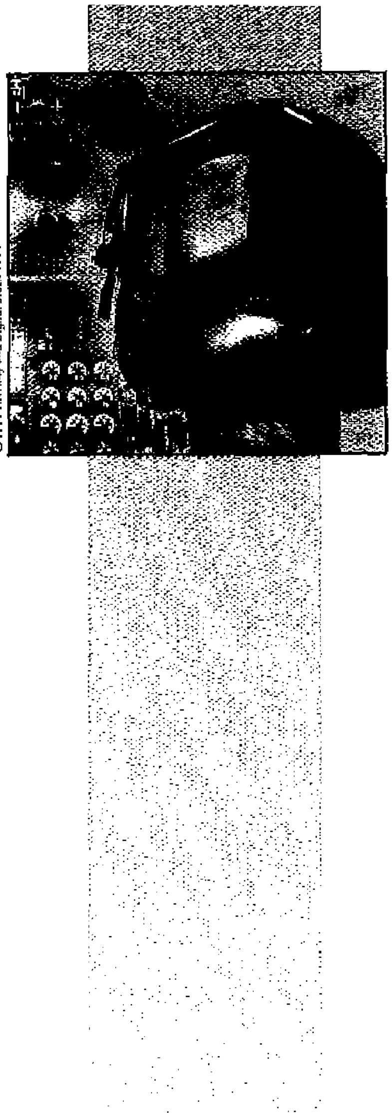

An Instrumentation Solution for Reducing Spatial Disorientation Mishaps

A More "Natural" Approach to Maintaining Spatial Orientation

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The multiple attempts to resolve spatial disorientation (SD) mishaps in aviation represent an interesting study in how engineers have approached a biological problem with continuous refinements of a single approach to a multifaceted problem. Spatial disorientation mishaps have occurred since terrestrial man, who evolved in a two-dimensional environment, entered the dynamic three-dimensional aeronautical environment. As long as the first aviators could maintain visual reference with respect to the ground or horizon, orientation did not pose a significant problem. However, "cloud flying" and other phases or forms of flight in reduced visibility claimed early aviators as victims with an alarming frequency. Pilots who entered clouds for prolonged periods would inevitably lose control of the aircraft, and if sufficient altitude remained when they exited the clouds while out of control, they could regain orientation and recover to fly another day. Otherwise, the pilot became another statistic, lost to spatial disorientation.

This article explores some of the engineering approaches to dealing with SD and their drawbacks, looks at nature's approach to spatial orientation, and then presents the Tactical Situation Awareness System (TSAS) as a solution to the SD problem (note: TSAS is a trademark for the service and product of the Naval Aerospace Medical Research Laboratory, Pensacola, Florida). The TSAS is an array of tactile stimulators arranged in columns and rows on a garment that a pilot wears on the torso and limbs. This array provides intuitive orientation information to aircrew and operators of remote platforms and is more compatible with a pilot's natural sensory system.

Engineering Approach

The solution to SD was straightforward and logical from the engineering perspective. The pilots of first-generation aircraft maintained pitch and roll control by visually referring to the horizon or ground. Since the pilot in clouds could no longer see the horizon, the engineer need only create an artificial horizon; thus, the beginning of the gyro-stabilized attitude indicator developed by the Sperry Gyroscope Co. (then in Brooklyn, NY). For the first time, pilots could maintain control while flying into clouds, snow, blowing sand, or other conditions of reduced visibility. However, most pilots did not immediately accept the new technology. Initially, there was considerable resistance by experienced pilots who staunchly believed that *real* pilots could fly intuitively by the "seat of the pants" sensations that were either innately present because the superior pilot possessed "the right stuff" or painstakingly acquired through years of experience honing flying skills.

Eventually, the artificial horizon was adopted and became mandatory, but SD mishaps continued. The engineers provided additional visual instruments including the vertical velocity indicator, altimeter, heading indicator, and turn and bank coordinator. Since pilots provided with all the information required to maintain controlled flight continued to experience SD mishaps, it was concluded that improved education and training was necessary. Didactic classroom education repeatedly emphasized to pilots that it was not scientifically possible to fly by the "seat of the pants" sensations, and that they must "trust their instruments" if they were to survive. It was recognized that monitoring several visual instruments simultaneously was a difficult task and required significant training both on the ground and in the air. The instrument scan pattern was developed to teach pilots how to visually monitor a large number of instruments and

Technology has, in part, become part of the problem contributing to SD in aircraft.

cognitively construct from this information the orientation of aircraft and pilot in space. It was assumed then, just as it is today, that since the pilot could maintain control by continuously or very frequently directing attention to the instruments, an SD mishap represented a failure by the pilot to scan his instruments. In today's terminology, a pilot who experiences SD has likely committed a skill-based error of breakdown in visual scan.

Despite the best of classroom training and in-flight practice scanning of the instruments, SD mishaps continued. Since even the most experienced pilots were susceptible, it was decided that engineers needed to solve the problem by providing improved orientation information. Visual instrument scanning was recognized as a challenging mental task requiring significant training time (tens to hundreds of hours) to acquire, and that frequent practice or currency training was necessary to maintain proficiency. The engineers proposed to simplify instrument scanning by providing all the pertinent information on a single visual display located directly in front of the pilot—a head-up display (HUD) that would also allow the pilot to look outside the aircraft without shifting gaze.

Since pilots, especially in the military, must frequently direct attention to points not in front of the aircraft, the next step for the engineers was to develop a helmet-mounted display (HMD). Even with HUDs and HMDs, the incidence of SD mishaps did not decrease. An additional engineering aid that has affected SD is the development of night-vision goggles (NVG), which has certainly changed the operating environment of army helicopter operations. Routine army missions now include night flying, formation flying at night, terrain following at night, and carrying of sling loads at night—all conditions that are conducive to experiencing SD mishaps. Indeed, the US Army has noted an increase of SD mishaps coinciding with the introduction and increased usage of NVG. Technology has, in part, become part of the problem contributing to SD in aircraft.

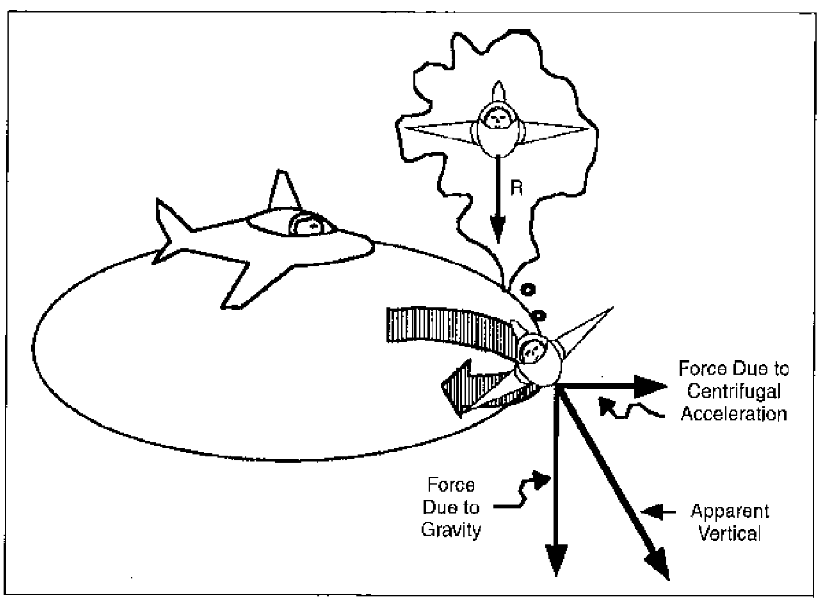
Every technological solution to improve aviation spatial orientation, from the first ADI through NVGs and HMDs, has represented an evolutionary process involving the visual representation of the external world, including the all-important horizon. Visualization has not solved the problem. Why is it that since Sperry's time, there have been no further landmark developments by human-factors engineers in introducing displays or instrumentation to solve orientation problems? It may be that spatial orientation, which even on the ground involves a simultaneous integration of information from multiple sensory systems, poses an even more complex problem in the aerial environment, such that human-factors solutions must come from more than one sensory system.

I contend that SD mishaps occur because aircraft designers, engineers, and specifically the human-factors engineers have failed to provide pilots with the information in a format that will permit them to fly as intuitively as they walk about on the earth. All the necessary information is available but poorly presented. The pilots are *not* at fault. They are the victims of poor design. The original engineers and their successors, the human-factors engineers, have made a series of steps in an evolutionary approach that would have resulted in extinction in the biological world. Let us examine how nature has approached and solved the problem.

Nature's Approach

Spatial orientation is so important for survival that nature has devoted much of the nervous system architecture to maintaining a high level of situation awareness. Terrestrially, each of the sensory systems involved in maintaining orientation (vestibular, skin-muscle-joint somatosensory, vision, and to a small extent auditory) provide independent, complementary, redundant, and reliable sources of information that are integrated in the central nervous system to formulate an appropriate response. However, in the aeronautical environment, the proprioceptive (vestibular and skin-muscle-joint, including tactile) sensations generally provide inaccurate information concerning the magnitude or direction of the gravity vector (Fig. 1). This is partly due to the continuous variations in magnitude and direction of the *resultant* gravito-inertial force vector with every aircraft maneuver, and partly due to the unusual nature of rotational movement to which the pilot is exposed.

In our day-to-day earth environment, gravity and resultant vectors rarely differ in directionfrom "down" for more than a



1. Forces experienced by a pilot in a coordinated turn.

few seconds. However, in flight the two coincide only in smooth, straight, and level flight. The vestibular and skin-muscle-joint systems use the resultant gravitoinertial force to determine where the direction "down" or gravity vector is located, which, as seen in Fig. 1, is frequently false. Of the three primary orientation sensory systems, it is only these two that provide *continuous* information. Since the information is continuous, the brain must process and use the vestibular and skin-muscle-joint information in an automated fashion, with little or no conscious awareness, in order to be able to carry out other tasks and not be preoccupied with the all-important orientation information. The vestibular information, in addition to providing orientation cues, is used reflexively to adjust posture and to control eye movements and vegetative reflexes in response to varying acceleration forces. The somatosensory (skin-muscle-joint) information providing limb position and surface contact cues is, likewise, used for orientation cues and automated functions, including posture and locomotion. The information from both systems does not come to our attention unless an unusual condition presents. Thus, two of the three sensory systems provide compelling false but concordant and redundant information at a persistent low level of awareness.

The only reliable source of information remaining is that obtained through the visual system. Visual orientation information is intermittent—that is, information is only available when the eyes are open and attention is directed to information sources that provide orientation cues. Most SD mishaps or close calls have an element of distraction, in which the pilot's attention is momentarily devoted elsewhere. During this period, the pilot receives continuous but false information from the vestibular and skin-muscle-joint systems that may incorrectly give him confidence that he is in controlled flight. Furthermore, visual information, whether from external horizon cues or the instruments, requires cognitive effort devoted to interpretation of the information, unlike the vestibular and skin-muscle-joint information, which is effectively automated.

Furthermore, each sensory system is susceptible to many perceptual illusions in addition to those discussed above. For these reasons it is *normal* for pilots to experience disorientation in the aviation environment.

Thus, in flight, the central nervous system has the added responsibility of determining what sensor information is valid. The typical SD mishap occurs when the visual orientation system is compromised (e.g., temporary distraction, increased workload, VFR/IFR transition, or reduced visibility) and the central nervous system must then compute orientation with the only information at its disposal (i.e., the continuous vestibular and somatosensory inputs), which happens to be incorrect. Even worse, these continuous sources of false information are concordant and redundant. In experiments where pilots are deprived of visual cues, they lose control at a rate dependent of the stability of the aircraft. Control of a fixed-wing stable aircraft might last one minute, but control of a training helicopter in hover without the benefit of stability augmentation systems would be lost in seconds.

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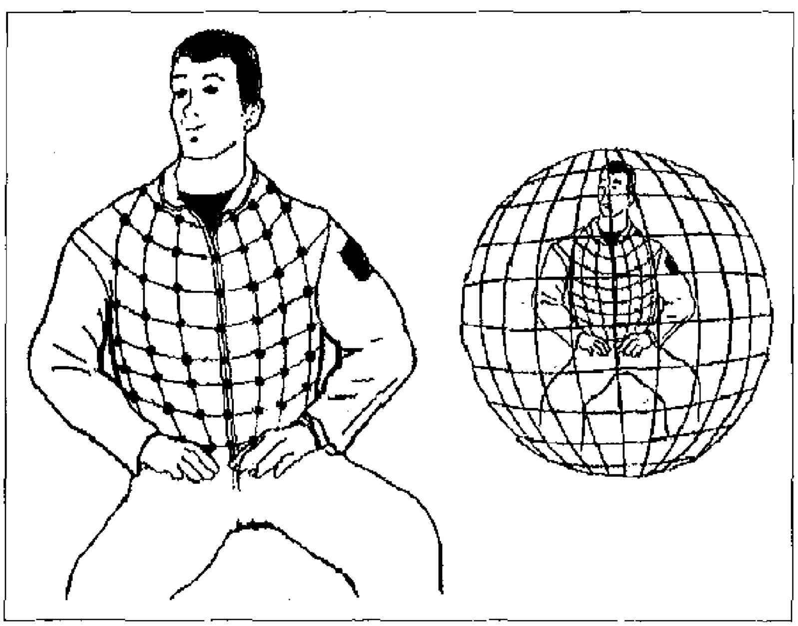
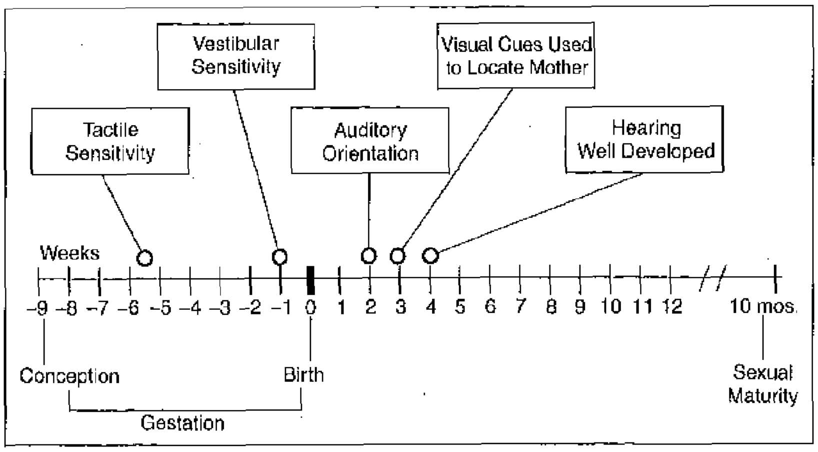


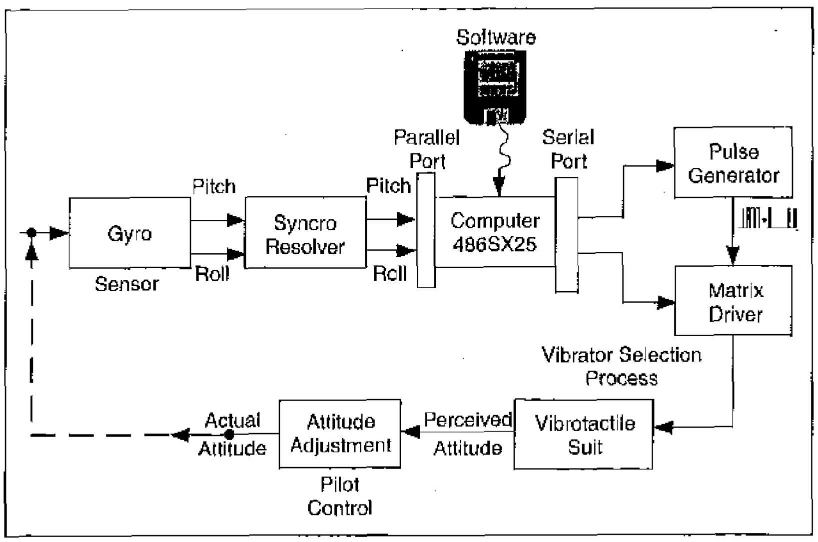
2. Conceptual view of tactor placement on the torso garment to map points from external environment onto pilot's torso.

In medicine, disease processes frequently shed light on normal functions that would otherwise not be appreciated. A sensory analog to the condition of the pilot is that presented by Ian Waterman, an English patient, who at the age of 19 lost all sense of touch and muscle stretch information below the neck [1]. Mr. Waterman, like the pilot, is entirely reliant on visual information for orientation and, in addition, must visually guide every limb movement. When standing in a room when the lights go out, he will collapse, just as the pilot loses control when deprived of instruments and outside visual cues. This patient has made the medical community aware that the most basic or primal orientation system is not vision, but rather the skin-muscle-joint system.

In summary, over millions of years, nature has developed an orientation system deriving information from multiple sensors that provide continuous, veridical (true), redundant, and concordant orienting cues. Most importantly, it has developed reflexes and neural circuitry to



3. Timetable outlining sensory development of the domestic cat [4].



4. Schematic illustrating components of prototype tactile orientation system.

automate much of the orienting behavior, which leaves cognitive reserve for carrying out other goal-seeking behaviors such as foraging, mating, etc.

In contrast, aircraft designers and human-factors engineers have isolated the pilot from the environment and restricted orientation information to intermittent visual glimpses of instruments, which requires considerable cognitive effort to interpret. As a result, under challenging flight conditions, very little cognitive reserve is left to accomplish the mission-related tasks (e.g., communication, navigation, weapons systems).

Solution

If engineers were to adopt an axiomatic approach to design an aviation interface compatible with the sensory system of pilots that nature has developed over millions of years, they would incorporate into the design:

- Continuous sources of orientation
- Redundancy
- True/accurate information to overcome false or illusory information
- Information complementary and concordant with other sensory systems.

The Tactile Situation Awareness System (TSAS) has accomplished this goal.

Cutaneous sensory information is not currently used to provide position or motion information to pilots. Rupert, Mateczun, and Guedry [2, 3] propose that spatial orientation can be continuously maintained by providing information from the aircraft attitude sensors to the pilot through the nonutilized sensory channel of touch (Fig. 2).

One approach is to use a torso harness fitted with multiple electromechanical stimulators (tactors) that can continuously update the pilot's awareness of position. This is analogous to the way our brain obtains orientation in the terrestrial environment. Thus, the pilot should be able to maintain orientation information in the absence of a visual horizon or during inevitable gaze shifts from the aircraft instrument panel. This device should free the pilot to devote more time to weapons delivery systems and other tasks requiring visual attention.

The rationale for utilizing touch to convey position and motion perception and to overcome vestibular, visual, and auditory illusions produced by unusual acceleration environments is based largely on knowledge about the ontology of sensory development (Fig. 3).

In vertebrates, the proprioceptive tactile system is the first sensory system to develop, followed by the vestibular system, then the auditory system, and finally the visual system [5]. In fact, the proprioceptive systems of somatosensory and vestibular function develop a rich interaction in utero. These follow logically, since the somatosensory system very early in development needs information concerning the direction of the gravity vector to properly control the antigravity and gravity muscles. It is only much later in development that the auditory and visual systems are integrated into this already well-functioning proprioceptive system. The primacy of touch and somatosensation in the development of orienting behavior has been demonstrated in several neurophysiological and anatomical studies [6, 7]. We propose that by providing veridical somatosensory orientation information, the illusory effects present in unusual acceleration and proprioceptive environments can be reduced to improve human performance in many facets of the military theater [3].

Procedures and Observations

A series of flight tests were conducted in both fixed-wing and rotor-wing (helicopter) aircraft. The initial proof of concept was conducted in a civilian Cessna 180 aircraft. Follow-on flight tests were in Navy T-34 (fixed-wing) and Army H-60 (rotor-wing) platforms.

Cessna Proof of Concept

We constructed a series of prototype devices to determine whether a pilot could maintain normal orientation and control over an aircraft using tactile cues. Multi-

A series of prototype devices was constructed to determine whether a pilot could intuitively maintain normal orientation and control by using tactile cues.

ple tactors were placed on a torso suit to represent combinations of roll and pitch (Fig. 2). An aircraft attitude sensor (Fig. 4) provided roll and pitch information to an IBM portable computer that selected (via a circuit designed in-house) the appropriate pattern of stimulation for a given combination of pitch and roll.

The circuit takes data from an IBM (or compatible) PC parallel printer port and expands it to drive a matrix of stimulators [8]. Although the initial matrix was an 8 × 24 (192-element) array, the user can define a maximum of 16 × 16 elements.

The tactors in the prototype display were miniature electromechanical speakers 1/8 of an inch in thickness and 1 inch in diameter. These tactors were mounted in a tactor locator system (TLS) consisting of a stretch Lycra suit that maintained an interface pressure between the tactor and the skin. The configurations used in the proof-of-concept flights were either 8 × 3 matrices or 8 × 5 matrices. Eight columns of three or five tactors were sewn into the TLS and placed at 45-deg intervals, beginning at the midline. The stimulus waveform consists of 10 pulses of a 150 Hz rectangular pulse train operating at a 10% duty cycle, followed by a break of approximately 450 msec. The software programs to drive the tactors evolved continuously in response to feedback from each user and were tailored to meet the requirements of each community (e.g., attitude awareness for aircraft and navigation information for divers).

The first software program developed and tested in an aircraft conveyed the direction of "down," or the gravity vector. The gravity vector direction was presented intuitively as the point or center of the area on the torso that would experience pressure for a pilot strapped into a seat in the normal earth condition. Thus, a tilt of the seat to the left representing a bank of an aircraft to the left would activate the tactors on the lower left side. The stimulus would progressively rise up the left side as the aircraft increasingly banked to the left. Similarly, a tilt of the seat backward would place pressure on the lower back, and hence this area would be stimulated to represent a pitch of the aircraft upwards. Continuing through a loop when the aircraft is pointed straight up, the stimulus would be in the center of the back, and when inverted the tactor stimulus would be over both shoulders (i.e., where the pressure would be felt if the pilot strapped in the seat on the ground were to be inverted). Using this algorithm, a stimulus to the lower front right quadrant of the abdomen would represent a pitch of the aircraft down and to the right. Straight and level is the condition of flight most often experienced by a pilot, so an informational "null" was used to represent level flight plus or minus 3 deg in roll and plus or minus 2 deg in pitch. Outside of this null condition, a tactor would be activated to indicate intuitively the direction of the gravity vector.

To experience the stimuli in the laboratory of the sensation of roll and/or pitch as presented to the pilot, the gyro-attitude sensor was replaced with a joystick, which permitted subjects to experience the same tactile sensation on the ground while visually observing the equivalent aircraft orientation changes represented on a laptop computer using standard aircraft attitude-indicator symbology.

In this configuration, most subjects could readily learn within 30 min how to ascertain within 5 deg the pitch and roll information presented on their torso displays. The pitch and roll limits of the first prototype display were ±15 deg and ±45 deg, respectively. Alternatively, subjects using the device in a closed-loop configuration could position by tactile cues alone the simulated attitude of the aircraft within 5 deg of accuracy in pitch and roll. Similar accuracies were attained in actual flights in the aircraft with no reference to instruments or outside visual cues.

The most serious problems with the proof-of-concept flights were inadequate tactors and tactor locator system. The speakers (tactors) frequently failed when too much pressure was applied.

T-34 Test Flights

Seven test flights flown in October 1995 demonstrated that a pilot could perform simple aerobatics and all the basic maneuvers used in normal flight relying solely on haptic cues for attitude information.

The test pilot in the rear seat was deprived of all visual instruments (Fig. 5)

5. Rear cockpit of T-34C, BuNo 160266, with instruments removed.

and shrouded to prevent access to any outside visual references (Fig. 6).

A variety of commercial off-the-shelf tactors proved inadequate for the high noise and vibration aviation environment. A development program was initiated to develop more appropriate tactors for aviation as well as undersea environments. More robust tactors, consisting of pager motors mounted inside 1 inch circular nylon castings, were used for the T-34 flights. It was determined that for the particular combination of motor and housing, the optimal carrier frequency in noisy environments was 90 Hz. The tactor was turned off and on at 1, 4, and 10 Hz to convey subgroups within a given tactor position on the body.

The TLS was a stretch cotton/Nomex custom-fitted suit with four columns of five tactors centered on the front and back and on the left and right sides. Additional elastic and Velcro straps were used to maintain sufficient pressure between the tactors and the skin. Given the combination of TLS and tactors used, the test pilot could not consistently distinguish among the three middle tactors in the columns of five.

The algorithm to represent pitch and roll differed significantly from the Cessna flight tests. With only four columns available to provide pitch and roll information, it was necessary to activate two tactors simultaneously to present attitudes, which involved combined pitch and roll. This is in contrast with the single tactor location approach used in the Cessna proof of concept flights.

TSAS is designed to be used in conjunction with visual instruments, auditory displays, and any other source of orienting information.

Different algorithms were used for acrobatics and for the fine control of normal flight. The algorithms are defined in Table 1.

The pilot performed a variety of maneuvers, including straight and level flight, bank and pitch angle capture, climbing and descending turns, unusual attitude recovery, simple acrobatics (loops and aileron rolls), and ground-controlled approaches (GCA). The safety check pilot maintained all power settings and performed the navigation and radio communications required for safety of flight. The navy test pilot could easily perform all maneuvers when the tactor and TLS performed properly. When the technical problem of poor tactor interface (i.e., missed tactor) occurred, the test pilot could perceive he was in a null condition for pitch or roll when he was actually in a bank or pitch condition.

6. **Hood over rear cockpit to exclude all external visual cues.**

Interesting points derived from the fixed-wing flights included:

- The stimulus algorithms were very intuitive, requiring less than 20 min to learn.
- The pilot could easily switch between the acrobatic and fine control algorithms without misconstruing the mode of operation.
- Recovery from unusual attitudes was trivial, since even without instruments or outside cues the test pilot was always aware of the maneuvers being made by the check pilot in the front seat. Thus, the rear-seat pilot never experienced an unusual attitude other than when a "missed tractor" condition occurred.
- When the front-seat check pilot was performing acrobatic maneuvers and the test pilot in the rear seat did not have the TSAS system actuated, the test pilot reported that he experienced vertigo, whereas with the TSAS system engaged the test pilot reported that he was free of vertigo and aware of what maneuvers the check pilot was performing.

The lessons learned and inadequacies of the T-34 TSAS included:

- The TLS was not adequate in maintaining consistent pressure and resulted in "missed tactor" conditions, which is unsatisfactory for safe flight. Furthermore, the suit was too cumbersome as it involved the use of multiple elastic and Velcro straps and even duct tape to minimize the missed tactor condition.
- The tactors must be lighter and more robust for practical application.

H-60 Flights

Three months following the fixed-wing T-34 flight tests, the TSAS system was flown in an Army H-60 helicopter with several modifications.

Tactors were modified to increase the perceived amplitude of sensation to accommodate the increased high-amplitude, low-frequency noise encountered in the helicopter and also to shield the aircraft electronics from the electromagnetic interference of the pager motors.

Additional tactor locations were added to maintain heading (left and right thigh) to demonstrate navigation capabilities and to provide information required by the unique capabilities of the helicopter. Unlike fixed-wing aircraft, a helicopter can be climbing while it is in a nose-down attitude. The parameter selected for altitude control was airspeed (loss of altitude reflects increased airspeed) due to the lag in the barometric altimeter. Airspeed was presented on the left shoulder and the left wrist. Pitch and roll were represented as in the fixed-wing condition, but with different scaling to accommodate the reduced pitch and roll extremes of the rotor-wing platform.

The flight maneuvers consisted of straight and level flight, standard rate turns, unusual attitude recoveries, and GCA. As per the fixed wing tests, the male and female pilots could perform all maneuvers in the aircraft after a few training sessions on the ground-motion-based H-60 simulator. The complaints from the pilots focused on the TLS and the difficulty in maintaining consistent tactor contact.

H-60 Hover Display

At the request of the Joint Strike Fighter program, the TSAS team developed a display to improve the performance of hover and transition to forward flight. The flight tests in the T-34 and the H-60 made it apparent that the two areas that required improvement for a product to meet pilot acceptance were:

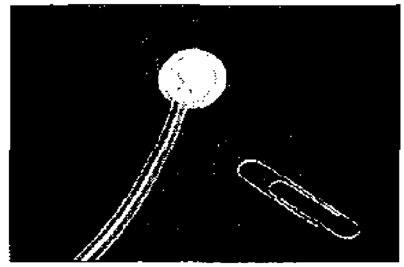
- Improved tactors. More perceptually robust, rugged, lightweight, and compatible with flight gear.
- Development of a TLS that maintains consistent tactor contact, yet is comfortable, easy to don and doff, very lightweight, and nonobtrusive to the point of being transparent to the user.

The tactor developed specifically for the hover demonstration was the Carlton Technologies Model 2856-Ao (now Steadfast Technologies, Tampa, FL) pneumatic tactor. This tactor has a hard-back plastic shell with a Latex diaphragm that faces the skin and vibrates when supplied with a source of oscillating air (Fig. 7). The optimal operating frequency for maximum perceived amplitude (psychophysical "loudness") was 50 Hz. This carrier frequency was turned on and off to provide pulse pattern frequencies of 1, 4, and 10 Hz.

The TLS problems were resolved with a prototype F-22 cooling/heating garment. The garment/vest, when connected to an air source, inflated slightly to provide a constant but light pressure that maintained the tactors snugly against the torso (Fig. 8). Tactors were arranged in eight columns as in the Cessna flight tests (front, back, left, right, and midway between these four cardinal axes to provide 45 deg spacing around the torso) but with only two tactors per column (9 cm between tactors) due to the restricted area available in the vest.

The flight parameters that were initially selected to enhance hover were velocity and acceleration. The limited torso coverage afforded by the prototype F-22 cooling/heating garment did not permit sufficient separation of the tactors to separate intuitively or to distinguish the velocity and acceleration vectors when provided simultaneously on the same column. Based on simulator trials, it was found that tactile cuing of only the velocity vector was sufficient to detect hover drift while using the traditional instruments for attitude information.

The torso tactor column pairs were stimulated to provide pilot cuing of the horizontal direction of the helicopter drift velocity, and the magnitude of the drift velocity vector was coded by frequency modulation of the 50 Hz carrier frequency. When the helicopter horizontal velocity magnitude was less than 0.3 m/sec, no



7. Carleton Technologies Model 2856-Ao pneumatic tactor.

tactors were activated. Between 0.3 and 0.7 m/sec horizontal velocity, the lowest frequency of 1 Hz was used to convey a slow drift. Between 0.7 and 2.0 m/sec horizontal velocity, the midrange frequency of 4 Hz was used to represent a medium drift rate, and above 2.0 m/sec the highest frequency of 10 Hz was employed.

The drift velocity sensor used for in-flight testing was a combination global positioning system/inertial navigation system (GPS/INS) that used differential GPS corrections to provide velocity accuracy of 0.025 m/sec.

Each of the four test pilots flew a familiarization flight to develop experience with the TSAS before the evaluation flight. For the evaluation flights, they performed a series of maneuvers with and without outside

Table 1. TSAS T-34 Tactile Display Algorithm

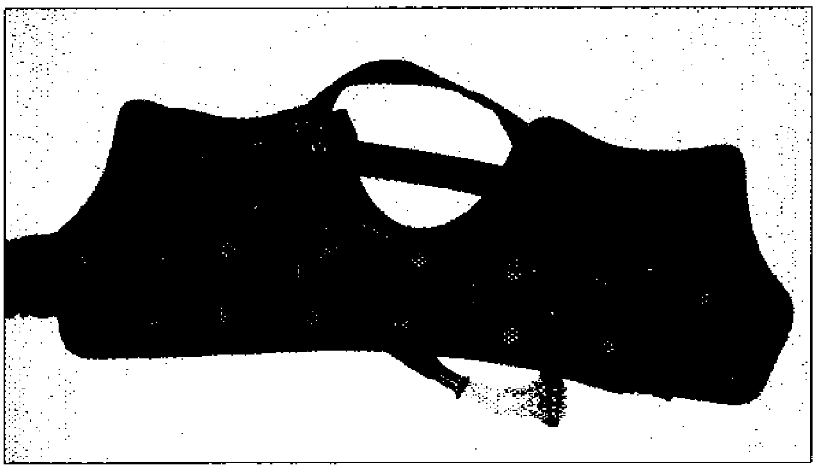
Fine Algorithm			Acrobatic Algorithm		
Angle (deg)	Pulse Pattern (Hz)	Tactor Nos.	Angle (deg)	Pulse Pattern (Hz)	Tactor Nos.
0-1	no tactor activated		0-1	no tactor activated	
1-3	1	1	1-5	1	1
3-5	4	1	5-10	4	1
5-10	10	1	10-20	10	1
10-15	1	3	20-30	1	2
15-20	4	3	30-40	4	2
20-25	10	3	40-50	10	2
25-30	1	4	50-60	1	3
30-35	4	4	60-75	4	3
35-40	10	4	75-90	10	3
			90-105	1	4
			105-120	4	4
			120-135	10	4
			135-150	1	5
			150-165	4	5
			165-180	10	5

visual cues, and with and without TSAS. For portions of the flight test that required denying the pilots access to outside references, the chin bubble of the aircraft was covered with opaque material and the pilots wore *foggles*, glasses that degrade distant vision to 20/200 acuity.

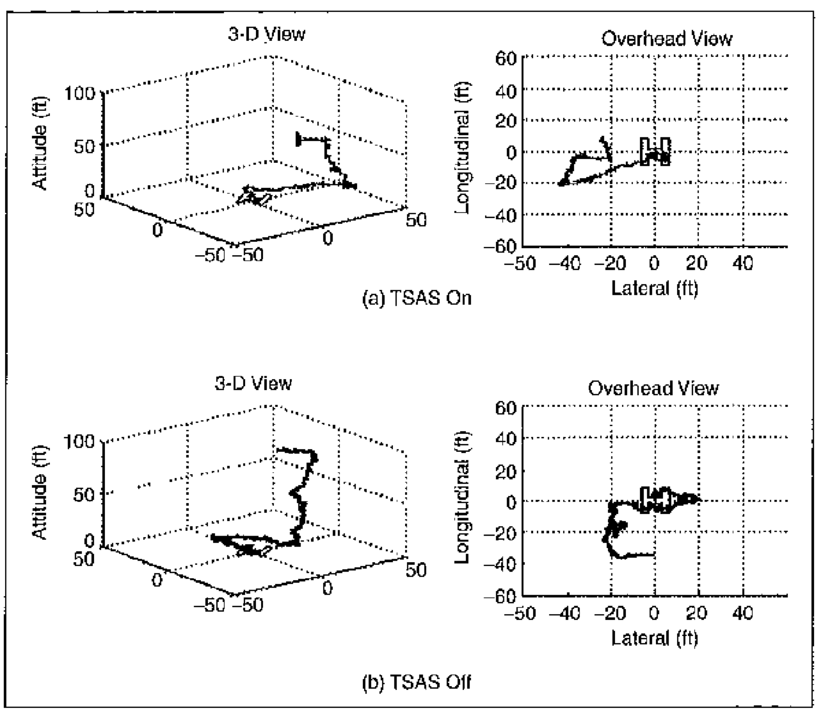
Pilots performed simulated shipboard departure operations maneuvers consisting of an ascent to an in-ground-effect hover (10 ft), a left sideward hover for 50 ft, ascent to an out-of-ground-effect hover (70 ft), and forward takeoff to translational flight.

With TSAS on, the pilot lifts off and is blown slightly to the right by the wind from the left, but he is aware of and able to compensate for this drift using the tactile cues. He performs the left 50 ft sideward hover to simulate clearing the ship, ascends to the 70 ft out-of-ground-effect hover, and departs safely. In contrast, with TSAS off, the same pilot on initial ascent drifts unaware and uncontrolled 70 ft to the right. His leftward drift to "clear the ship" places him at the point of origin for the ascent and departure. Similarly, the pilots performed the other complex flight maneuvers with improved control in both visual and simulated instrument flight conditions.

The pilots were asked to rate their situation awareness using the Modified China Lake Situation Awareness Scale (Table 2). During the simulated shipboard departures, all pilots with TSAS on rated their situation awareness as good, between 1.5 and 2.0. That is, they had full control of the aircraft and did not have to shed any normal tasks to maintain control. However, with TSAS off, they ranked their situation awareness between poor (4.0) and very poor (5.0). Simply having an intuitive awareness of helicopter velocity and change of velocity permitted the pilots to perform the complex task safely and without stress.



8. TSAS tactor locator system.



9. Simulated shipboard take-off with and without TSAS.

Discussion and Recommendations

The use of tactile displays to control aircraft is not new. Several attempts to present complex information have failed in the past when researchers attempted to provide information in a nonintuitive manner. For example, it requires a period of months or years to train an individual to learn Braille. However, we have been trained from birth to direct attention to, or be aware of, the location of a stimulus that is tapping on the body. Except in the microgravity conditions of space, or when immersed in water, our body is always in contact with objects that provide us with an awareness of down. Even when flying, we continue to be provided with this information, but it is false. TSAS merely takes advantage of the lifelong training we have experienced to provide the true direction of down in the unusual condition of flight

Although TSAS in its prototype configurations has proven an excellent tool to maintain spatial orientation, the ultimate capabilities of intuitively designed tactile displays have yet to be realized:

1) Tactor technology is an area that must receive attention to advance the development of haptic devices. To date, all the tactors used successfully in the TSAS program have been vibratory and stimulate the skin perpendicularly to its surface. Direct electrical tactors, although much improved, still present difficulties in maintaining a consistent interface with the skin. The Navy sponsored several tactor developments in the TSAS program to produce alternative tactors (e.g., "stroke" the skin parallel to the surface vs. the traditional "poke" the skin perpendicular to the surface) using new materials and microelectromechanical systems (MEMS)

Table 2. Modified China Lake Situation Awareness Scale

SA Scale Value	Interpretation
Very Good 1	- Full Knowledge of Aircraft Energy State /Mission - Full Ability to Anticipate/Accommodate Trends
Good 2	- Full Knowledge of Aircraft Energy State /Mission - Partial Ability to Anticipate/ Accommodate Trends - No Task Shedding
Adequate 3	- Full Knowledge of Aircraft Energy State /Mission - Saturated Ability to Anticipate/ Accommodate Trends - Some Shedding of Minor Tasks
Poor 4	- Fair Knowledge of Aircraft Energy State /Mission - Saturated Ability to Anticipate/ Accommodate Trends - Shedding of All Minor Tasks as well as Many not Essential to Flight Safety/Mission Effectiveness
Very Poor 5	- Minimal Knowledge of Aircraft Energy State /Mission - Oversaturated Ability to Anticipate/Accommodate Trends - Shedding of All Tasks not Absolutely Essential to Flight Safety/Mission Effectiveness

technologies. Tactors that can provide a wide range of frequency, amplitude, and waveforms will be more versatile.

2) The tactor locator system has considerable room for improvement. The TLS certainly posed the most difficult technical problem in the first flight tests. The F-22 cooling/heating garment provided three benefits: the skin was maintained in a constant-temperature, comfortable, moisture-free condition, ensuring controlled conditions for stimulation; the tactors were held in place with the appropriate amount of pressure; and pilots did not object to the garment since it was comfortable, unobtrusive, and aircraft friendly. A drawback of the current garment is the small area of torso coverage. This issue is being addressed in order to provide full torso coverage for complete pitch and roll information for fixed-wing aircraft, and to offer similar pitch and roll information to the helicopter pilots as they transition out of hover.

3) There are many basic science questions in the realm of tactile/haptic psychophysics that must be answered to optimize TSAS. Optimization of tactor location and spacing will vary with different types of tactors and will need to be readdressed as new tactors are developed. The skin, like all the other sensory systems, is subject to a variety of well-known illusions that will serve to enhance the effectiveness of tactile torso and limb devices. When using multiple stimulators, as in the torso vest, it is possible to take advantage of basic psychophysical principles to effect changes in perceived magnitude, position, and motion of the stimulus. For example, the perceived magnitude of a pair of vibrotactile stimuli presented in close temporal succession is dependent on the relative frequencies of the two stimuli [9]. The perceived position of two tactile pulses presented in rapid succession at different spatial locations will appear as a single moving source [10]. The latter principle was used in the torso suit to create the sensation of motion or directional flow over the thorax. Using these and other sensory illusions, it is actually possible to create compelling position and motion perceptions using *fewer* tactors than in some of our current prototype suits. Hans-Leukas Teuber [11] demonstrated that the number of dimensions of a perception exceeds that of the physical stimuli. By varying only the frequency and intensity, his subjects experienced changes in four psychophysical measures: pitch, density, volume, and loudness. Given the large number of available stimulus parameters (intensity, frequency, body position, interstimulus interval, multiple tactors with different qualities, etc.), it will be possible tactually to present a wide variety of perceptions to convey position, motion, and target information in a way analogous to the observations of Teuber. Research using multiple parameters and tactor types will provide the answer as to how many types of information can be presented and used simultaneously through the sensory channel of touch.

4) When and what information to provide during different phases of the flight and the mission is an issue to be decided by the users and to be incorporated into intelligent software [12]. For example, at what point in the transition between hover and forward flight, or if a pilot loses control in hover, should the information transition from hover cues to provide pitch and roll information?

5) Although spatial orientation can be maintained through TSAS operating independently, TSAS was not designed to provide stand-alone information. It is to be used as nature uses her sense of touch; that is, in conjunction with visual instruments, auditory displays (especially three-dimensional sound), and any other source of orienting information. To optimize the benefits of TSAS, the synergy and integration of these sensory systems must be addressed in the context of their interaction with the effects of dynamically changing gravito-inertial force fields, a variable that profoundly affects each sensory system.

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