - \nu(\sigma_y + \sigma_z) ] + \alpha\Delta T$$

$$\varepsilon_y = 1/E [ \sigma_y - \nu(\sigma_x + \sigma_z) ] + \alpha\Delta T$$

$$\varepsilon_z = 1/E [ \sigma_z - \nu(\sigma_x + \sigma_y) ] + \alpha\Delta T$$

From the above conclusion and by assumption (1)

$$\varepsilon_x = (-\nu\sigma_z)/E$$

$$\varepsilon_y = (-\nu\sigma_z)/E$$

$$\varepsilon_z = \sigma_z/E$$

Considering the mechanical properties of plastics:

$$\text{Modulus of Elasticity, } E = 0.35 - 0.4 \text{ ksi}$$

$$\text{Poisson's Ratio, } \nu = 0 - 0.4$$

Strains in all directions have magnitudes of  $10^{-3}$  or less. Thus we can expect an extremely small percentage of deformation on the plastic surface of our device during the upward acceleration. Besides, bolts supporting the lower and upper cases will be used to secure the inner components in place. This significantly decreases the elasticity of the lower and upper plate, which makes the deformation negligible.

The internal components in the plastic casing will exert 6.5 pound-force when it is accelerated at 9g. Compared to the compressive/tensile strength of the plastic ( $6 \text{ ksi} < \sigma_y < 8.5 \text{ ksi}$ ), this

loading becomes insignificant and thus will not deform the casing. Moreover, the stability of the casing is aided by the backpack that embraces the entire device.

### ***Conclusion***

The structural configuration of the device has been chosen so that maximum stresses in the components do not exceed the allowable stress. When loads are considered, the maximum applied load does not exceed, and is much less than, the allowable load (ultimate strength). The results ( $300 < FS < 400$ ) of this analysis are well above the normal range of values for the normal factor of safety 1.3 – 3.0 [6]. There is no likelihood that failure will result.

### **Electrical Load Analysis**

The device does not require an electrical power supply from the aircraft.

### **Pressure Vessel Certification**

This is not applicable to the experiment.

### **In-Flight Test Procedures (Check List)**

#### ***Initial Setup***

- \_\_\_\_\_ 1. Test subject puts on control box containing the supporting electronics and positions the factor on his/her back.
- \_\_\_\_\_ 2. Turn on Camcorder.
- \_\_\_\_\_ 3. Ensure new Videotape is loaded.
- \_\_\_\_\_ 4. Set Record mode on Camcorder.
- \_\_\_\_\_ 5. Start Recording on Camcorder.
- \_\_\_\_\_ 6. Turn on electronics.
- \_\_\_\_\_ 7. Setup any Outreach Materials.

#### ***Testing***

- \_\_\_\_\_ 8. At the beginning of 0-g, the experimenter begins the experiment by pressing the “start signal” key on the keypad.
- \_\_\_\_\_ 9. Experimenter enters the perceived intensity into the data recorder.
- \_\_\_\_\_ 10. Experimenter chooses another signal by again pressing the “start signal” on the keypad.
- \_\_\_\_\_ 11. Experimenter enters the perceived intensity into the data recorder.
- \_\_\_\_\_ 12. At the beginning of 2-g, the experimenter chooses another signal by pressing the “start signal” key on the keypad.

- \_\_\_ 13. Experimenter enters the perceived intensity into the data recorder.
- \_\_\_ 14. Experimenter chooses another signal by pressing the “start signal” on the keypad.
- \_\_\_ 15. Experimenter enters the perceived intensity into the data recorder.
- \_\_\_ 16. Repeat steps 8-15 for each parabola.
- \_\_\_ 17. Do any additional Outreach activities.

### ***Test Conclusion***

- \_\_\_ 23. Put away all Outreach materials.
- \_\_\_ 24. Turn off the electronics.
- \_\_\_ 25. Stop Recording on Video Camcorder.
- \_\_\_ 26. Turn off Camcorder.
- \_\_\_ 27. Stow all remaining materials
- \_\_\_ 28. Test Subject removes the control box and factor.
- \_\_\_ 29. Prepare for landing.

### **Parabola Requirements, Number, and Sequencing**

Due to the nature of this experiment, no special parabola sequencing is necessary. Although this experiment was designed around a forty-parabola flight, the procedure can be easily altered while in flight. Data will be collected during each parabola and during the transition periods between cycles. This permits useable data to be obtained from any number of parabolas.

### **Test Support Requirements, Ground and Flight**

This experiment will not require any major ground or flight assistance from the Johnson Space Center Reduced Gravity Office.

### **Data Acquisition System**

The data acquisition system plays an extremely crucial role in the design of the experiment. During the August 1999 flights, paper and pencil were used to record data. This proved to be very inefficient for a variety of reasons. During the periods of zero gravity, papers were flying around, causing chaos and confusion. Also, one member of the team had to be designated as the data recorder on the flight. Our present project will implement a fully automated data acquisition system. Twice as much data will be collected, since both team members will be able to perform the experiment at the same time.

Visual prompts will be given on a LCD screen. The user will input information such as starting and stopping the tactile vibrations, and ranking the intensity of the vibrations perceived. A 16-digit keypad will be used as the input device. This data will be collected into the microprocessor’s memory and will be stored for later retrieval.

Data must also be collected from the accelerometers. This will give us insight into the dynamics of the factors in an altered-gravity environment. The accelerometer data will be sampled at a fixed rate and will be stored in RAM external to the microprocessor. However, since there will not be enough RAM to hold all of the data points, a wearable computer will be used and the data will be stored onto its hard disk.

In addition, a small video camcorder will be utilized in order to help document all test subject comments and corresponding orientations. The stored data will be examined along with the video recordings of the experiments for off-line data analysis.

## **Test Operating Limits**

The calculation on structural load analysis indicates that the equipment is very safe to bring aboard the aircraft. The temperature limitations on all of the important electronic components fall into the range of 0°C to 70°C. The multiplexer (CD4053) has temperature ranges from 65°C to 150°C [9] and the amplifiers have a temperature range from 0°C to 70°C [14], but for safety we have provided a heat sink. The Motorola 68HC912BC32 has an operating range of 0°C to 70°C [12]. The Oscillator (XR2206) has a range from -55°C to 125°C [8]. The board has been designed to accept a load from 10 to 16 volts. In order not to tether the subject wearing the backpack, a 12-volt battery will be used to power the electronics.

## **Proposed Manifest for Each Flight**

- Control Box (contains the supporting electronics)
- Video Camcorder (small)
- Camcorder Tapes (4)
- Wearable Computer
- Batteries (2)
- Outreach Activities

## **Photographic Requirements**

A small video camcorder will be used to help document all test subject comments and orientations. Still cameras will be brought aboard and will be used for personal photographs only. Any photographs taken by the zero-g office would be appreciated.

## **Hazard Analysis**

The electronic hardware and its enclosure have been designed to withstand a 6-g acceleration, which is well within the expected range of accelerations. The vibrators are driven by a 10-V peak-to-peak signal. Higher inputs to the vibrator will result in clipping. A 12-V lead acid gel cell battery furnishes the main source of power. The battery is completely sealed and there will be no possibility of acid leakage. In addition, the backpack and the box are constructed out of

flame retardant fabric and plastic materials. As an extra safety precaution, a “panic button” can be pressed to electronically isolate the battery from the main circuitry should any electrical hazard be suspected.

## **Safety Certification**

This is not applicable to the experiment.

## **Outreach Program**

(See letters in Appendix C)

An extensive outreach program, to reach people of all ages, has been designed around this proposal. The following are summaries of these outreach activities.

### ***Elementary School***

Oakland Elementary School (Lafayette, IN) has agreed to participate in our outreach program once again. We will be presenting in April to a selected group of fourth and fifth graders. During the presentation, we will discuss the effects of reduced gravity, suggest potential projects for the program, as well accept feedback on our presentation and answer any questions the students may have. The students will have an opportunity to suggest experiments for our team to fly aboard the aircraft, should our proposal be selected. Next fall, we will follow up with another presentation. We will show video footage of the flight and discuss their in-flight experiments.

### ***Middle School***

Sunnyside Middle School (Lafayette, IN) has agreed to participate in our outreach program once again. We will be presenting in April to a selected science class. During the presentation, we will discuss our project and the technology involved. The students will have the opportunity to suggest experiments for our team to fly aboard the aircraft, should our proposal be selected. Next fall, we will follow up with another presentation. We will present video footage of the flight and discuss their in-flight experiments and the results of our research.

### ***High School***

Jefferson High School (Lafayette, IN) has agreed to participate in our outreach program once again. We will be presenting in April to selected sophomores and juniors. During the presentation, we will discuss our project in depth, both problem and solution, as well as the technology involved. The students will have the opportunity to suggest experiments for our team to fly aboard the aircraft, should our proposal be selected. Next fall, we will follow up with another presentation. We will present video footage of the flight and discuss their in-flight experiments and the results of our research.

Henry Harrison High School (West Lafayette, IN) has agreed to participate in our outreach program. We will be presenting in April to selected group of science students. During the presentation, we will discuss our project in depth, both problem and solution, as well as the technology involved. The students will have the opportunity to suggest experiments for our team to fly aboard the aircraft, should our proposal be selected. Next fall, we will follow up with another presentation. We will present video footage of the flight and discuss their in-flight experiments and the results of our research.

John Marshall High School (Rochester, MN) has agreed to participate in our outreach program. We presented this past March to three Honors Physics classes. During the presentation, we discussed our project in depth, both problem and solution, as well as the technology involved. The students asked numerous questions and had many suggestions for our research. Next fall, we will follow up with another presentation. We will present video footage of the flight and discuss the results of our research.

### *Undergraduate*

We will be setting up a display in the Materials Science and Electrical Engineering Building at Purdue University. Engineering students of all ages, as well as visitors to Purdue, will be able to see our project.

We will be presenting to ENGR 116 next fall. This is an honors freshman-engineering course with approximately 100 students. During the presentation, we will discuss our project in depth, and the technology involved. We will present video footage from the flight and then discuss the results of our research. This will be an opportune time to inform the students of the Reduced Gravity Student Flight Opportunities Program and offer our expertise to those interested in submitting a proposal.

### *Museums*

The Imagination Station (Lafayette, IN) has agreed to participate in our outreach program. This coming spring and next fall we will provide a workshop for visitors of all ages. It will be for community interest and will provide for significant feedback opportunity.

## **Participant Information Forms**

The signed Participant Information Forms and identification are enclosed in Appendix D.

## **Official Verifications**

(See letters in Appendix C)

### Letter from Committee on the Use of Human Research Subjects

The Committee on the Use of Human Research Subjects writes that our project is currently under review.

### Letter from Dr. Hong Tan

Our faculty advisor explains that the Purdue students involved will receive academic credit for the project.

### Letter from Dr. W. Kent Fuchs

The head of the school of Electrical and Computer Engineering at Purdue University pledges his support for the project.

### Letter from Dean Richard J. Schwartz

The Dean of Engineering at Purdue University pledges his support for the project.

## **Human Research Consent Forms**

The signed Human Research Consent Forms are enclosed in Appendix D.

## **Publicity**

(See letters in Appendix C)

### Purdue Exponent

The school newspaper of Purdue University writes that it would excitedly cover the story should the proposal be selected.

### Lafayette Journal and Courier

The main newspaper for the city of Lafayette, IN and the surrounding area plans to cover the story, should the proposal be selected.

## **Additional Support**

(See letters in Appendix A)

### Letter from Roger W. Cholewiak, Ph.D.

Princeton professor and researcher Dr. Roger Cholewiak writes in support of the team, the project and the relevance it has to his research.

*Letter from Mark N. Brown*

Retired USAF Colonel and former astronaut Mark Brown writes in support of the project after speaking with various members of the team and anxiously awaits the results.

*Letter from Guy S. Gardner*

Former fighter pilot and astronaut Guy Gardner writes in support of the project and looks forward to discussing the results of the project.

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## **Appendix A**

- Letter from Dr. Roger W. Cholewiak
- Letter from Mark N. Brown
- Letter from Guy S. Gardner

## **Appendix B**

- Letter from Committee on the Use of Human Research Subjects
- Letter from Dr. Hong Z. Tan, Faculty Advisor
- Letter from Dr. W. Kent Fuchs, Electrical and Computer Engineering Department Head
- Letter from Dean Richard J. Schwartz, Dean of Engineering

## Appendix C

- Letter from Oakland Elementary School
- Letter from Sunnyside Middle School
- Letter from William Henry Harrison High School
- Letter from John Marshall High School
- Letter from Marion Delp
- Letter from Imagination Station
- Letter from the *Purdue Exponent*

## **Appendix D**

- Participant Information Forms
- Team Member Identifications
- Human Research Consent Forms
- Certification of Undergraduate Status

## About Us

### *Ryan Casteel*

Ryan Casteel is a senior in the school of Computer and Electrical Engineering at Purdue University. His hometown is Decatur, IL and his current interests include control systems, communications, international affairs and Arabic. He enjoys soccer, piano, mathematics, and national security issues. Mr. Casteel eventually plans to join the Navy and have a career in government.

### *Ryan Traylor*

Ryan Traylor is a junior in the school of Computer and Electrical Engineering at Purdue University. His hometown is Dale, IN and he is currently studying the psychophysics involved in tactual directional displays. He is interested in embedded microcontroller systems and is studying Russian.

### *Adrian Lim*

Adrian Lim is a senior in the school of Mechanical Engineering at Purdue University. He is from Malaysia and is involved in the research of Human Psychophysics. His academic interests are turbomachinery, robotics, and control systems. Adrian is fluent in five languages.

### *Daniel Hromis*

Daniel Hromis is a junior in the school of Computer and Electrical Engineering at Purdue University. His hometown is Granger, IN and his current interests include digital systems and computer architecture. Daniel is fluent in Ukrainian.

### *Lauren Naessens*

Lauren Naessens is a sophomore in the school of Aeronautical and Astronautical Engineering at Purdue University. Her hometown is Rochester, MN and her current interests include dynamics and controls, rocket propulsion and French.

## **Academic Advisor Profile**

Dr. Hong Z. Tan received her Bachelor's degree in Biomedical Engineering and Computer Science from Shanghai Jiao Tong University, P. R. China in 1986. She received her Master's and Ph.D. degrees in Electrical Engineering and Computer Science from Massachusetts Institute of Technology in 1988 and 1996, respectively. Her graduate work focused on the development of haptic interfaces for sensory substitution. As a research scientist at the MIT Media Lab, she has developed the augmented smart chair project that aims at a sensing and reactive chair for novel human-computer interactions. Her current research activities include psychophysical studies of haptic displays, pattern recognition algorithms for distributed contact sensors, and an information-based framework for interface design and evaluation. For more info, please visit <http://www.ece.purdue.edu/HIRL>.