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TACTILE INSTRUMENT FOR AVIATION

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Aviation in itself is not inherently dangerous. But to an even greater degree than the sea, it is terribly unforgiving of any carelessness, incapacity or neglect.

*Original author unknown,
dates back to a World War II advisory.*

Abstract

Spatial disorientation and the subsequent loss of situation awareness account for a significant percentage of fatal mishaps in aviation. In our normal earth-bound environment, spatial orientation is continuously maintained by correct information from three independent, redundant, and concordant sensory systems: vision, the inner ear or vestibular system, and the skin, joint, and muscle receptors or somatosensory system. However, in the aviation environment, the vestibular and somatosensory sensations currently do not provide accurate orientation information. The only reliable source of orientation information is vision. For this reason, spatial disorientation mishaps occur when information from the visual system is compromised (e.g., temporary distraction, increased workload, transitions between visual meteorological conditions and instrument meteorological conditions, reduced visibility, or boredom), and the pilot subsequently becomes disoriented.

The Tactile Situation Awareness System (TSAS¹) is an advanced flight instrument that uses the sensory channel of touch to provide situation awareness information to pilots. The TSAS system accepts data from various aircraft sensors and presents this information via tactile stimulators or “tactors” integrated into flight garments. TSAS has the capability of presenting a variety of flight parameter information, including, attitude, altitude, velocity, navigation, acceleration, threat location, and/or target location.

A series of flight demonstrations were conducted to demonstrate that a pilot could receive situation awareness information using a tactile instrument during flying operations. The first flight demonstration project was conducted in a United States Navy T-34 aircraft. The objectives of the T-34 TSAS flight demonstration program were to demonstrate:

- That a significant amount of orientation information can be intuitively provided continuously by the under-utilized sense of touch.
- That a pilot using TSAS can effectively maintain control of an aircraft in normal and certain acrobatic flight conditions with no visual cues.

The first flight of the TSAS-modified T-34 was 11 October 1995, and seven flight test events were completed by 19 October 1995. During the flight tests, the test pilot in the rear seat was shrouded to block any outside visual cues and all visual flight instruments in the rear cockpit were removed. The test pilot flew the following maneuvers: straight and level for 5 minutes; bank angle capture; pitch angle capture; climbing and descending turns; unusual attitude recovery; loops; aileron rolls; and ground controlled approaches. Results showed that roll and pitch information could be provided by tactile cues via an array of tactors incorporated into a torso harness. The test pilot performed all maneuvers without visual cues, relying solely on tactile cues for attitude information. The T-34 TSAS flight demonstration showed that a pilot relying on tactile information could maintain control of an aircraft.

Following the success of the T-34 flight test program, the Joint Strike Fighter TSAS flight demonstration project integrated an array of tactors, a cooling vest, and Global Positioning/Inertial Navigation System technologies into a single system for evaluation in an UH-60 Helicopter. A 10-event test operation was conducted to demonstrate the utility of this advanced human-machine interface for performing hover operations. Objectives of the Joint Strike Fighter TSAS flight demonstration program were to demonstrate:

¹ Pronounced Tee - Sas.

- The potential for TSAS technology to reduce pilot workload and enhance situation awareness during hover and transition to forward flight.
- That a pilot using TSAS can effectively hover and transition to forward flight in a vertical lift aircraft with degraded outside visual cues.
- The feasibility of integrating tactile instrument technology into military flight garments.

The first flight of the TSAS-modified UH-60 was 09 September 1997, and 10 flight test events were successfully completed by 19 September 1997. The pilots successfully performed all maneuvers with degraded outside visual cues, relying on tactile cues for the necessary information. Summary results showed that TSAS increased pilot situation awareness and reduced pilot workload when using the tactile instrument to obtain hover information, especially during simulated instrument meteorological conditions shipboard operations. Prototype hardware development showed that tactile instruments could be integrated into military flight garments. The tactile instrument reduced pilot workload and provided the opportunity to devote more time to other instruments and systems when flying in task saturated conditions. These effects can substantially increase mission effectiveness.

TSAS, integrated with visual displays and audio systems into a synergistic situation awareness instrument represents the basis for the next generation human-machine interface for military and commercial aircraft. The TSAS flight demonstrations were the first time tactile instruments were successfully flown in military aircraft and these demonstrations showed that TSAS has the potential to save lives and increase mission effectiveness. To fully realize the potential of TSAS, the further development, testing, and evaluation of the following technology areas need to be pursued:

- Integration of tactile instruments with helmet mounted displays and 3D audio displays.
- Significant improvement in tactor technology.
- Tactor integration with flight garments.
- Miniaturization of all TSAS components.
- Development of “smart” software to enable intelligent switching between various modes of situation awareness information.

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Acronyms

The following lists alphabetically the acronyms used in this thesis.

ADS	Aeronautical Design Standard
AFCS	Automatic Flight Control System
AFSOC	Air Force Special Operations Command
AGL	Above Ground Level
AIS	Airborne Instrument System
AOA	Angle of Attack
AOB	Angle of Bank
CLSA	China Lake Situation Awareness
COTS	Commercial Off The Shelf
CSS	Coastal Systems Station
DGPS	Differential Global Positioning System
EAI	Engineering Acoustics, Inc
EVA	Extra Vehicular Activity
FET	Field Effect Transistor
FSIPT	Flight Systems Integrated Product Team
GCA	Ground Controlled Approach
GPS	Global Positioning System
GUI	Graphical User Interface
HMD	Head Mounted Display
HUD	Heads-Up Display
IGE	In Ground Effect
IHADSS	Integrated Helmet and Display Sighting System
IMC	Instrument Meteorological Conditions
INS	Inertial Navigation System
INS/GPS	Inertial Navigation System/ Global Positioning System
IO	Instructor Operation
JSF	Joint Strike Fighter
MFD	Multi-Function Displays
MSL	Mean Sea Level
NAMRL	Naval Aerospace Medical Research Laboratory
NATOPS	Naval Air Training and Operating Procedures Standardization
NASA	National Aeronautics and Space Administration
NAWC-AD	Naval Air Warfare Center – Aircraft Division
NVD	Night Vision Device
NVG	Night Vision Goggle
OGE	Out of Ground Effect
ONR	Office of Naval Research
ROC	Rate of Climb
RTCM-SC 104	Radio Technical Commission for Maritime Services, Special Committee 104
RSD	Recognized Spatial Disorientation
SBIR	Small Business Innovative Research
SV-2	Survival Vest – 2
TCLS	Tactor Control Laboratory System
TLS	Tactor Locator System
TSAS	Tactile Situation Awareness System
US	United States
USAARL	United States Army Aeromedical Research Laboratory
USD	Unrecognised Spatial Disorientation
UTM	Universal Transverse Mercator
UWF-IHMC	University of West Florida, Institute for Human and Machine Cognition
VMC	Visual Meteorological Conditions

VME	Versa Module Europa
V/STOL	Vertical Short Take Off and Landing
VTOS-N1	VibroTactile Orientation System – Navy 1
WGS	World Geodetic Survey

Chapter 1

A fierce and monkish art; a castigation of the flesh. You must cut out your imagination and not fly an airplane but regulate a half-dozen instrumentsAt first, the conflicts between animal sense and engineering brain are irresistibly strong.

-- *Wolfgang Langewiesche, describing flying on instruments, 'A Flier's world,' 1943.*

Introduction

Spatial disorientation and the subsequent loss of situation awareness account for a significant percentage of mishaps in aviation. As aircraft have become more reliable and safer from a mechanical perspective, the proportion of human-related mishaps has increased. In the aviation environment, the safety of the aircraft and the ability to perform the aircraft's mission is highly dependent on the pilot having an accurate awareness of the current situation, including the state of one's own aircraft, mission goals, external conditions, other aircraft, and other hostile factors. Without this situation awareness, the pilot will be unable to effectively perform the mission. Although not restricted to the aviation environment, when loss of situation awareness occurs in aviation, the consequences are more severe, frequently resulting in loss of life and or aircraft. Acquiring and maintaining situation awareness becomes increasingly more difficult as the complexity and dynamics of the military aviation environment increase.

Situation awareness has been defined in the following manner.

The perception of the elements in the environment within a volume of space and time, the comprehension of their meaning and the projection of their status in the near future (Endsley, 1988, 1995).

The first and critical step in acquiring and maintaining situation awareness is to perceive the status, attributes, and dynamics of elements in the environment (Figure 1, shaded region, Endsley, 1995). For aviation, a pilot would perceive elements such as aircraft attitude, altitude, or motion relative to the earth or other significant objects. Without an accurate percept of Level 1 in situation awareness, the pilot will experience a loss of situation awareness that can have severe and costly consequences.

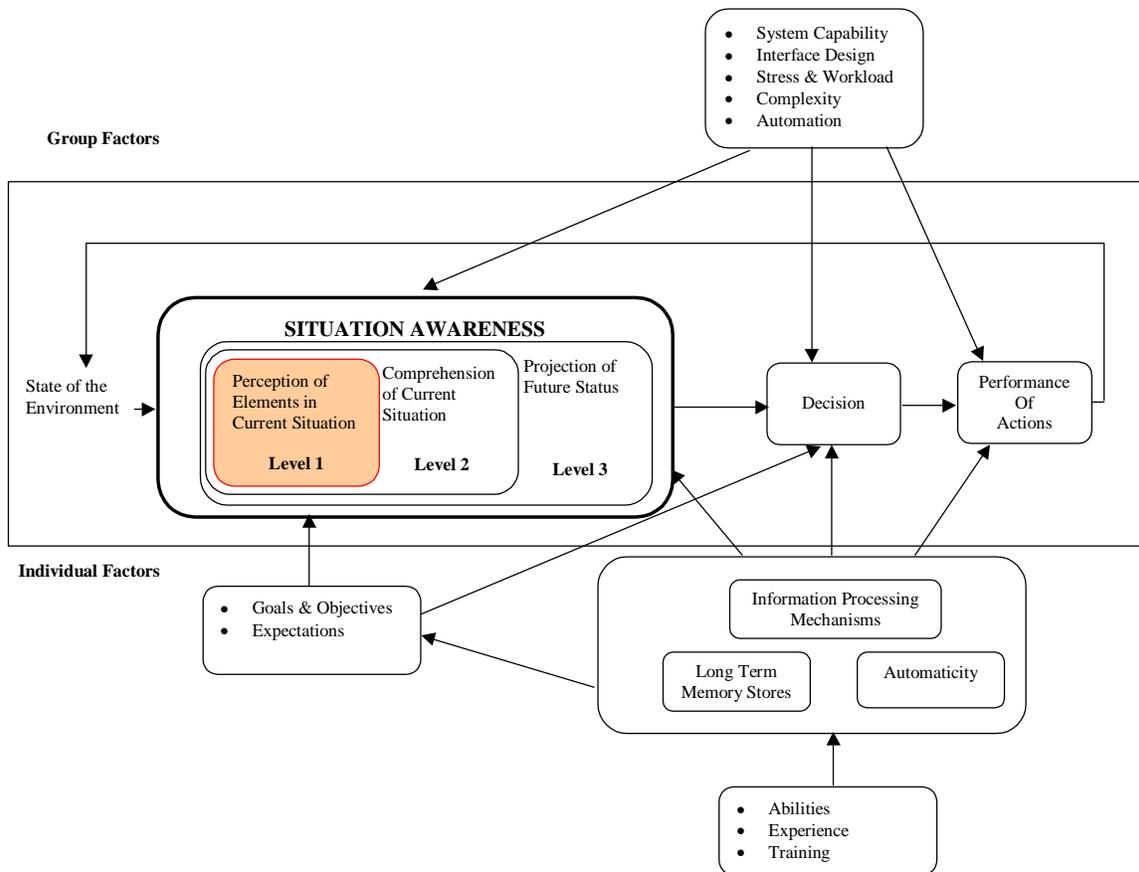


Figure 1: Model of situation awareness (from Endsley, 1995).

Spatial disorientation occurs when the pilot has an incorrect perception of the attitude, altitude, or motion of one's own aircraft relative to the earth or other significant objects. This corresponds to an inaccurate perception of the elements in the current situation (Figure 1, Situation Awareness Model, Level 1). Spatial disorientation and the subsequent loss of situation awareness account for a significant percentage of mishaps in aviation. Based on accident rates for the United States (US) Air Force, Navy, and Army, spatial disorientation mishaps result in the tragic loss of 40 lives on average per year (Gillingham, 1992; Matthews and Gregory, 1999; Braithwaite, Groh, and Alvarez, 1997). The cost of spatial disorientation mishaps also includes mission failure, the impairment of mission effectiveness, and the monetary value of aircraft and equipment loss. Considering the number of military air forces, commercial and general aviation, the estimated annual material cost of spatial disorientation mishaps is in the billions of dollars (Gillingham, 1992). In today's military aviation, there is an added emphasis on night flying, all weather capability, and low altitude missions which are all factors that increase spatial disorientation. An increased rate of spatial disorientation accidents can be expected unless interventions are made through improved understanding of spatial disorientation, advances in man-machine interfaces, and better pilot selection and training.

Spatial disorientation mishaps have occurred ever since the terrestrial human entered the dynamic three-dimensional aeronautical environment. As long as early aviators could maintain clear visual reference with respect to the ground or horizon, orientation did not pose a significant problem. However, "cloud flying" and other forms of flight in reduced visibility claimed the lives of early aviators with an alarming frequency (Ocker and Crane, 1932). The incidence of spatial disorientation mishaps declined when pilots received the appropriate training in the correct use of aircraft instruments developed by Dr. Elmer A. Sperry of the Sperry Gyroscope Co., including the gyro-stabilized artificial horizon and the turn indicator (Stark, 1935). However, spatial disorientation mishaps were not eliminated completely because the gyro-stabilized

artificial horizon or attitude indicator is a visual instrument, and only provides orientation information when the aviator looks at the instrument for sufficient time to see and cognitively process the information.

In our day-to-day terrestrial dynamic activities, spatial orientation is continuously maintained by accurate information from three independent, redundant, and concordant sensory systems (Figure 2):

- Vision.
- Vestibular system or balance component of the inner ear.
- Somatosensory system (skin, joint, and muscle sensors²).

These complementary and reliable sources of information are integrated in the central nervous system to maintain accurate spatial orientation awareness during static and ambulatory terrestrial conditions.

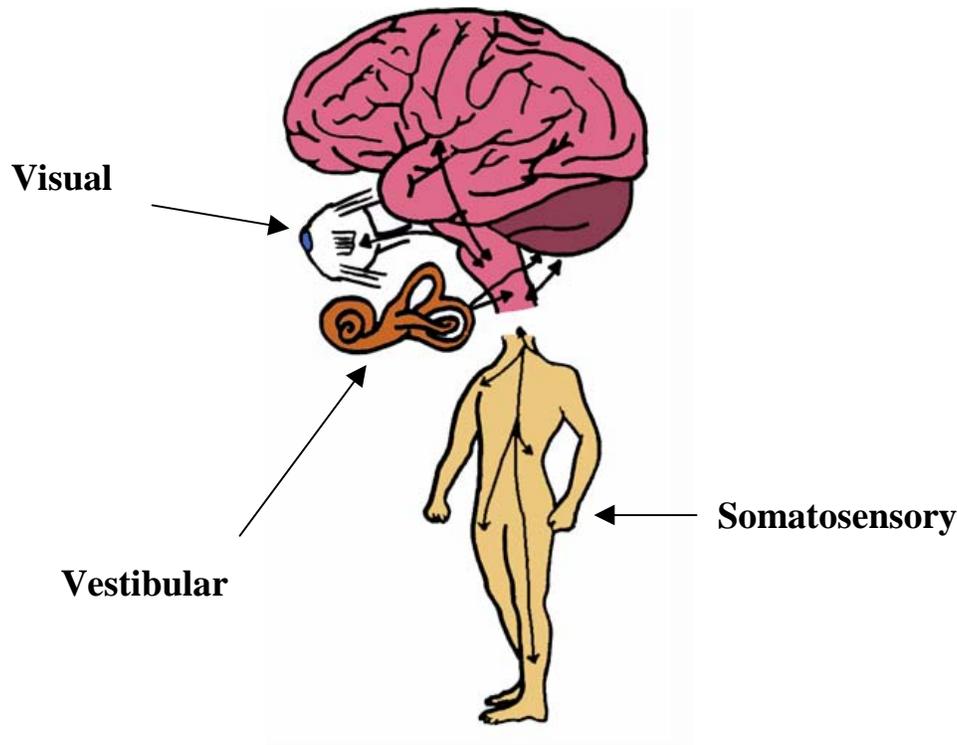


Figure 2: Spatial orientation system (from Correia and Guedry, 1978).

In the aeronautical environment, the vestibular and somatosensory systems no longer provide reliable information concerning the magnitude or direction of the gravity vector or “down” (Figure 3). During aircraft maneuvers, the almost continuous changes in aircraft acceleration expose aircrew to a resultant gravito-inertial force that is constantly changing in magnitude and direction. Under such circumstances, somatosensory and vestibular information concerning the direction of “down” will be inaccurate, and increased reliance must be placed on visual information if spatial orientation is to be maintained. The only reliable source of information is that obtained visually. Furthermore, the varying gravito-inertial force fields, misleading visual information and prolonged rotations can produce illusions of motion and position (see Benson, 1999a,b or Gillingham and Previc, 1996 for a complete description of spatial disorientation illusions). Thus the central nervous system, which normally integrates continuous accurate information from multiple sources, must now face the task of maintaining orientation and overcoming illusions by determining which sensory channel(s) is presenting correct information, and ignoring information from the other sensory channel(s).

² Baroreceptors and other sensors of internal pressure have orientation significance, but for this research, somatosensory system connotes only cutaneous and muscle-joint information.

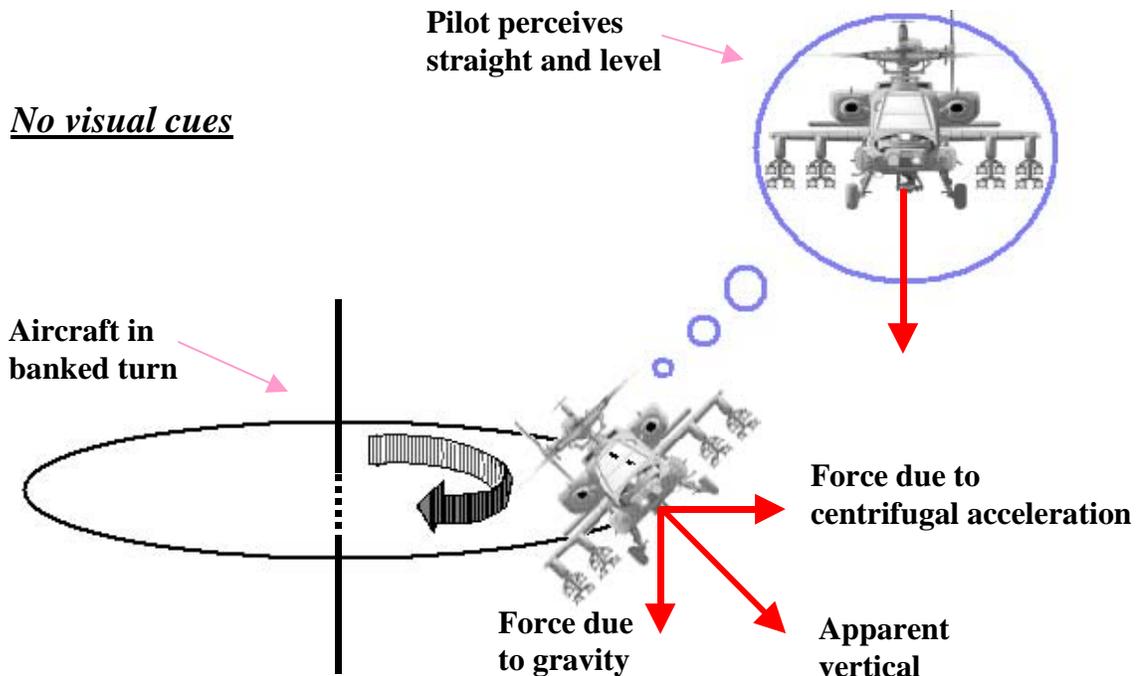


Figure 3: Inaccurate perception of down (adapted from Benson, 1999b).

Aviators are instructed to use a strategy of visual dominance, where visual orientation cues must be used to maintain spatial orientation at the exclusion of all other sensory cues, including vestibular and somatosensory (Gillingham and Previc, 1996). When the pilot has a clear view of the horizon, peripheral vision provides visual orientation cues through normal neural pathways. However, without a clear view of the horizon, visual orientation cues are obtained through focal vision of the attitude indicator, and as a result of training and experience are integrated to maintain spatial orientation. The pilot has learned to interpret the focal visual information on the attitude indicator and other flight instruments to develop a concept of where he is, what he is doing, and where he is going; and he refers to that concept when controlling his aircraft. As described by Wolfgang Langewiesche (1943), this complex talent must be developed through extensive training and maintained through practice; and it is the fragility of this concept that makes spatial disorientation such a hazard.

The typical spatial disorientation mishap occurs when visual attention is distracted (for example, temporary distraction, increased workload, cockpit emergencies, transitions between visual and meteorological conditions, reduced visibility, or boredom). Lyons, Ercole, Freeman, and Gillingham (1992) reported that for the US Air Force during 1990–1991, “most of these (spatial disorientation) accidents (11 / 13, 85%) had one or more cockpit attention factors”. While there are many situations that contribute to spatial disorientation, the most common is when a pilot looks away from the aircraft’s orientation instruments and the horizon. Most spatial disorientation mishaps are not due to radical maneuvers. When a pilot looks away from the horizon (loss of focal and peripheral visual cues), or looks away from his artificial horizon in instrument weather (loss of focal visual cues), the central nervous system computes spatial orientation with the information at its disposal, vestibular and somatosensory. This vestibular and somatosensory information is redundant but frequently incorrect. In such circumstances, it is a physiologically normal response to experience spatial disorientation. Furthermore, conflicts between focal visual and vestibular orientation information tend to resolve themselves in support of the vestibular information (Gillingham and Previc, 1996). This may lead the pilot to make or fail to make corrections to the aircraft’s flight path, possibly causing a mishap. Finally, the central nervous system must not only contend with attempting to determine what is reliable versus unreliable sensory information, but must also formulate a muscular

response directed through aircraft controls rather than the reflex postural mechanisms learned over many years. The control characteristics of the aircraft do not always match the natural aptitudes of man.

The apparent solution to spatial disorientation was the introduction by Dr. Elmer A. Sperry in the 1920's of gyro stabilized instruments to give accurate attitude and heading information, especially under non-visual flight conditions (Ocker and Crane, 1932). Human factors engineers then redesigned instrument presentation of information, as well as rearranging instruments in clusters that permitted the pilot to quickly visually interpret more accurately the aircraft orientation. Despite the improvements made by organizing information spatially, eliminating highly coded information and utilizing pictorial presentation, spatial disorientation accidents have not been eliminated.

The opportunities for spatial disorientation mishaps are constantly increasing due to new technology in modern aircraft, more frequent night operations, requirements for all weather flying, and increased low-level or "nap-of-the-earth" flight. In addition, the more demanding pilot workload during sustained operations of overseas deployment produces subjective fatigue (Neville, Bisson, French, Boll, and Storm, 1994). All of these factors are conducive to spatial disorientation.

New technology in modern aircraft has in some circumstances actually increased spatial disorientation problems. The problems associated with vestibular illusions have intensified by the introduction of high agility thrust-vectoring aircraft. The increased occurrence of vestibular illusions can affect the reliability of the already compromised visual system, in addition to disturbing the postural reflexes necessary to execute proper muscle responses. The pilot has been progressively isolated from somatosensory cues because of improved cockpit vibration absorption, and the loss of feedback through stick, rudder and throttle controls with the advent of fly-by-wire technology.

Similarly, technology has not been kind to the visual channel. In current aircraft cockpits, the sensory channel of focal vision is the only channel capable of assessing many flight functions, including orientation. The term "visual clutter" has been created to describe the wide variety and number of visual instruments that comprise a cockpit panel in a modern aircraft (Figure 4). Sophisticated visual displays such as Heads-Up Displays (HUDs), Multi-Function Displays (MFDs) and Head-Mounted Displays (HMDs) have been developed to provide the aviator with mission critical information, including orientation information.



Figure 4: F18 C/D cockpit showing the complex array of visual instruments.

The HUD uses the technique of placing symbology or information collimated at optical infinity in the pilot's field-of-view. This allows the pilot to access both the out-the-cockpit view of the world and onboard aircraft visual displays in the same location. The flight information symbology on HUDs, MFDs and HMDs is often presented in a complex and non-intuitive manner, and extensive training and practice is required to quickly interpret the meanings of all the presented symbology (Figure 5). Furthermore, Foyle, Sanford, and McCann (1991) showed that limitations on visual attention prevented simultaneous processing of the HUD symbology and the "out-the-cockpit" information. The placement of MFDs and forward-looking infrared displays on the instrument panel directly in front of the pilot has demoted the traditional primary flight instruments to smaller and remote locations on the instrument panel (Figure 4). MFDs and HMDs are capable of displaying large amounts of information by using different modes or "pages". Each display page contains specific information (weapons, navigation, engine status, orientation). Switching between pages to obtain the required information is either automatic or pilot selectable.



Figure 5: HUD symbology from HH-60 helicopter (from O'Rourke and Foggin, 1997).

Just as in Sperry's time, these sophisticated displays provide no orientation information when the pilots' attention is directed to other visual tasks including weapons systems and navigation. The result is that pilot workload to maintain orientation has actually increased (Gillingham, 1992). HUDs, MFDs and HMDs, which present a wide range of information in addition to attitude information, have not proven to be the solution for spatial disorientation as was once envisioned.

In the early 1970's, Night Vision Devices (NVDs) were introduced that have been very successful for military flight operations in the dark (Crowley, 1991). However, NVDs significantly reduce the effective visual field width and depth perception of a pilot, thus reducing visual orientation cues and predisposing aviators to spatial disorientation. Between 1987 and 1995, the US Army reported that in helicopters, the spatial disorientation accident rate for day-time flight was 1.66 per 100,000 flight hours, and for NVD flight an astonishing 9.00 per 100,000 flight hours (Braithwaite, Douglass, Durnford, and Lucas, 1998). This represents a 550% increase in spatial disorientation mishaps while using NVDs.

Not since Sperry has there been any further landmark developments in introducing instruments or instrumentation to reduce spatial disorientation mishaps. It may be that spatial orientation, which even on the ground involves the simultaneous integration of information from multiple sensory systems, poses an even more complex problem in the aviation environment, such that future human factors solutions must involve more than one sensory system.

Examination of aircraft mishaps emphasizes that momentary visual distraction from primary flight instruments caused by any number of factors including in-flight emergencies may result in a mishap (Figure 6). In a study of pilot situation awareness, Fracker (1989) showed that a pilot's attention capacity is limited, and when that attention capacity limit is reached, more attention to some elements (such as hostile aircraft) may cause a loss of situation awareness on other elements (such as spatial orientation). The limit of attention of a pilot can occur rather quickly in the complex aviation environment. Furthermore, Fracker (1989) showed that attention is allocated to elements based on the degree to which they can enhance or threaten task performance. In an aviation environment with multiple attention elements, if spatial orientation elements are not perceived to be a threat or a performance enhancement - which can occur when vestibular and somatosensory senses are providing incorrect information - attention to the correct visual spatial orientation cues may be reduced. The pilot's attention filtering is focused on other visual elements,

and not on the primary flight instruments. This distraction from primary flight instruments may be catastrophic.



Figure 6: Helicopter mishap.

As individual aircraft costs escalate and defence budgets are further constrained, we cannot afford the continued loss of what in many cases are becoming non-renewable resources. When aircraft mishaps are categorized by causation factors, the largest single factor is consistently human or pilot error (United States General Accounting Office, 1996). The US Air Force has indicated that the most significant human-factors problem in aviation is spatial disorientation (Dehart, 1986).

Surveys spanning the past 40 years have shown that spatial disorientation mishaps have a critical and often severe outcome. Spatial disorientation mishaps are categorized as Type I, Unrecognised Spatial Disorientation (USD), or Type II, Recognized Spatial Disorientation (RSD), with Type I the most common type of spatial disorientation mishap. One hundred percent of the US Air Force spatial disorientation mishaps during 1990–1991 were Type I (Lyons *et al.* 1992). US Army surveys show that 90% of the US Army spatial disorientation mishaps for the 1987–1995 timeframe were Type I. Furthermore, although only 30% of rotary wing accidents involved spatial disorientation, spatial disorientation mishaps were responsible for 54% of fatalities (Braithwaite *et al.* 1997; and Durnford, Crowley, Rosado, Harper, and DeRoche, 1995). Aviators need improved tools to recognize and/or prevent spatial disorientation.

Spatial disorientation frequently compromises mission success. The Iran hostage rescue team was forced to turn back due to a spatial disorientation mishap at the Desert One rendezvous site (Kyle, 1990). Of the 15 US Navy aircraft lost to non-combatant action in the Desert Shield/Storm conflict, seven were spatial disorientation mishaps (Alkov, 1991). During the Falkland conflict, 5 of the 6 helicopter losses experienced by the British Defence Forces were due to spatial disorientation (Vyrnwy-Jones, 1988).

An example of the devastating effects of spatial disorientation is illustrated by the following mishap (Figure 7). In January 1996, shortly after take off, a US Navy F-14 Tomcat crashed into a residential suburb destroying several homes. The two aircrew and three people on the ground were killed instantly.

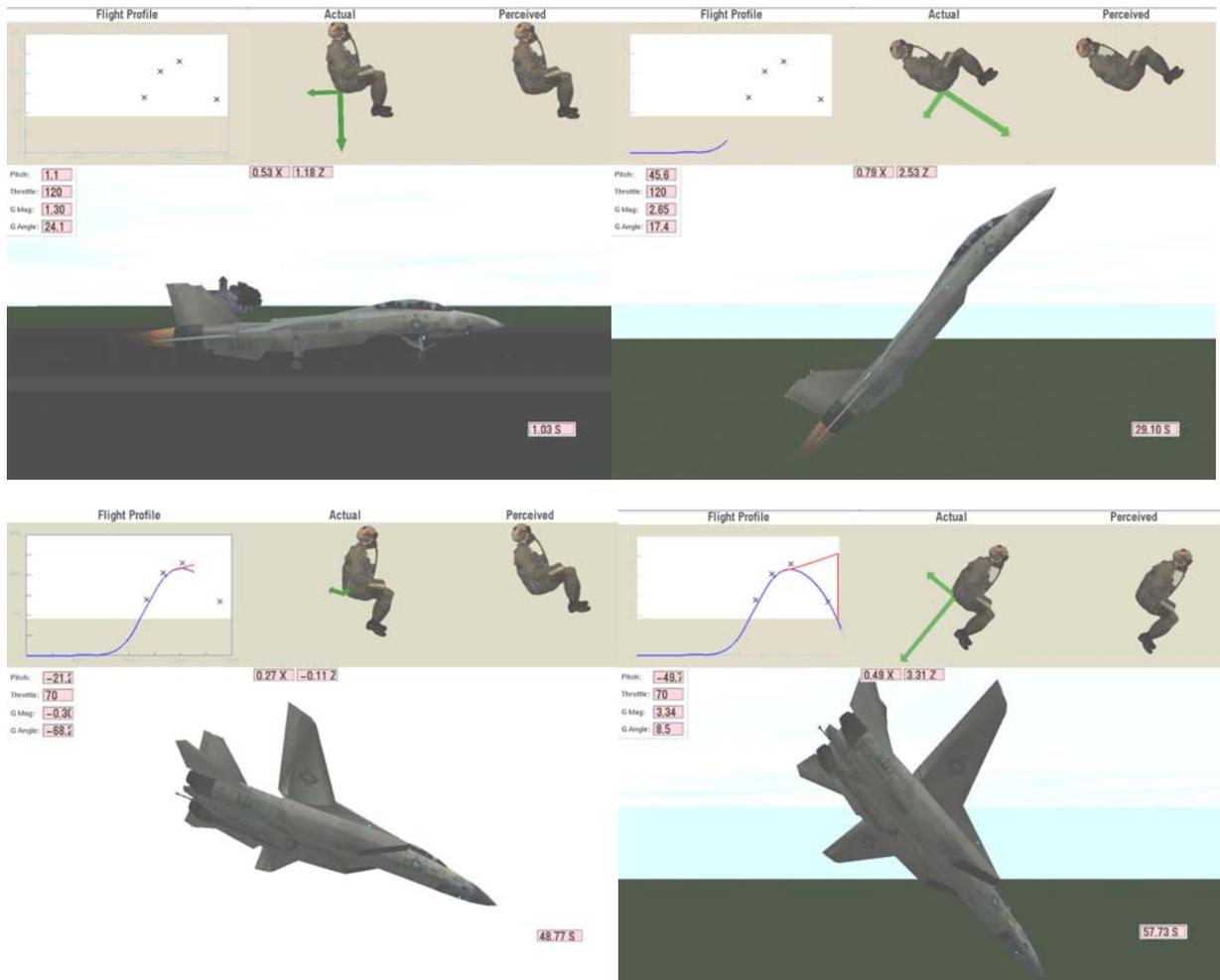


Figure 7: F-14 mishap time sequence.

After becoming airborne, the F-14 accelerated and climbed at a steep angle into an overcast cloud layer. Shortly afterwards, the F-14 was observed descending below the cloud layer in a steep nose-down attitude, followed by a transition to nose-up, slight left wing down before impact with the ground. While the exact cause of the mishap and what occurred in the cockpit will never be known, the mishap board identified spatial disorientation and cockpit distraction as causal factors in the mishap (Smith, 1996).

During the critical approximately 10 sec of the flight from the start of the maneuver to level the aircraft at 5000 ft to when the aircraft is unrecoverable just prior to exiting the clouds the pilot had:

- No outside visual cues.
- A resultant gravitational force vector that likely caused a misperception of pitch attitude (Figure 7, frame 3).
- Cockpit distractions that likely included conversations with the radar intercept officer regarding correct altitude to level off, and possible warning lights due to the inverted nature of the G-forces (-Gz).

The presumed momentary distraction leading to spatial disorientation resulted in the tragic loss of five lives, and a financial cost of millions of dollars.

Spatial disorientation mishaps are not confined to military aviation alone. In general aviation, spatial disorientation was a factor in 2.5% of all accidents, but was a factor in 16% of all fatal accidents.

Significantly, if spatial disorientation was a factor in a general aviation accident, there was a fatality in 90% of these mishaps (Kirkham, Collins, Grape, Simpson, and Wallace, 1978).

In summary, human factors problems account for the bulk of aircraft mishaps, and spatial disorientation is the most significant human factors problem both in terms of material and personnel losses as well as mission degradation. The 1990 Naval Research Advisory Committee Panel on Aviator Physical Stress (Jones, 1990) concluded, "current displays are not adequate to prevent spatial disorientation mishaps. It is imperative that research and development be focused to ensure introduction of improved displays, controls and decision aids to reduce pilot workload."

Spatial orientation awareness is a very complex problem (Figure 8). The visual system, vestibular system, somatosensory system, memory of preceding motion, expectation based on planned action and perceptual motor interactions are all intimately involved. Due to the complex physiological and psychological nature of spatial orientation, a coordinated effort between research, training, and operational communities and between engineering, medical, and aviator disciplines is required to reduce spatial disorientation mishaps in aviation.

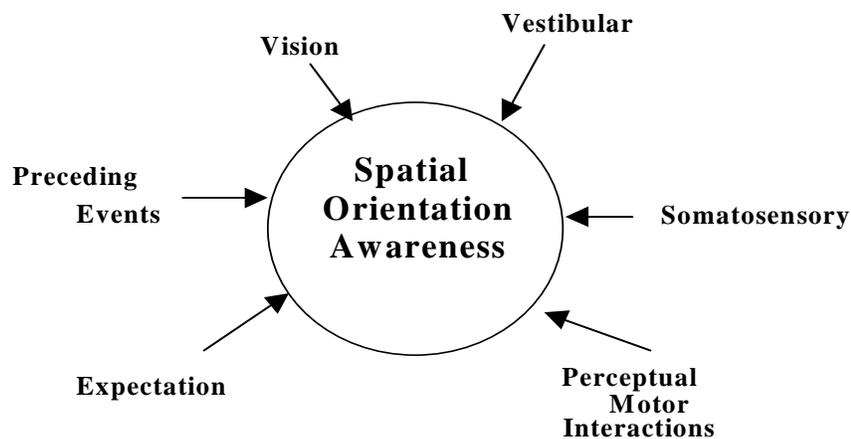


Figure 8: Complexity of spatial orientation awareness.

The following four-step research approach should reduce spatial disorientation mishaps in aviation:

1. **Advanced Human-Machine Interface.** Develop instruments that give continuous, accurate information to pilots on the attitude and motion of their aircraft. The information processing capabilities of under-utilized sensory channels such as hearing, peripheral vision, and the somatosensory system have not been adequately investigated. By utilizing alternate sensory channels to maintain aircraft situation awareness, the central visual system is released to focus on other critical aircraft control parameters and other tasks.
2. **Better Understanding of Spatial Disorientation.** Conduct extensive research on the dynamics of spatial orientation with the objective of developing mathematical models that will predict spatial orientation dynamics in the complex acceleration environments of flight simulators and real flight.
3. **Improved Aviator Selection.** Develop a clinical assessment capability to assure that pilots have normal spatial orientation function and are not predisposed to spatial disorientation. During the initial screening of aviators, the only test of vestibular function currently administered by United States military and National Aeronautics and Space Administration (NASA) flight surgeons is the 10-second Romberg (self balance) test, which can be passed by vestibular compromised subjects who have developed good non-labyrinthine compensatory mechanisms. Occasionally, vestibular deficits present as the inability to maintain controlled flight in instrument meteorological conditions when the pilot is deprived of outside visual references.

4. Improved Aviator Education. Develop better techniques of training pilots to recognize and deal with spatial disorientation situations, including ground based and in-flight instruction.

1.1 THESIS GOALS

The overall goal of the research and development described in this thesis is to reduce pilot loss, mission failure, and aircraft loss due to pilot spatial disorientation, and to enhance pilot performance by reducing the flight workload. This thesis research has been a collaborative effort between the United States Naval Aerospace Medical Research Laboratory (NAMRL) and the University of Sydney, Department of Aeronautical Engineering, with assistance from numerous United States Military, Government, Academic, and Industry organizations.

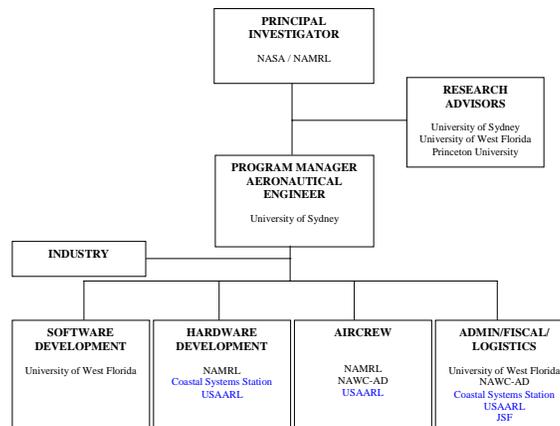
The specific objective of this thesis is to present results from a series of related flight tests of an advanced human-machine interface, the Tactile Situation Awareness System (TSAS). TSAS is a non-visual flight instrument that uses the under-utilized sensory channel of touch to display situation awareness information to pilots. These flight tests represented the first time tactile instruments were successfully used in actual flight in military aircraft.

1.2 THESIS ORGANIZATION

Chapter 1 provides a general introduction to the problem of spatial disorientation and the underlying causes and costs of spatial disorientation mishaps. Chapter 1 also introduces the research and the steps required for the reduction of spatial disorientation mishaps, including the need for improved human-machine interfaces. Chapter 2 details the background of tactile devices and describes the efforts leading to the two TSAS flight test demonstrations described in this thesis. Chapter 3 describes the flight test demonstration of a tactile instrument in a T-34 fixed wing aircraft during forward flight. Chapter 4 describes the flight demonstration of a tactile instrument designed for the V/STOL variant of the Joint Strike Fighter (JSF) aircraft during hovering flight. Chapter 5 is a commentary on aviation tactile instruments based on the results from the two TSAS flight demonstrations presented in chapters 3 and 4. This chapter also includes the work on developing intelligent software for TSAS. Chapter 6 draws conclusions from the flight demonstrations and considers possible directions for future investigation.

1.3 TSAS FLIGHT TEST MANAGEMENT

The successful flight tests described in Chapter 3 and Chapter 4 were due to the combined efforts of a large team of people. Figure 9 shows the program organization for the T-34 (Chapter 3) and JSF (Chapter 4) flight test demonstrations. See Appendix A and B for a complete list of the T-34 and JSF TSAS teams respectively.



Organizations in black were involved in the T-34 and JSF efforts.
Organizations in blue were involved in the JSF effort only.

Figure 9: TSAS flight test management.

The program manager/aerospace engineer reported directly to the principal investigator and was responsible for:

- All specifications and final design decisions on flight hardware and software.
- Assisting in the preparation of the test plan and approving the final plan.
- Development of the tactile algorithms (i.e. which tactors should fire when). Working closely with the principal investigator and pilots, the program manager/aerospace engineer specified the type, number, and location of the tactors.
- Analyzing all the subjective and flight test data.
- Writing the reports.
- Organizing and coordinating all of the various organizations, including budgeting and scheduling.

For the JSF flight demonstration (Chapter 4), the program manager/aerospace engineer role was expanded due to the larger number of people and organizations involved. The program manager/aerospace engineer was also responsible for the proposal, cost estimates and scheduling. The JSF flight test was successful, on time, and on budget.

Instrument flying is when your mind gets a grip on the fact that there is vision beyond sight.
-- U.S. Navy 'Approach' magazine circa W.W.II.

Background

In our day-to-day earth-bound terrestrial activities, spatial orientation is continuously maintained by accurate information from three independent, redundant, and concordant sensory systems: vision, the vestibular system, and the somatosensory system. However, when we go flying, the vestibular and somatosensory sensors no longer provide accurate information concerning the magnitude or direction of the gravity vector. The only reliable source of information remaining is that obtained visually. Understandably, the typical spatial disorientation mishap occurs when the visual orientation system is compromised (for example; temporary distraction) and the pilot uses incorrect orientation information from the vestibular and somatosensory sensors to make judgements on aircraft control.

In a North Atlantic Treaty Organization publication, Rupert, Mateczun, and Guedry (1990), proposed that to maintain spatial orientation awareness, pilots could use an advanced instrument that uses the under-utilized sensory channel of touch. The approach, as shown in Figure 10, was to use a tactile device that consists of a garment, located on the torso, fitted with multiple vibrators or tactors that can continuously update the pilot's orientation perception (Rupert, Guedry, and Reschke, 1994). This approach is analogous to how the brain obtains orientation information in the terrestrial environment. Therefore, the pilot should be able to maintain spatial orientation in the absence of a visual horizon or during inevitable temporary gaze shifts from the aircraft instrument panel.

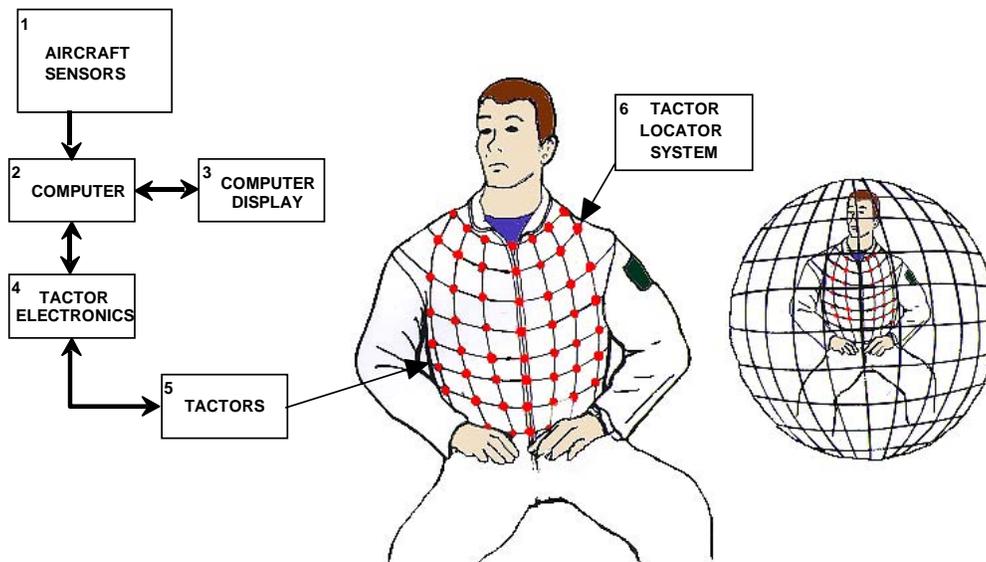


Figure 10: One-to-one tactile interface for aviation.
(Reproduced from Rupert, Guedry, and Reschke. 1994 in a modified form)

Simmons, Lees, and Kimbal (1978) showed that pilots in instrument meteorological conditions (IMC) expend more than 60% of their visual scan time attending to two flight instruments, the attitude indicator and the directional gyro. By presenting this information non-visually, pilots will be free to attend to other tasks and visual instruments that do require visual attention. Endsley (1988) suggests the use of auditory or tactile modes to provide information, especially about critical events.

The sense of touch is not currently utilized to provide flight information to pilots. The underlying principle for using touch to communicate flight orientation and performance information, reduce spatial disorientation illusions, and maintain situation awareness, is based upon the following precepts:

- 1) The tactile sense component of the somatosensory system is under-utilized in aviation information instruments when compared to vision and audition. A well-designed tactile instrument will increase situation awareness without a corresponding increase in workload for the already over-loaded pilot.
- 2) The time course of sensory development suggests that information from a tactile instrument will be intuitive and easy to understand. If a person is tapped on the left shoulder, that person reflexively and intuitively focuses their attention in that direction. As demonstrated in Figure 11 for the cat, the somatosensory system is the first sensory system to develop in most vertebrates, followed by the vestibular system, then the auditory system, and finally the visual system (Gottlieb, 1971). The somatosensory and vestibular systems develop a strong interaction *in utero*, since the somatosensory system needs information very early in development concerning the direction of the gravity vector in order to properly control the antigravity and gravity muscles. It is only later in development that the auditory and visual systems are integrated into the already well functioning somatosensory and vestibular systems.

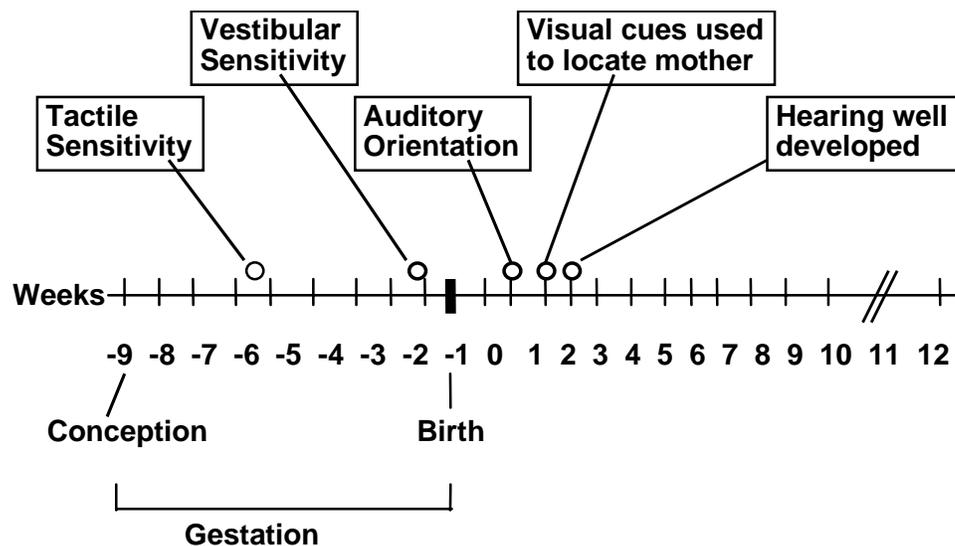


Figure 11: Ontology of cat sensory development (from Turner and Bateson, 1988).

- 3) The tactile sensory system is capable of high information throughput when properly stimulated and trained. Individuals with visual and auditory sensory deficiencies that use the Tadoma method for communication have showed speech comprehension at rates and accuracy's that approach normal values (Reed, Rabinowitz, Durlach, Braida Conway-Fithian, and Schultz, 1985).

The somatosensory system is comprised of two subsystems, the tactile and kinesthetic senses. Tactile sense refers to the sensation of skin stimulation, and kinesthetic sense refers to the awareness of limb positions, movements and muscle tensions. Corresponding to these subsystems, there are two categories of tactile communication devices that are in use or in development. The first is the sensory substitution type of tactile communication device that involves presenting information via the tactile sense of touch.

The sense of touch is used to detect mechanical, thermal, and electrocutaneous stimuli at the skin's surface. The skin surface is the largest organ in the body, with an area of approximately 2 m² and weighs 5 kg, and is a highly complex structure that consists of three distinct areas, the glabrous skin, hairy skin, and mucocutaneous skin. Glabrous skin covers the palms of the hands and soles of the feet, and the anatomy and physiological organization of glabrous skin have been extensively studied and modelled (Bolanowski, Gescheider, Verrillo, and Checkosky, 1988). The remaining majority of the skin surface contains hair follicles and hairs, and is classified as hairy skin (Burgess, 1973). Finally, mucocutaneous skin borders the body's orifices.

The skin surface is composed of an outer layer, the epidermis, and an inner layer, the dermis. The outermost layer of the epidermis protects the body and consists of dead cell tissue that have migrated outward from the deeper strata of the epidermis as the skin renews itself from inside out. The dermis is composed of connective tissue and elastic fibres in a semifluid mixture called the ground substance. Embedded within the ground substance are fat cells, sweat glands, smooth muscle, blood and lymphatic supplies, and in hairy skin, hair follicles and their associated structures.

The cutaneous sensory receptors that are responsible for transducing the mechanical, thermal, and electrocutaneous stimuli, and the nerve fibres innervating these receptors are located within the dermal layer or at the epidermal-dermal interface. Due to differences in the density of these cutaneous sensory receptors, and the varied structure of the three types of skin surfaces, the sensitivity and resolution of tactile stimulation vary significantly from site to site over the entire surface of the body. Because this thesis is necessarily restricted in extent to the flight tests of an aviation tactile display, the interested reader is referred to the following review articles for a complete description on the subject of tactile anatomy, physiology and psychophysics (Sherrick and Craig, 1982; Boff and Lincoln, 1988; Cholewiak and Collins, 1991; Bolanowski, Gescheider, and Verrillo, 1994; Greenspan and Bolanowski, 1996).

The ability to detect tactile stimulation from a tactile communication device has been shown to depend upon the body location; the stimulus waveform, frequency, and temperature; the area of the contactor; the duration of the stimulus; the static force of the stimulus; the presence of a surround; and the age, sex, and hormone levels of the observer (Boff and Lincoln, 1988; Cholewiak and Collins, 1991). The most widely used forms of tactile displays³ that use the sense of touch are vibro-mechanical or electrocutaneous (Kaczmarek, Webster, Bach-y-Rita, and Tompkins, 1991).

Examples of tactile displays are:

- 1) Providing visual information for blind people, and hearing information for deaf people.
- 2) Vestibular prosthesis and for limb prosthesis control.
- 3) Providing vehicle control information, including aviation, automobile, and underwater applications.

The second category is the use of force-feedback or kinesthetic devices in the field of robotics and teleoperation. Displays for robotic or teleoperator applications are primarily devices that use force feedback to provide an awareness of limb positions, movements and muscle tensions. In virtual environment applications, kinesthetic displays monitor the position of a contact point and deliver a force based on the penetration of this point into a virtual object. The user of a kinesthetic display experiences virtual objects through force information. In teleoperation, kinesthetic displays deliver a force based on the force exerted on a contact point by a remote object. Force feedback devices are commercially available and are used in teleoperation and virtual environment applications. Tan and Pentland, (1997) reported that force displays enhance a user's performance, but the results are highly task-dependent.

Tactile communication devices that use both tactile and kinesthetic feedback to provide information to the operator have also been developed. Examples of this type of display have been developed for vehicle control, and research results have shown that under certain circumstances, kinesthetic and tactile displays

³ The traditional definition of display is a device that gives information in a visual form. In the field of tactile research, "tactile display" is defined as a device that gives information in a tactile form. Other researchers have used "tactile interface" and "tactile device" to convey the same meaning.

are an effective adjunct or replacement for visual displays (Jagacinski, Flach, and Gilson, 1983). No commercially available kinesthetic and tactile display is currently available.

2.1 TACTILE COMMUNICATION DEVICES

Tactile Displays as Hearing or Visual Aids

The majority of research on tactile communication devices has been directed toward the development of hearing or visual aids (Bliss, 1970; Geldard, 1974; Sherrick, 1984, 1991; Summers, 1992). Efforts to develop tactile devices date back to the beginning of the century, when in 1907 a French scientist, Du Pont, proposed a tactile device that used direct electrical stimulation as an aid to communicate acoustic messages (Sherrick, 1984). Tactile displays used as a hearing aid are typically based on the cochlea model of speech (von Békésy, 1955). In the cochlea model, the acoustic signal from speech is sent through several bandpass filters that then modulate the amplitudes of a corresponding array of tactors. A commercially available example of a tactile hearing aid is the Tactaid VII™ (Audiological Engineering Corp., Somerville, Massachusetts). In general, results from tactile hearing aid displays have been encouraging, but have not achieved great success or widespread use (Sherrick, 1984). Tactile displays as a visual aid use a pictorial method (Bliss, Katcher, Rogers, and Shepard, 1970; Collins, 1970). The spatial and temporal information from video camera images is directly translated to the skin by the spatial stimulation patterns of tactile stimulator arrays. An example of a tactile visual aid is the Videotact™ (Unitech Research Inc. Madison, Wisconsin).

Tactile Displays for Vestibular Prosthesis and for Prosthesis Control

The balance prosthesis is a tactile device that provides information about body position and motion to patients with vestibular pathology, in order to aid daily activities and reduce the risk of falls. The balance prosthesis will aid balance-impaired people to stand and walk more safely, and consists of wearable instrumentation that detects body sway and vibro-tactile tactors that provide sway cues (Schmidt, Wall, Krebs, and Weinberg, 1999; Kadhane, Benda, Schmidt, Balkwill, and Wall, 1999). For a balance prosthesis, a tactile device has advantages over visual or auditory display because the vibrotactile device does not obstruct vision or interfere with hearing and can be unobtrusively worn under clothing.

Tactile devices have also been used to receive feedback of limb prosthesis. Tupper and Gerhard (1989) discussed the development of an electro-tactile stimulator for giving positional and rate-command feedback to the user of a motorised prosthetic arm.

Tactile Instruments in Aviation

The use of tactile instruments in aviation is not a new concept. Ballard and Hessinger (1954) proposed a vibro-mechanical tactile display system for aircraft orientation (pitch and roll). The tactile display consisted of four tactors mounted on the thumb. Two of the tactors provided pitch information and two provided roll information. The frequency of vibration indicated the magnitude of the error. No results or further work on this instrument have been reported in the open literature.

Hirsch (1961) proposed a tactile display that provides the operator of aerospace vehicles pitch, roll, and yaw accelerations or velocities via vibro-mechanical tactors located on the thumb and forefinger. In a single-axis tracking experiment to investigate the use of a tactile display in the ground control of flying vehicles, Hirsch and Kadushin (1964) showed that there was a significant improvement in operator performance on average when using visual and tactile feedback as opposed to visual alone. When used in a dual axis tracking experiment, subjects became confused with the tactile display and showed no improvement.

A pulsed air-jet tactile display was developed and evaluated in a series of tracking experiments (Hill, Bliss, and Gardiner, 1970). The tactile display used seven air jets located on the back of the hand and the left index finger. Results showed there was no significant change in performance on a visual tracking task when tactile cues were provided.

Ross, Sannerman, Levison, Tanner, and Triggs (1973) conducted a series of manual tracking experiments to determine the suitability of tactile displays for presenting aircraft flight information in multi-task environments. Results showed that with the tactile display, tracking error scores were considerably greater than scores obtained with a continuous visual display especially for a two-axis tracking task. They argued that the degradation of performance with the quantised tactile display versus the continuous visual display appears to be a result of the tactile algorithm coding scheme rather than limitations of the somatosensory system. In their review of the Hirsch and Kadushin tactile display, Triggs, Levison, and Sanneman (1974) hypothesized that the limitations can be attributed in part to the lack of separation between the stimuli applied to the thumb and forefinger. In their experiments, Ross *et al.* (1973) found that “the most suitable factor excitation code tested to date has been one in which the outermost factor is always excited first, thus providing maximal spatial separation for even small error displays.”

A kinesthetic and tactile aviation display was developed and flown by Gilson and Fenton (1974). This device differed from previous aviation tactile instruments in that it involved both kinesthetic and tactile feedback as opposed to a pure tactile display. This display consisted of an actuator mounted in the control stick that stimulated the hand holding the stick. Movement of the actuator corresponded to angle of attack error from a desired angle of attack. Test flight results in a Cessna 172 showed that a kinesthetic and tactile display of angle of attack error permitted novice pilots to perform a tight turn about a point with less tracking error, decreased altitude variations, and decreased speed variations.

Morag (1987) proposed a tactile display that located factors inside the pilot’s helmet to provide the spatial locations of targets or threats (Figure 12). The part of the head that is stimulated represents the pilot head-referenced angular direction of the targets or threats location.

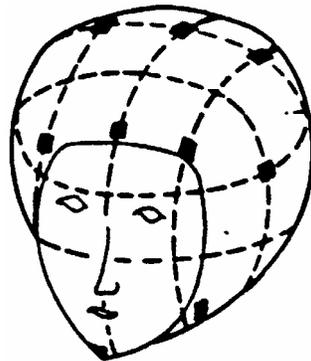


Figure 12: Helmet mounted tactile display (from Morag, 1987).

Morag also proposed that amplitude or frequency modulations could be used to represent detailed information about the target or threat including distance or urgency.

Zlotnik (1988) proposed an aviation tactile display consisting of a matrix of electrocutaneous factors located in a sleeve mounted on the forearm (Figure 13). Zlotnik proposed that the tactile stimulators would present information on such aircraft flight parameters as airspeed, angle of attack, or altitude. This tactile display would allow fighter pilots to receive flight-critical data in an ‘eyes-out’ mode, without dependency on the already overloaded auditory and visual senses. A series of experiments in a Northrop simulator were planned, but similar to the Ballard and Hessinger’s vibro-mechanical tactile display, no results or further work on this electrocutaneous device have been reported in the open literature.

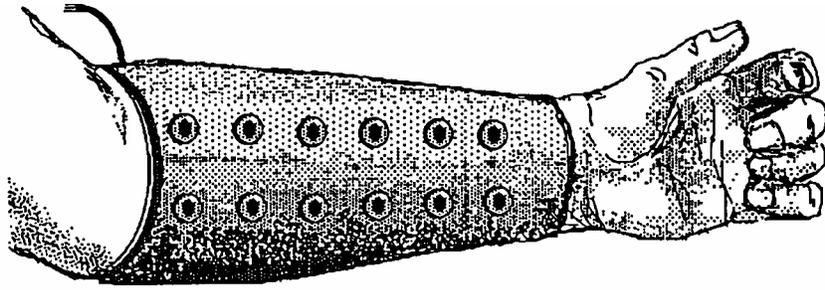


Figure 13: Arm mounted tactile display (from Zlotnik, 1988).

To evaluate the effectiveness of a head mounted tactile display proposed by Morag (1987); Gilliland and Schlegel (1994) conducted a series of laboratory experiments using vibro-mechanical tactors positioned on the head. In the first study they showed that the head was sensitive to tactile stimulation, with 100% of subjects detecting the tactile stimulation. In a second study on the number of locations on the head that could be reliably localized, Gilliland and Schlegel showed that localization accuracy and response times improved for a lower number of tactors (93% accuracy for six tactor locations compared with 47% accuracy for 12 tactors). The second study on localization accuracy and response times using 8 tactor locations was repeated with a dual memory/tracking task or an air combat simulation to evaluate the effectiveness of the head-mounted tactile instrument under high workload conditions. Results showed that the dual memory/tracking task did not interfere with the response or localization. However, the manual control needed to provide responses caused difficulty and resulted in longer response times. For the air combat simulation, results showed lower accuracy and longer response times due to the demands of the simulated combat scenario. Gilliland and Schlegel also noted “performance for the extreme sites tended to be better than for other sites.”

Why is it that none of the earlier aviation tactile instruments have progressed past the proposal phase (Ballard and Hessinger, 1954; Zlotnik, 1988) or the laboratory phase (Ross *et al.* 1973; Gilliland and Schlegel, 1994) and into a real aircraft cockpit? Only the hybrid kinesthetic and tactile display developed by Gilson and Fenton (1974) was tested in an aircraft, but this display never progressed to commercial development. The following factors are relevant and were addressed in the current research:

1. Tactor technology. All of the previous tactors developed for aviation instruments were too big and heavy and/or did not provide enough intensity of signal to be felt in an aircraft cockpit. In the case of the electrocutaneous tactors, the range between absolute threshold and pain is very small and this dynamic range of usability varies with skin environmental conditions. This caused both detection and user acceptability problems (Ross *et al.* 1973).
2. Non-intuitive algorithms, including the location of the tactors. None of these tactile communication devices used the entire torso of the body. Hill *et al.* (1970) in their conclusions noted that, “Tactile displays are correctly interpreted more often when located on body locations not involved with motion.” The head, arms, and hands are constantly in motion when flying an aircraft, so a tactile instrument on the torso is potentially more accurate. Hill *et al.* (1970) also commented “Displays which are always felt (like vibrators attached to the body) are better than displays which need to be actively felt (like thumb buttons).”
3. Evaluating tactile instruments in tactile-only tracking experiments. Spatial disorientation mishaps are not typically aircraft control problems. Most spatial disorientation mishaps occur when a pilot does not recognize disorientation, and is distracted from the visual instruments that can provide the necessary orientation information. Tactile instruments should provide necessary information to the pilot when visual and auditory senses are occupied, and are best used in a multi-sensory mode. Bliss (1967) showed that with similar tactile and visual displays, reaction times with both displays were faster than either display alone. A tactile instrument should complement visual information, and the tactors should provide information when vision is compromised. The next

generation cockpit needs to provide visual + audio + tactile information. History has shown us that a single modality instrument (for example, visual attitude indicators, HUDs) does not eliminate the spatial disorientation mishap problem. A system that combines multiple senses – visual, audio, and tactile is required. Just as in terrestrial life, aviators need multi-sensory orientation instruments.

Rupert *et al.* (1994) developed a prototype proof-of-concept tactile interface with miniature electromechanical speakers 5 mm in thickness and 25 mm in diameter. Multiple tactors in a 5 row by 8 column matrix were placed on a tactor locator system (TLS) to represent pitch of ± 15 degrees and roll of ± 45 degrees. The stimulus waveform consisted of 10 pulses of a 150 Hz rectangular pulse train operating at a 10% duty cycle, followed by a break of approximately 450 ms. A stretch Lycra TLS maintained the appropriate interface pressure between the tactor and the skin. .

With this prototype proof-of-concept tactile interface, a novice pilot was able to determine pitch and roll information within 5 degrees after 30 minutes of training. Flight demonstrations in a Cessna 180 showed that subjects using tactile cues alone could maintain the attitude of the aircraft to within 5 degrees of accuracy in pitch and roll. The tactors and TLS used for the prototype, proof-of-concept, tactile instrument were unsuitable for military aircraft flight-testing. The electromechanical speaker tactors did not produce a tactile sensation strong enough to be felt in the vibration environment of a military aircraft, and the Lycra TLS did not meet US Navy aviation fire retardant standards. After the development of this prototype tactile instrument, Rupert was awarded an Advanced Technology Demonstration (ATD) program from the Office of Naval Research (ONR) to develop the Tactile Situation Awareness System (TSAS). The TSAS tactile instrument is a non-visual display that uses the sensory channel of touch to provide situation awareness information to pilots. TSAS accepts data from various sensors and presents this information via vibrators or tactors integrated into flight garments. TSAS has the capability of providing a wide variety of flight parameter information, for example, attitude, altitude, velocity, navigation, acceleration, threat location, and/or targets. TSAS, integrated with visual and audio display systems, should be able to provide the right information at the right time by the right sensory channel(s), and represents the next generation human interface for tactical aircraft.

One of the goals of the ATD was to conduct a flight demonstration to show that a pilot could receive aircraft orientation information using a tactile instrument during normal and acrobatic military flight operations. This demonstration was intended to show that a pilot could maintain spatial orientation using only tactile cues. In a collaborative effort, military, university, government, and industry participants carried out the T-34 TSAS flight demonstration project to achieve this ATD goal (Figure 9). See Appendix A for a complete list of the T-34 TSAS team.

The T-34 TSAS flight demonstration project integrated a tactile instrument into a United States Navy T-34 aircraft to demonstrate that a pilot could receive aircraft orientation information using only a tactile instrument whilst flying. The objectives of the T-34 TSAS flight demonstration program were to demonstrate:

- That a significant amount of orientation information can be provided continuously by the under-utilized sense of touch in an intuitively effective manner.
- That a pilot using TSAS can effectively maintain control of an aircraft in normal and acrobatic flight conditions with no visual cues.

The T-34 TSAS flight demonstration project was initiated in August 1994. The first flight of the TSAS-modified T-34 was 11 October 1995, and 7 flight test events were successfully completed by 19 October 1995. The methods, results and discussion for the T-34 TSAS flight demonstration project are presented in Chapter 3.

After the successful flight test program for the ONR funded ATD, the Joint Strike Fighter (JSF) technology maturation program sponsored the TSAS research team to integrate tactile and sensor technologies to demonstrate the operational utility of an advanced human systems interface for hover operations in reduced visibility.

The JSF program was chartered to enable the development and production of a next-generation strike aircraft for the US Air Force, US Marine Corps, US Navy, United Kingdom, and allied nations. The JSF technology maturation program conducted a series of analyses and demonstrations aimed at laying the foundation for mature, affordable technologies and other concepts in support of the JSF aircraft. The JSF Flight Systems Integrated Product Team (FSIPT) is a multi-service, multi-agency, group of government and industry representatives, working together to develop safe, reliable, affordable flight systems technologies that meet the aviator needs for the JSF. The FSIPT includes traditional, advanced, and integrated subsystems, and cockpit/aircrew systems. The FSIPT managed and participated in the JSF TSAS flight demonstration.

The JSF TSAS project was conceived as a short-duration technology integration and flight demonstration program. The JSF TSAS project was not intended to conduct basic research, but rather to integrate and demonstrate technologies that had previously been developed. Figure 14 shows the historical research programs relevant to JSF TSAS.

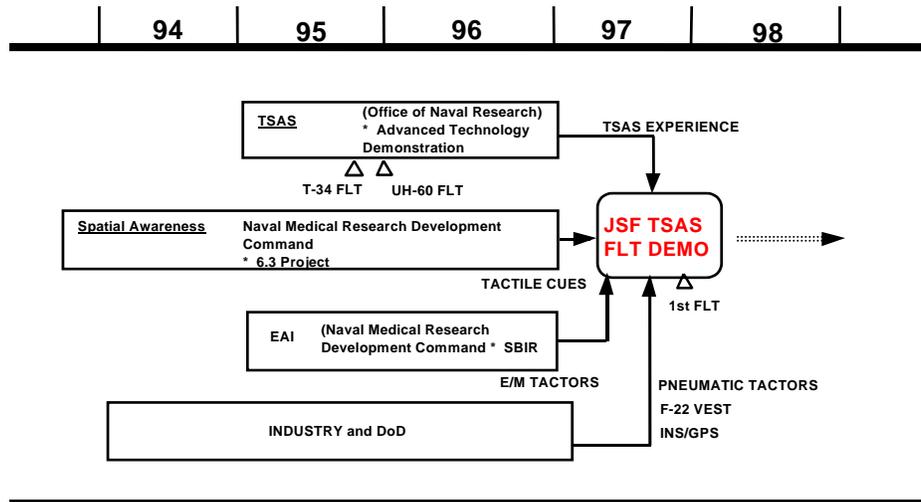


Figure 14: Research programs related to the JSF TSAS project.

The objectives of the JSF TSAS flight demonstration program were to demonstrate:

- The potential for TSAS technology to reduce pilot workload and enhance situation awareness during hover and transition to forward flight.
- That a pilot using TSAS can effectively hover and transition to forward flight in a vertical lift aircraft with degraded outside visual cues.
- The feasibility of integrating tactile instrument technology into military flight garments.

The JSF TSAS flight demonstration project integrated an array of factors, F-22 cooling vest, and GPS/INS technologies into a single system in an UH-60 Helicopter. A 10-event test operation was conducted to demonstrate the utility of this advanced human-machine interface for performing hover operations in a single-seat V/STOL aircraft.

The JSF TSAS project was a true team effort consisting of military, university, government, and industry participants (Figure 9). Appendix B provides a complete list of the JSF TSAS team. The first flight of the TSAS-modified UH-60 was 09 September 1997, and 10 flight test events were successfully completed by 19 September 1997. The methods, results and discussion for the JSF TSAS flight demonstration project are presented in Chapter 4 of this thesis.

Chapter 3

"...decide...whether or not the goal is worth the risks involved. If it is, stop worrying."
-- *Amelia Earhart*

T-34 TSAS Flight Demonstration

3.1 INTRODUCTION

The T-34 TSAS flight demonstration project integrated a tactile instrument into a T-34 to demonstrate that a pilot could receive aircraft orientation information using a tactile instrument during flight operations. The T-34 flight demonstration project was the first attempt to develop and use a tactile display in actual flight in a military aircraft. The focus of this project was to demonstrate that a pilot could fly the following maneuvers without visual cues, relying solely on tactile cues for attitude information.

- Straight and level for 5 minutes.
- Bank and pitch angle capture.
- Climbing and descending turns.
- Unusual attitude recovery.
- Loops and aileron rolls.
- Ground controlled approach (GCA).

3.2 METHOD

TSAS VTOS-N1 Description

The following sections describe the test aircraft, TSAS, and integration requirements, including ground-based testing systems. The components that made up the TSAS system were integrated into the T-34 as shown in Figure 15. The TSAS system utilized data from the aircraft attitude pitch and roll gyroscope to determine the aircraft attitude. This information was then displayed via electro-mechanical driven tactors mounted in a NOMEX vest. The tactors were arrayed around the torso in four columns. Location of the tactors on the torso and tactor activation pulse pattern was used to indicate pitch and roll of the aircraft attitude.

The tactor control hardware used in this flight test was designated VibroTactile Orientation System – Navy 1 (VTOS-N1) and was developed at Naval Aerospace Medical Research Laboratory (NAMRL) and tested in the three months prior to the flight test. A man-wearable system with commercial-off-the-shelf components and electromagnetic shielding was emphasized to minimize aircraft integration time.

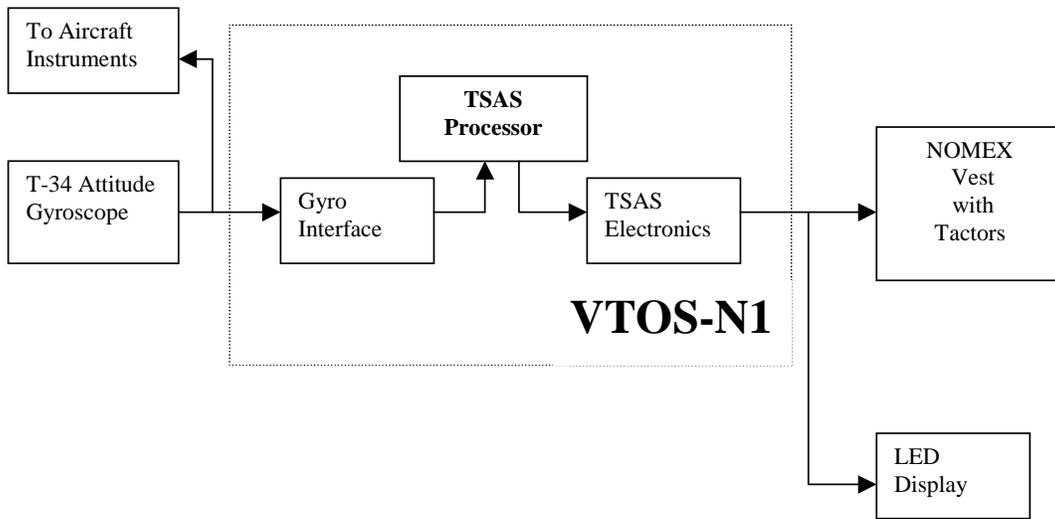


Figure 15: VTOS-N1 architecture.

T-34C Airplane

The T-34C aircraft is an un-pressurised, two-place tandem cockpit, low-wing single engine monoplane manufactured by Beech Aircraft Corporation. The aircraft is powered by a Pratt & Whitney of Canada turbo-prop engine, model PT6A-25 with inverted capabilities. The PT6A-25 engine is flat rated at 550 shp maximum, with normal operations at 425 shp. A more detailed description can be found in the T-34 Naval Air Training and Operating Procedures Standardization (NATOPS) flight manual (NAVAIR 01-T34AAC-1, 1998).

The test airplane, Naval Air Warfare Center–Aircraft Division (NAWC-AD) NT-34C BuNo 160266 (affectionately known as “266”, Figure 16), is a US Navy NT-34C equipped with a rudimentary rear cockpit with controls but no instruments.



Figure 16: NT-34C, “266”.

To remove all visual cues from the subject pilot including instruments, the subject pilot was located in the rear cockpit of 266. This aircraft had flight controls but no visual flight instruments in the rear cockpit (Figure 17), and also was fitted with an instrument hood (Figure 18). During all phases of the flight demonstration the instrument hood was used to deprive the subject pilot of any outside visual cues.



Figure 17: NT-34C, “266” rear cockpit showing absence of visual instruments.



Figure 18: Instrument hood used to eliminate outside visual cues.

T-34 TSAS Sensor

The VTOS-N1 tactile instrument used aircraft pitch and roll data from the aircraft’s attitude gyroscope. The VTOS-N1 system was connected to the T-34 on-board vertical gyro via a NAWC-AD custom built “T” connector to provide the flight attitude data, pitch and roll (Figure 19). The connection between the aircraft attitude gyroscope and the VTOS-N1 was a breakaway connector designed to release in the event of a rapid egress from the aircraft.



Figure 19: Gyro "T" connector.

VTOS-N1 Hardware

The VTOS-N1 hardware consisted of a computer and an electronics package. The computer and the electronics package were physically integrated in the subject pilot's SV2 survival vest (Figure 20). The computer conformed to MIL-STD-810 and was a small PC-based wearable, ruggedized computer (Badger GT-486P2) containing two National Instruments data acquisition PC cards. The computer received flight information from the aircraft attitude gyroscope, and custom software determined which factor(s) should fire to indicate a given aircraft attitude. The software then activated the appropriate digital lines that control the factors.



Figure 20: Subject pilot's SV-2 containing VTOS-N1 computer and electronics.

The Badger GT-486P2 computer has the following specifications:

- 50MHz CYRIX 80486SLC2
- 16MB RAM
- 80MB solid state disk
- 2 Type II PC card slots
- Size 269 x 152 x 53 mm
- Weight: 1.8 kg with battery

Located in the type II PC Card slots were two National Instruments DAQCards™. One was a DAQCard DIO-24 and the second was a DAQCard 700.

The VTOS-N1 electronics package provided the following functions:

- Converts the aircraft gyro pitch and roll signals to digital signals suitable for input to the computer using an Analog Devices AD2S44 syncro/resolver to digital converter.
- Amplifies the digital signal from the computer to a signal that can drive the tactors using Sprague ULN-2004 Darlington driver array chips.
- Battery power for the tactors (7.2 VDC NiCd rechargeable battery pack).
- Connectors and switches.

The VTOS-N1 electronics package was housed in a cast aluminium box size 190 x 114 x 50 mm and weight 1.1 kg.

The tactor control signals from the VTOS-N1 electronics package were sent to the tactors located on the subject pilot, and to an LED display (Figure 21) located in the front cockpit for tactile and visual presentation, respectively. The LED display provided a visual display of the signal sent to the corresponding activated tactor. The LED display was video taped for data analysis. A quick release mechanism was provided between the aircraft attitude gyros and the VTOS-N1 system to allow for rapid unencumbered egress of the subject pilot in the event of an emergency.

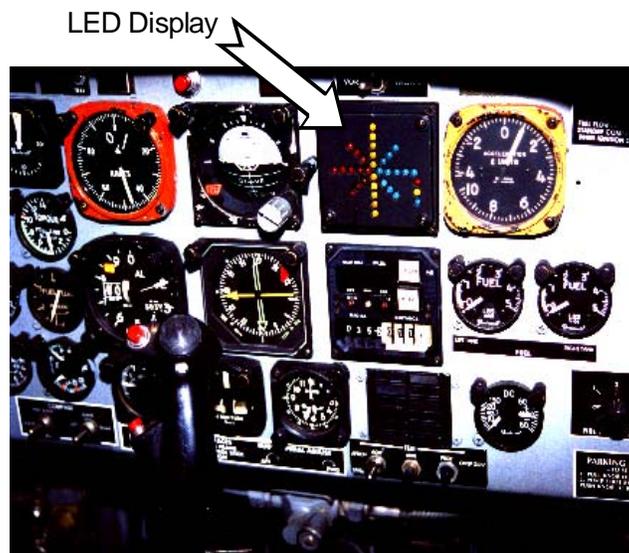


Figure 21: Front instrument panel with tactor LED display.

VTOS-N1 Software

The VTOS-N1 controller software program was developed at the University of West Florida, Institute for Human Machine Cognition (UWF-IHMC), and Mr. Niranjan Suri provided material for this section. The software was written in Borland C++ version 4.2 and targeted for the DOS operating system. Other

software modules used in addition to the standard C++ libraries include the National Instruments NI-DAQ software for DOS and a timer package to obtain high-resolution (1 ms) timer services in DOS. Block diagram is shown in Figure 22.

The controller software input module used the NI-DAQ software to read the raw pitch and roll values from the DAQCard 700. These values were scaled and then converted into Euler angles before being used by the control module.

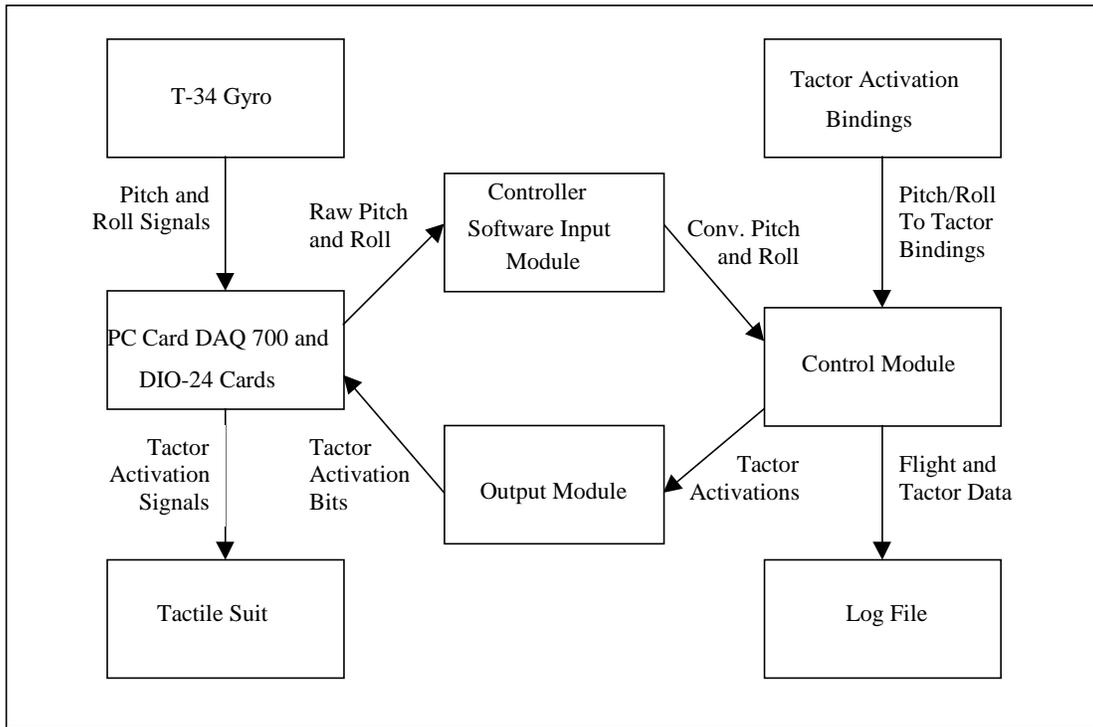


Figure 22: VTOS-NI software architecture.

The control module used the pitch and roll values to look up the tactor(s) to activate from the tactor activation binding module. The bindings were loaded at runtime by reading a configuration file. Once the control module had the tactor numbers to activate, commands were sent to the output module that then used the NI-DAQ libraries again to communicate with the DAQCard 700 and DAQCard DIO-24. The control module also recorded to a log file the data acquired from the aircraft and the tactors activated.

T-34 TSAS Tactor Locator System

The Tactor Locator System (TLS) consisted of a lightweight cotton and fire retardant NOMEX garment that was worn underneath the flight suit. The TLS positioned the 20 electro-mechanical tactors on the torso of the body. The TLS positioned the 20 electro-mechanical tactors on the torso of the body. The tactor array consisted of a matrix of four columns of five tactors. The TLS tactor columns were located on the front midline, the left side, the midline of the back, and the right side of the subject (Figure 24). The bottom four rows were located on the torso, with the bottom row positioned at the navel and each subsequent row separated by a distance of 90 to 100mm. The top row of four tactors were located around the neck, with the left and right side tactors located on top of the shoulders, and the front and back tactors located below the base of the neck. The T-34 TSAS TLS was worn on the torso over an undershirt, and underneath the flight suit (Figure 20).

T-34 TSAS Electro-Mechanical Tactor

The electro-magnetic tactor (Figure 23) used for this flight test was designed by Dr. Anil Raj and constructed by the Engineering Prototype Facility at NAMRL. The tactor consisted of a low voltage direct current motor (Namiki 7CE-1701 WL-00; 1.2 VDC, 90-120 mA) with a small eccentric weight (~4.5 g) attached on the shaft. Total weight of the tactor was 29 g. The motors were mounted inside 25.4 mm circular casings constructed of 66-Nylon. Energizing the motors caused rotation of the eccentric weight causing the casing to vibrate at approximately 90 Hz ($\pm 20\%$). An adequate tactile sensation for the purposes of this flight demonstration was achieved in the T-34 aircraft.

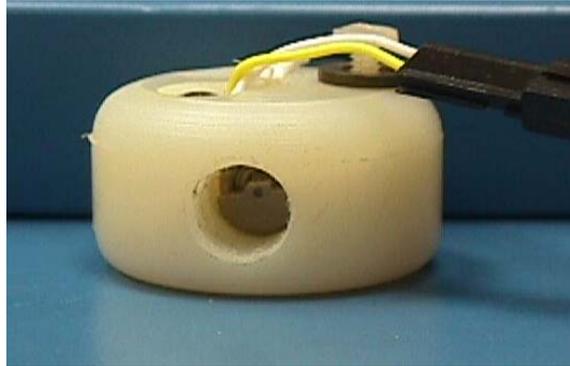


Figure 23: VTOS-N1 electro-mechanical tactor.

T-34 Tactile Algorithm

Using a desktop flight simulator and the TSAS VTOS-N1 flight hardware, preliminary research was performed to develop an adequate tactile symbology or algorithm to meet project goals. Tactile algorithm is defined as the number of tactors, the tactor positions, the pulse or activation patterns, carrier frequencies, waveforms, and amplitudes chosen to represent the value of a particular aircraft flight parameter variable.

Tactor pulse pattern is defined as the sequence of turning the tactor on and off. It is separate from the carrier frequency, which represents the vibration frequency of the tactor when the tactor is on. For example, the electro-magnetic “pager motor” tactor has a carrier frequency or vibration of 90 Hz, but the tactor can be turned on and off once per second, thus the pulse pattern frequency is 1 Hz, separate from the carrier frequency (Figure 24).

The pager motor tactor was selected due to its availability and its ability to be sensed in the aircraft. The electro-magnetic tactor activation was fixed at the amplitude and carrier frequency (90 Hz) to provide the strongest tactile sensation. The fixed tactor amplitude and frequency allowed only tactor position and pulse pattern as the restricted tactor stimulus variables that could be used to present different aircraft attitude values. The high weight of the individual tactor caused problems since it limited the total number of tactors to twenty that could be comfortably worn in a vest underneath a flight suit. Therefore, the single tactor tactile algorithm that was flown by Rupert *et al.* (1994) could not be implemented, since that required a minimum of 40 tactors. The single tactor tactile algorithm presented the combined pitch and roll information by activating a single tactor on the body. The inability to implement the single tactor algorithm resulted in a compromise two-tactor tactile algorithm that presented pitch and roll independently being implemented.

To communicate aircraft pitch using the tactile instrument, the front and back columns of tactors were used, and to present aircraft roll, the left and right columns were used. If the aircraft was pitched down, tactors on the front column were activated and if the aircraft was pitched up, tactors on the back column were activated. Similarly, if the aircraft was rolled left, tactors on the left column were activated and if the aircraft was rolled right, tactors on the right column were activated.

To communicate the magnitude of pitch or roll, the tactor activation pulse pattern and the tactor location on the body was used as shown in Figure 24. Geldard (1960), and Sachs, Miller, and Grant (1980) reported that only three absolute levels of tactile amplitude intensity could be identified accurately. Similar to the ability of subjects to accurately determine only three levels of tactile amplitude intensity, preliminary laboratory research showed that the test pilot could only accurately distinguish between three different tactor pulse patterns intuitively and quickly. For the tactor used in this flight demonstration that had a fixed amplitude and carrier frequency, the variation of pulse pattern was detected as a change in overall perceived intensity. Perceived intensity is a complex function of the combination of tactor parameters that can be manipulated to display information at a given tactor position (for example, pulse pattern, carrier frequency, waveform, and amplitude). The three pulse patterns that were the most easily identifiable were selected for the flight demonstration. The tactor pulse patterns selected were a 'slow', 'medium', and 'fast' of 1, 4 and 10 Hz respectively. Coupled with the five tactors in a column, a total of 5x3 different combinations were available to display aircraft magnitude of pitch and roll in a particular direction.

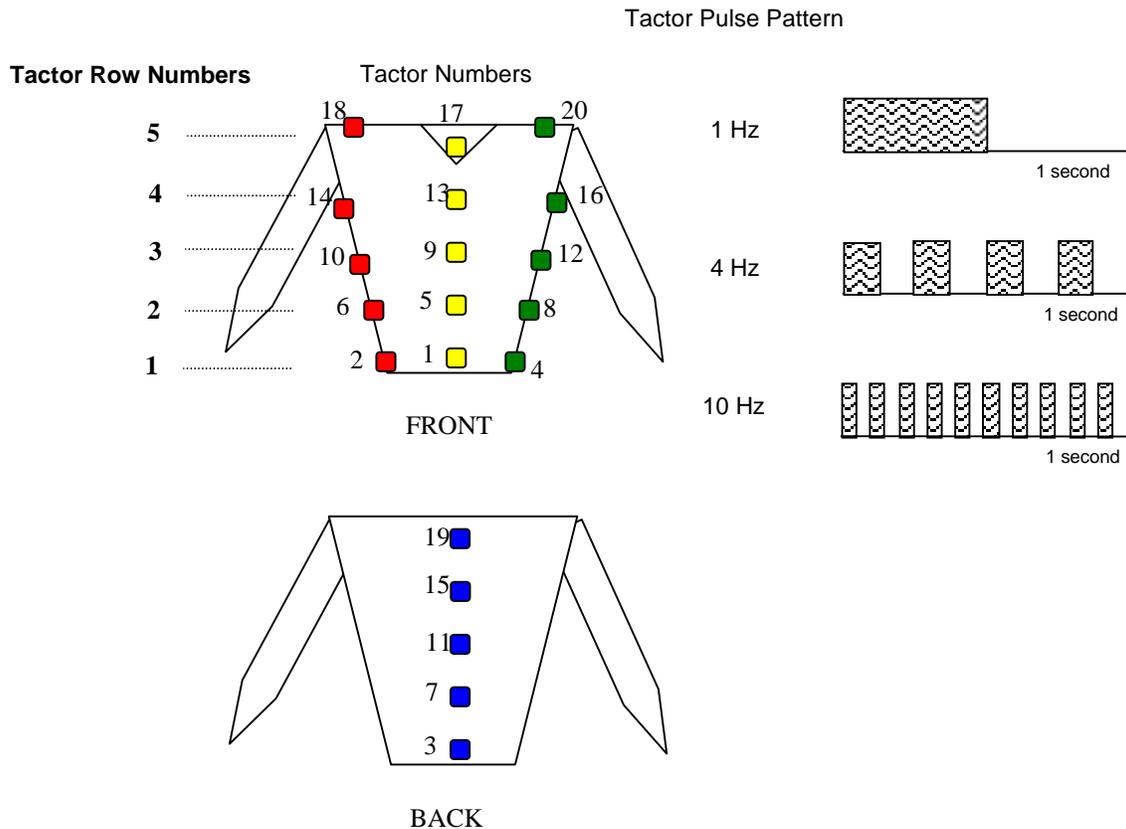


Figure 24: T-34 Tactor pulse pattern.

However, during desktop simulator testing, the test pilot reported a problem with the physical separation of the tactors selected for the flight test. The five tactors in a column were each separated by 90 to 100 mm. The test pilot found that it was difficult to distinguish between the five tactor locations in a column, especially between the middle tactors in rows 2, 3, and 4. Gilliland and Schlegel (1994) showed that for a head-mounted tactile instrument, a smaller number of tactor locations provided fastest response times and higher accuracy. Our test pilot found it was much easier to distinguish between a low, middle and high tactor location, analogous to the identification of tactor intensity described previously. The ability to quickly distinguish three tactor positions was also due in part to the limitation of the electro-magnetic tactor available for the flight test. The limitations of the tactor resulted in the development of a more intuitive tactile algorithm that used three tactors in each column. With the three pulse patterns and three tactor locations, 3x3 combinations were available to present pitch and roll magnitude in a given direction.

Further development using the desktop simulator found that the 3x3 tactile algorithm was adequate for normal flight, but was not suitable for acrobatic flight. The limited number of combinations (3x3=9) was not sufficient to cover the ± 180 degrees attitude coverage required for acrobatic flight. This result necessitated developing an algorithm using five factors in a column even though earlier desktop simulator results had shown that five factors in a column were difficult to distinguish. The five factor acrobatic algorithm was deemed an adequate solution for acrobatic flight. The more intuitive three factor algorithm was chosen for normal flight because three factors showed improved performance as compared to five factors in a column. The need for two different numbers of factors in a column necessitated the use of two different algorithms for the flight demonstration.

The first or “fine” algorithm had a pitch and roll range of ± 40 degrees and used three factors per column (factor rows 1, 3, and 4), and the second or “acrobatic” algorithm that had a pitch and roll range of ± 180 degrees and used five factors per column. Table 1 shows the two factor algorithms used during the T-34 flight demonstration.

For example, using the fine algorithm, if the aircraft was pitched down 9 degrees, the lower factor (Figure 24; factor 1) would activate at 10 pulses per second with a carrier frequency of 90 Hz. Similarly, when the aircraft was rolled right 18 degrees, the middle factor (Figure 24; factor 10) would activate at 4 pulses per second. When the acrobatic algorithm was used, and the aircraft was pitched up 9 degrees, the lower factor on the back (Figure 24; factor 3) would activate at 4 pulses per second. Similarly, when the aircraft was rolled left 65 degrees, the middle factor on the left side (Figure 24; factor 12) would activate at 4 pulses per second.

For the loop maneuvers the tactile algorithm was modified due to the inaccuracy of the aircraft attitude gyroscope. At the top of the loop maneuvers the aircraft attitude gyroscope would provide erroneous pitch and roll information. Therefore, the factors were deactivated in a zone ± 5 degrees of the top of the loop.

Table 1. T-34 TSAS Tactile Instrument Algorithm.

Fine Algorithm

Angle (degree)	Pulse Pattern (Hz)	Tactor Row Nos.
0 to 1	no tactor activated	
>1 to 3	1	1
>3 to 5	4	1
>5 to 10	10	1
>10 to 15	1	3
>15 to 20	4	3
>20 to 25	10	3
>25 to 30	1	4
>30 to 35	4	4
>35 to 40	10	4

Acrobatic Algorithm

Angle (degree)	Pulse Pattern (Hz)	Tactor Row Nos.
0 to 1	no tactor activated	
>1 to 5	1	1
>5 to 10	4	1
>10 to 20	10	1
>20 to 30	1	2
>30 to 40	4	2
>40 to 50	10	2
>50 to 60	1	3
>60 to 75	4	3
>75 to 90	10	3
>90 to 105	1	4
>105 to 120	4	4
>120 to 135	10	4
>135 to 150	1	5
>150 to 165	4	5
>165 to 180	10	5

3.3 TEST PLAN

One US Navy test pilot was selected to fly the flight demonstrations. The US Navy test pilot had 6843 total flight hours and 68.1 flight hours in a T-34. All test demonstration flights occurred at NAWC-AD, Patuxent River, Maryland. The series of flight tests included:

TSAS Flight Demonstration (FLT 1,2,3,4,5). These five flights were performed to demonstrate that an aviator could maintain control of the aircraft without visual cues, relying solely on tactile cues for attitude information. For flights 1 and 2, the precision (fine) tactile algorithm was used, and during flights 3, 4 and 5, the acrobatic tactile pattern was used.

TSAS Tactile Algorithm Evaluation (FLT 6). This flight was conducted to evaluate the effectiveness of switching between the different tactile algorithms (fine and acrobatic) during flight conditions.

TSAS Photography Flight (FLT 7). This flight was to collect internal and external in-flight video and photography of the T-34 TSAS flight demonstration. A chase plane was used to capture the external video and photographs. These video data were collected for use in multi-media presentations. Table 2 represents the TSAS test event matrix.

Table 2. T-34 TSAS Test Event Matrix.

Flt Nos	Pilot	Purpose	Algorithm
1	JB	Flight Demonstration	fine
2	JB	Flight Demonstration	fine
3	JB	Flight Demonstration	acrobatic
4	JB	Flight Demonstration	acrobatic
5	JB	Flight Demonstration	acrobatic
6	JB	Tactile Algorithm Evaluation	fine/acrobatic
7	JB	TSAS Photography Flight	acrobatic

The two seat T-34C described above was used for all six test flights. The safety pilot was seated in the front cockpit and the subject pilot wearing TSAS was seated in the aft cockpit (Figure 17). The subject pilot performed all maneuvers (Table 3). After both the safety pilot and subject pilot determined that a maneuver was performed adequately, the next maneuver was performed. The subject pilot was under the hood and had no outside visual reference and also no visual flight instruments. The safety pilot monitored all flight parameters necessary during each maneuver to ensure safe flight, including the TSAS LED display to determine that the electro-mechanical factors were activating correctly. The TSAS LED display informed the safety pilot that the factors were working, but did not give an indication that the subject pilot was feeling the factor.

During the GCA approaches, the safety pilot took control of the aircraft at a predetermined point as defined by the following criteria:

- 150 feet AGL.
- Greater than 30° AOB.
- Greater than 23 units AOA.
- Descent rates greater than altitude in ft/min AGL.

Table 3. T-34 TSAS Test Maneuvers.

No.	Maneuver type	Config.	Altitude (ft)	Time	Airspeed(kt)	Load factor
1	Straight and Level	Cruise	5,000-10,000	60 secs	120 – 190	1
2	Constant Altitude, Heading Changes	Cruise	5,000-10,000	30 secs	120 – 190	1
3	Constant Heading, Altitude Changes	Cruise	5,000-10,000	30secs	120 – 190	Approx. 1
4	Climbing and Descending Turns	Cruise	5,000-10,000		120 – 190	Approx. 1
5	Unusual Attitude Rec.	Cruise	5,000-10,000		120 – 190	0 to 3.0
6	Loops	Cruise	5,000-10,000		120 – 190	0 to 3.5
7	Aileron Rolls	Cruise	5,000-10,000		120 – 190	Approx. 1
8	GCA Approaches	Cruise	5,000-10,000		100 – 150	Approx. 1

The safety pilot maintained all power settings, navigation and radio communications necessary for safe execution of the required maneuvers. The hazard analysis completed prior to the flight test is provided in Appendix C.

Subject Pilot Debrief

The US Navy test pilot was interviewed after each TSAS flight demonstration. Table 4 represents the interview questions

Table 4. T-34 TSAS Debrief Interview.

- Was the factor TLS comfortable?
- Any suggestions for improvement of the factor TLS?
- Could you feel the factors?
- Was the factor signal intensity strong enough?
- Was the tactile information intuitive?
- Was the tactile sensation annoying?
- Any suggestions for improvements of the factors and/or tactile information?
- Any further comments?

Data Recording

The VTOS-N1 computer logged all of the attitude data from the aircraft and the corresponding factor activation. Video documentation of flight activities was performed using a video recording system. The system consisted of a small camera, time code inserter, and video recorder. The camera was located behind the pilot in the front cockpit. The lens size for the camera was selected to provide over-the shoulder field of view that included the attitude indicator, TSAS LED display, and mechanical clock. The time code inserter displayed the time to a tenth of a second on the video. All audio from subject pilot and safety pilot was recorded on the video recorder.

Data Analysis

Flight data analysis consisted of converting the binary data log files stored by the VTOS-N1 processor to ASCII format. The resultant data files contained five channels of data, which were converted to MatLab™ (MathWorks, Inc. Natick, Massachusetts) format variables for production of flight data graphs. Corresponding video was analysed to obtain subject pilot comments.

3.4 RESULTS

Flight-testing was conducted in accordance with the test plan described in Section 3.3.

Pilot Comments

Was the tactor TLS comfortable? Any suggestions for improvement of the tactor TLS?

The US Navy test pilot commented that the tactor TLS was “OK” and as a prototype was more than adequate for the flight demonstration. The modified SV-2 that housed the VTOS-N1 equipment “felt no different than a normal fully loaded SV-2.” The test pilot remarked that the goal for the tactor TLS should be to integrate the tactors and auxiliary tactor electronics equipment into existing flight garments. “I don’t want to wear another piece of equipment”.

Could you feel the tactors?

US Navy test pilot reported that he could feel the tactors “the majority of the time.” The safety pilot would on occasion have to inform the subject pilot when he was not responding to a tactor signal. The test pilot commented that there could have been more vibration or sensation from the tactors, “(in a critical situation) I would rather be bruised than miss a tactor.”

Was the tactor intensity of signal strong enough?

Test pilot reported that the tactor intensity was not strong enough. He commented, “(I) had fear of missing a tactor”.

Was the tactile information intuitive?

“If the tactor is appropriately positioned the tactor information was intuitive.” The test pilot used the analogy of the highway rumble strip. “Using the rumble strip, the information was intuitive because the analogy is in my mind, in that I was (located) between 2 boundaries as on a highway. Any vibration informed me that I had deviated from a desired parameter. The [desired] parameter being a null⁴ or no tactor condition.”

Was the tactile sensation annoying?

The US Navy test pilot responded that the tactile sensation was not annoying or distracting.

Any suggestions for improvements of the tactors and/or tactile information?

1. Number of tactors:

“I would use the least amount of tactors as possible. No more than three rows and four columns on the torso.” “5 rows more difficult (to use) than 3 rows. The information was not as intuitive with five rows. I lost confidence or I couldn’t get the information quickly enough with 5 rows.”

2. Tactor strength

“The tactors need to be more robust.”

3. Tactor algorithm

“The best use of the tactile display (with these tactors) is when deviating from the null condition. I was instantly alerted to any deviation from that desired parameter. For example, during unusual attitude recovery the difference between a front and back tactor was instantly and intuitively recognized thus informing me that I had passed through the null, which represented straight and level.”

Any further comments?

“When the safety pilot was flying and I had the tactors off, I often experienced vertigo, however, with the tactors on, I did not experience vertigo. During one loop, with the tactors off, I experienced a tumbling sensation at the end of the loop, however with the tactors on, I was aware of the aircraft attitude, and (I) did not experience a tumbling sensation.”

⁴ The null condition is when no tactors are activated.

“(The factors) do not prevent leans but I could still control aircraft. Similar to vision overcoming sensation of leans, the factors also prevent/overcome the sensation of leans.”

“The loss of factor sensation was critical and repeatedly caused problems.” (See Figure 32 for an example of a missed factor.)

Flight Data

The US Navy test pilot relying solely on tactile cues for attitude information was able to successfully fly the following general flight maneuvers:

- Straight and Level
- Bank angle capture
- Pitch angle capture
- Climbing and Descending turns
- Unusual Attitude Recovery
- GCA approaches

And the following acrobatic flight maneuvers:

- Loops
- Aileron rolls.

BANK ANGLE CAPTURE

Figure 25 shows the subject pilot execute bank angle captures successfully in both left and right turns. Bank angle captures are defined as rolling the aircraft to a precise and predetermined roll angle. Verbal comments by the subject pilot are shown in inverted commas to indicate awareness of aircraft bank angle.

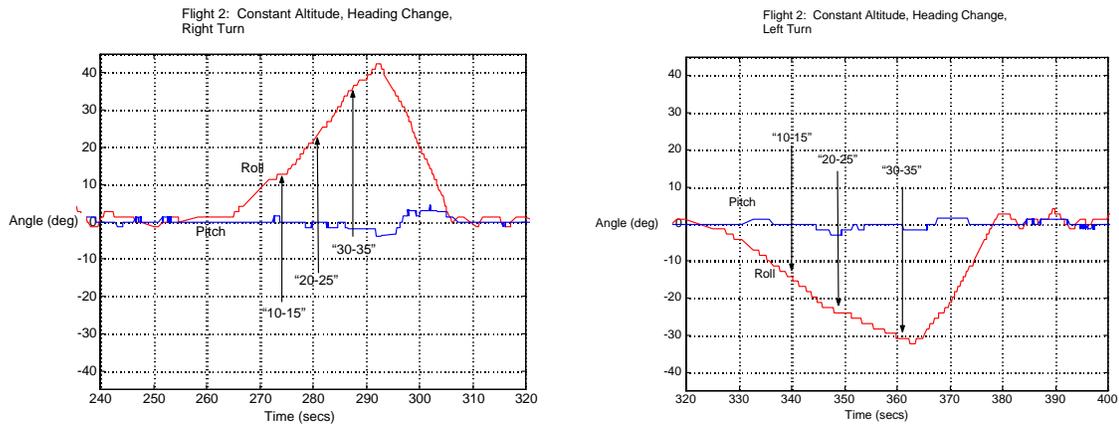


Figure 25: Bank angle capture.

PITCH ANGLE CAPTURE

Figure 26 shows the subject pilot performing a pitch down of 5-10 degrees and a pitch up of 10-15 degrees. Verbal comments by the subject pilot to indicate awareness of aircraft pitch angle are shown in inverted commas.

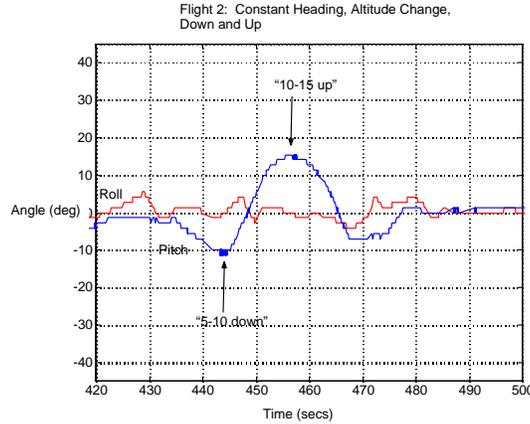


Figure 26: Pitch angle capture.

CLIMBING AND DESCENDING TURNS

This proved to be the hardest of the maneuvers as it involved simultaneously distinguishing between two different factors at two locations on the body firing at a certain frequency. For example, for the maneuver shown below in Figure 27 (1) the desired aircraft attitude was 15 degrees up and 25 degrees right. This translates to a tactile sensation of the number 11 tactor located on the back with a pulse pattern of 1 Hz and the number 10 tactor located on the right with a pulse pattern of 10 Hz. The US Navy test pilot was able to accomplish the task of differentiating between the two tactile sensations as shown in the successful completion of the climbing turn illustrated in Figure 27 (1). However, it was not intuitive and often problems occurred, as shown in Figure 27 (2) in that the test pilot was confused due to difficulty in distinguishing between the third and fourth tactor rows on the left column.

The test pilot commented that “Going to null was easier than going to a precise attitude.”

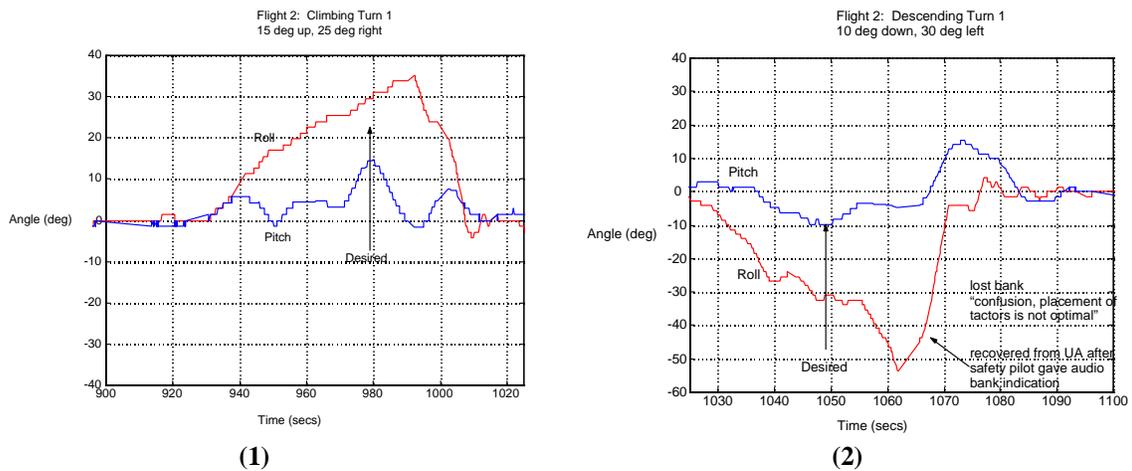


Figure 27: Climbing and descending turns.

UNUSUAL ATTITUDE RECOVERY

Figure 28 shows the subject pilot perform an unusual attitude recovery from pitch down 5 degrees rolled right 25 degrees (Figure 28 (1)), and a unusual attitude recovery from pitch down 10 degrees rolled right 35 degrees (Figure 28 (2)). This maneuver was considerably easier and more intuitive because the end point was the “null” or no factor condition. The test pilot would start correcting in one direction or axis, and then correct for the second axis. When the null condition was satisfied, no factors activated, straight and level flight had been achieved.

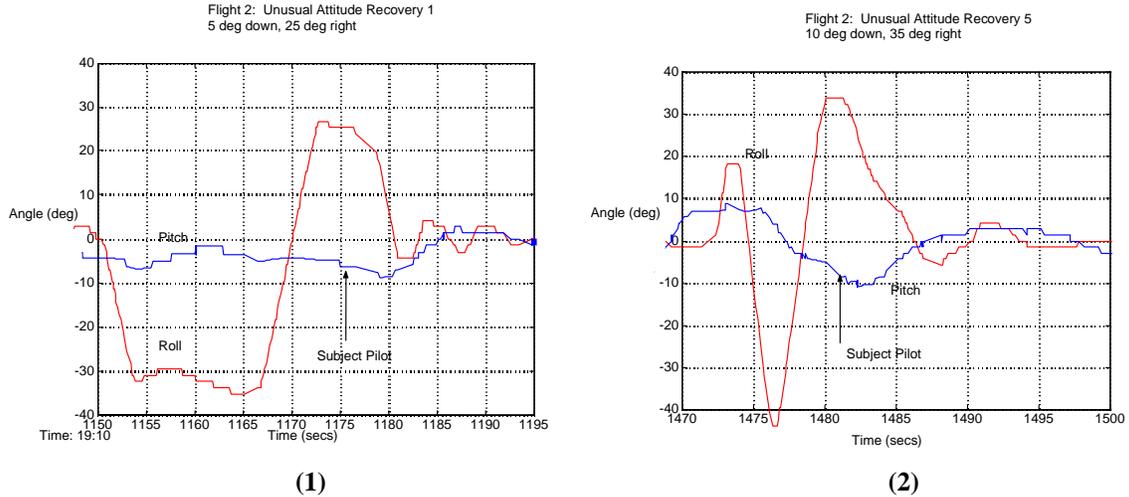


Figure 28: Unusual attitude recovery.

GCA APPROACHES

Using the ability to capture bank angles corresponding to half-rate and full-rate turns, and the ability to capture pitch angles for altitude adjustment, the test pilot was able to successfully perform GCA approaches down to the minimum safe altitude (Figure 29). The safety pilot performed all power setting changes during GCA approaches.



Figure 29: GCA approach.

LOOPS

The US Navy test pilot successfully performed loops using only tactile cues for attitude information (Figure 30). To keep wings level, he maintained a null condition between the left and right factor columns. Any activation of these left or right factors alerted the pilot that his wings were no longer level. To maintain the appropriate pitch attitude, the required pitch angle of approximately 10-15 degrees nose-down was captured to begin the loop. Tactors would move to his back, and then move up and over his shoulders (inverted flight at this stage) to the front and then down the front column. At the end of the loop the pilot would typically overshoot the “null “ by waiting for the back tactor to activate. The marked tactile sensation difference between a front and back tactor would instantaneously alert the test pilot that he had overshoot the null, and then he would make the appropriate pitch control inputs to null the tactors and bring the aircraft to straight and level.

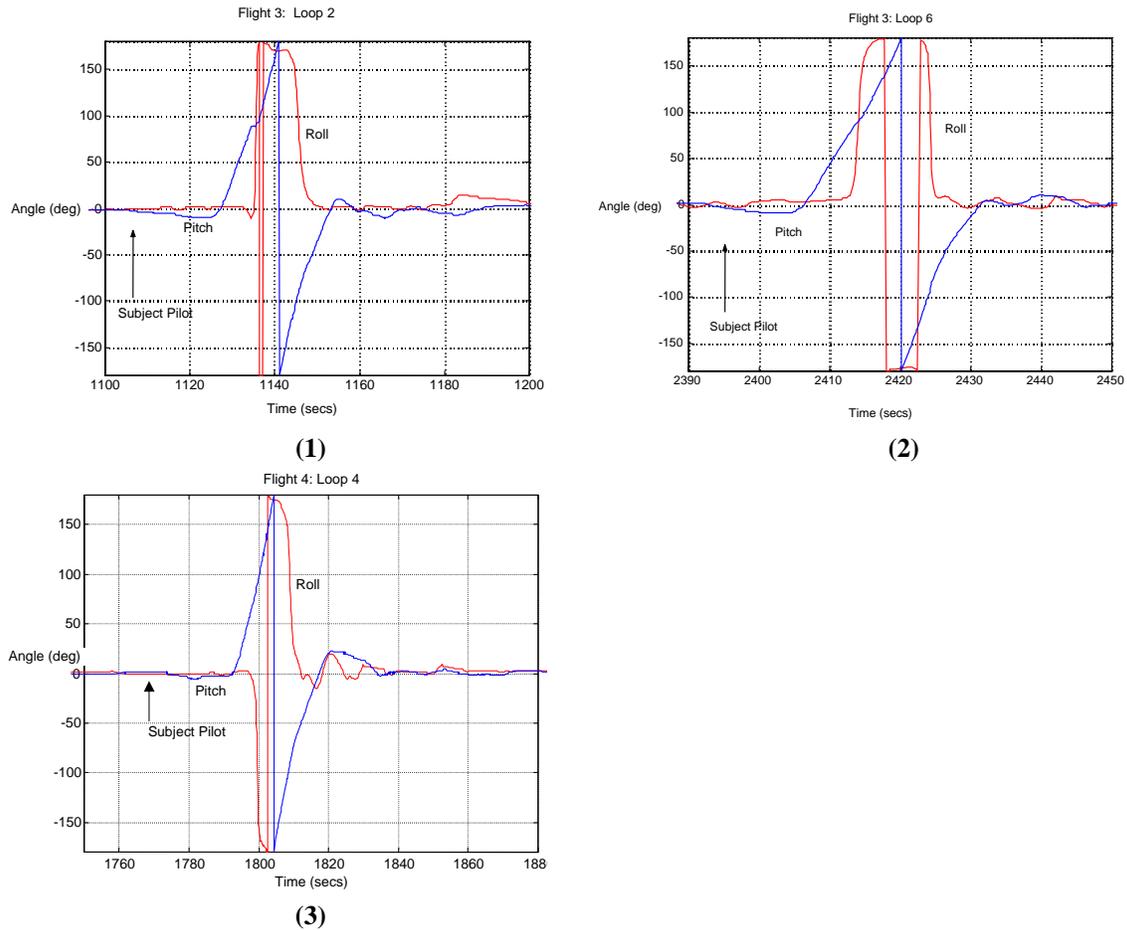


Figure 30: Loops.

The test pilot commented that the loop was a learned skill, you get better and better, but as can be seen in Figure 30 (1) the second loop ever attempted, Flight 3, Loop 2, was very successfully performed.

AILERON ROLL

The US Navy test pilot successfully performed aileron rolls using only tactile cues for attitude information with a similar strategy as the strategy used to perform the loops (Figure 31).

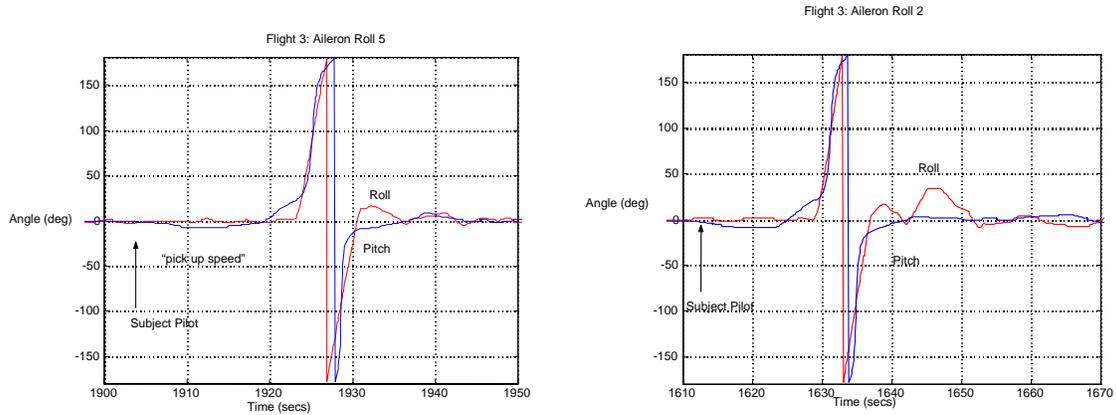


Figure 31: Aileron rolls.

3.5 DISCUSSION

The T-34 TSAS flight demonstration test program accomplished at NAWC-AD was successful in demonstrating the potential capabilities of a tactile instrument. This flight demonstration was the first time that a military aircraft was controlled with reference only to orientation information provided through a tactile sensory pathway. Using only the tactile instrument, the test pilot was able to successfully perform the following maneuvers: straight and level for 5 minutes; bank angle capture; pitch angle capture; climbing and descending turns; unusual attitude recovery; loops; aileron rolls; and GCA approaches. This demonstration showed that a pilot using tactile information could maintain control of aircraft. From this result, a tactile attitude instrument has the potential to allow pilots to devote more time to other visual instruments when flying in task-saturated conditions.

The majority of technical problems encountered in this flight demonstration were attributable to the subject pilot failing to detect a tactor. This became the “missed tactor” problem and is illustrated in Figure 32. When the subject pilot failed to respond to a tactor signal, the safety pilot would take control of the aircraft as indicated by the arrows in Figure 32. With only tactile cues available to the subject pilot, if he did not feel the tactile sensation from the tactor then he would assume that the aircraft was straight and level, even if the aircraft were not straight and level. Three sources of the missed tactor problem were identified and steps were taken to minimize this problem during the flight demonstration. Future development is required to eliminate the missed tactor problem in an operational tactile instrument.

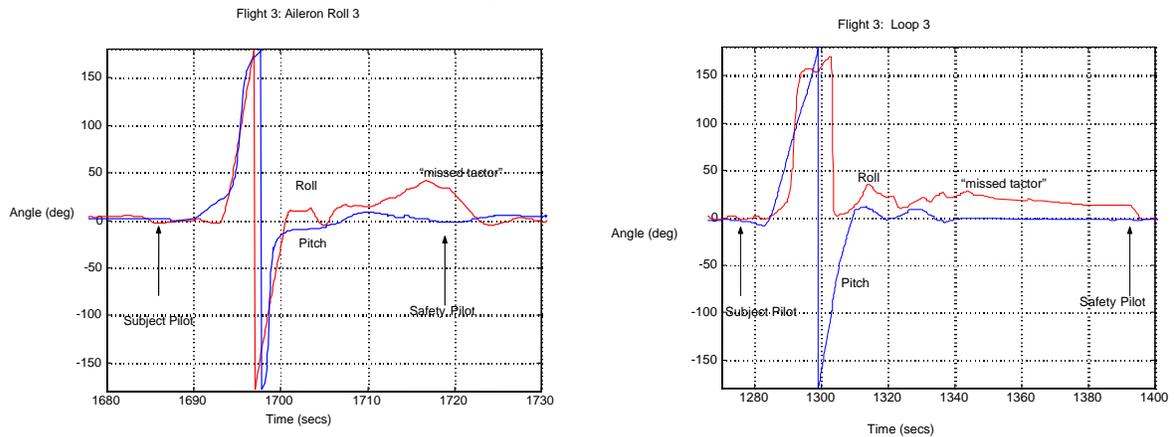


Figure 32: Missed tactor.

The first source of the missed tactor problem was the aircraft vibration. At certain times the tactile sensations would be lost in the aircraft vibration. Limitations in tactor design precluded any short-term fixes for this problem. Future development of a more robust or “stronger intensity” tactors is required.

The second source was subject pilot confusion of the tactor location. As mentioned previously, the subject pilot had problems differentiating between the middle tactors in a column of five (Figure 24, tactors 2, 3, and 4). Therefore, for non-acrobatic maneuvers the fine algorithm was used which consisted of three tactors, thus minimizing this potential source of confusion.

The third source was poor fitting of the tactor TLS. The tactor would move away from the torso during some phases of flight, especially in later flights when the weight of the tactor had caused the NOMEX to stretch. The addition of sports bandages and electrical tape minimized, but did not eliminate this problem (Figure 33). The addition of the tape was adequate to meet project goals, but was an unacceptable solution for an operational TLS. Improved tactor locator systems are required, including the integration of tactors into existing flight garments.



Figure 33: T-34 TSAS tactor locator system.

The other technical problem that occurred involved the aircraft attitude gyroscope. After certain acrobatic maneuvers the gyro would precess, causing erroneous tactile signals to be sent to the subject pilot. This problem was intermittent and only occurred at the end of the acrobatic maneuvers, and is consistent with normal T-34 gyroscope operation. The safety pilot was instructed to take the controls if the gyroscope “tumbled.”

The T-34 TSAS flight demonstration showed that a pilot using TSAS technologies could maintain control of an aircraft, however, the tactile algorithm that was used to present attitude information was not optimal and further development is required in a number of areas. The first area relates to the number and location of the tactors. Rupert *et al.* (1994) proposed a one-to-one tactile algorithm that uses a single tactor to provide attitude information. Pitch and roll information is combined into a single variable – direction of down – and the direction of down is indicated by the location of the tactor on the torso of the pilot. To implement this tactile algorithm, a matrix of tactors covering the torso is required (Figure 10). The exact

number of factors has never been determined, but a minimum $5 \times 8 = 40$ factors or a possible $12 \times 8 = 96$ factors would be required. The only factor available for the T-34 TSAS flight demonstration with an adequate intensity of tactile sensation was the “pager motor” which weighed 29g. This high weight of the individual factor limited the total number of factors that could be comfortable worn in a vest underneath a flight suit to twenty. Therefore, the single factor tactile algorithm could not be implemented, and the compromise two-factor tactile algorithm that presented pitch and roll independently was implemented. The test pilots’ comment that he preferred three rows to five rows, and his flight performance in climbing and descending turns implies that the tactile algorithm required cognitive effort. This cognitive effort to interpret the tactile signal negates to a certain extent the value of a tactile instrument system. The best tactile algorithm is one that is intuitive.

Another problem with the “heavy” factor is that the acceleration to which the pilot was exposed (up to 3 to 3.5G) pulls the factor down. After the initial flights, the TLS started to sag under the weight of the factor causing the NOMEX to stretch. A lighter factor is required to implement multiple factor designs and to minimize the missed factor problem caused by “sagging” TLS.

The tactile algorithm that presented pitch and roll independently caused problems during climbing and descending turns, since two factors would fire simultaneously. Even though these two factors were at different locations on the body and often at different pulse patterns, the quality of the tactile sensation was not sufficiently different to allow for the subject pilot to intuitively and quickly distinguish between the two factors. This confusion, or need to think, often caused problems and difficulty in that maneuver. In contrast, the large difference in the tactile quality between a front and back or a right and left and the null allowed for an intuitive and fast response to the tactile sensation. One solution that may overcome the limitations of the two-factor algorithm problem is to use a one-to-one mapping that uses a single activated factor that corresponds to the direction of the ground. Technical limitations of the factor (weight) and TLS design precluded implementation of this tactile algorithm concept for this T-34 flight demonstration.

The factors and TLS used in the T-34 TSAS flight demonstration were adequate to meet project goals. However, the factors were not strong enough to give complete confidence to the subject pilot, and they were too heavy to develop an optimal tactile algorithm. Similarly, the TLS needed a great deal of improvement with the goal to integrate the factors into existing flight garments.

For the T-34 TSAS flight demonstration, two different tactile algorithms were developed using variations of factor stimulus selected from pulse pattern and factor location. The first tactile algorithm was used for fine control of the aircraft, and the second page was used for acrobatic control. The first or “fine” algorithm had a pitch and roll range of ± 40 degrees and used only three factors per column, and the second or “acrobatic” algorithm had a pitch and roll range of ± 180 degrees and used five factors per column. During TSAS Evaluation flight 6, the pilot performed similar maneuvers with the tactile instrument in fine or acrobatic mode. No quantitative data was recorded during this flight due to a computer problem. Subjective pilot comments during this flight showed that it was more intuitive and easier to distinguish between a low, middle and high factor, therefore during non-acrobatic maneuvers improved qualitative performance was noted using the fine algorithm as compared to using the five factor acrobatic algorithm. Only the acrobatic control program could be used for the acrobatic maneuvers. This result indicates that the test pilot could distinguish between factor algorithms and that the tactile instrument should provide information optimised for a particular flight regime. Further work is required to fully examine the effectiveness of switching between different tactile algorithms in a manner analogous to “pages” on a visual instrument.

One objective of the T-34 TSAS program was to investigate the notion that by providing tactile orientation information, the illusory effects present in the aviation environment can be reduced. Subjective comments by the test pilot shed a little light on this notion but do not provide a definitive answer. The relevant comments were:

“When the safety pilot was flying and I had the factors off, I often experienced vertigo, however, with the factors on, I did not experience vertigo. During one loop, with the factors off, I experienced a tumbling

sensation at the end of the loop, however with the tactors on, I was aware of the aircraft attitude, and (I) did not experience a tumbling sensation.”

“(The tactors) do not prevent leans but I could still control aircraft. Similar to vision overcoming sensation of leans, the tactors also prevent/overcome the sensation of leans.”

The first comment supports the notion that the tactile instrument could reduce illusions experienced in flight, whereas the second comment suggests that illusions can occur even with a tactile instrument. Further research to answer this intriguing notion is required.

Following the T-34 TSAS flight demonstration, a similar flight demonstration was conducted in an UH-60 helicopter in forward flight (Raj, McGrath, Newman, Rochles, and Rupert 1998). The UH-60 TSAS flight demonstration project integrated the tactile instrument from the T-34 flight demonstration with slight modifications into a UH-60 helicopter to show that a pilot could receive aircraft orientation and performance information using a tactile instrument during helicopter forward flight operations. The first flight of the TSAS-modified UH-60 was 11 December 1995, and nine flight test events were completed by 20 December 1995. Roll and pitch tactile cues were provided via a matrix array of vibro-tactors incorporated into a torso harness as used for the T-34 flight demonstration. Additionally, airspeed and heading error tactile cues were provided by tactors located on the arms and legs, respectively. These limb tactors were Tactaids (Audiological Engineering, Somerville, Massachusetts) that have a slightly different tactile sensation than the pager motors. This difference can be described as a weaker intensity sensation.

For attitude information, results confirmed the findings from the T-34 effort in that test pilots were able to successfully perform all forward flight maneuvers without visual cues, relying solely on tactile cues for the necessary attitude information. However, the auxiliary arm and leg tactile cues caused significant difficulties. In an effort to provide the UH-60 pilot with a greater amount of information (four independent variables) than the T-34 pilot (two independent variables), tactile information “overload” occurred. Heading control remained problematic throughout the demonstration, as pilots had difficulty picking up the heading error signal when the pitch and roll tactors were active. This result confirms that a tactile instrument can overload the pilot, just as visual displays can provide too much information and cause a problem. By trying to display four separate pieces of information (pitch, roll, airspeed, and heading error) all simultaneously with similar tactors on different parts of the body, the tactile algorithm was not intuitive (McGrath, Suri, Carff, Raj, and Rupert, 1998). Efforts in tactile technology and tactile algorithm development to avoid this problem are required for the successful development of a tactile instrument.

The T-34 TSAS flight demonstration met project test objectives and demonstrated that a tactile instrument could provide attitude information to a pilot in actual flight. The flight demonstration showed that a pilot using TSAS technologies could maintain control of an aircraft. TSAS has the potential to permit the pilot to concentrate on visual mission tasks while maintaining awareness of orientation, thereby potentially increasing situation awareness and reducing workload. These effects could substantially increase mission effectiveness. Further work is required in tactor technology, integrating tactors into existing flight garments, and improving the tactile algorithm. Overall, given the limitations of the tactile instrument technology, especially the tactor, the T-34 TSAS flight demonstrations have shown that a tactile instrument can provide attitude information to a pilot, and has the potential to decrease pilot workload, enhance pilot situation awareness, and thus increase survivability and mission effectiveness.

If you are sweating too much before a flight, you surely haven't asked enough questions. If you are not sweating just a little during the flight, you may not be attentive enough. And, if you are not sweating out the answers with all the experts you can think of after the flight, you may never find that very beautiful pearl in all that pig litter.

-- Corwin H. Meyer, Grumman test pilot W.W. II.

JSF TSAS Flight Demonstration

4.1 INTRODUCTION

The focus of the JSF TSAS flight demonstration project was to demonstrate reduced pilot workload and enhanced situation awareness during hover operations in poor visibility conditions with the use of TSAS, and to provide insight into the impact of TSAS technologies on a single-seat aircraft. The specific objectives of the JSF TSAS flight demonstration program were to demonstrate:

- The potential for TSAS technology to reduce pilot workload and enhance situation awareness during hover and transition to forward flight.
- That a pilot using TSAS can effectively hover and transition to forward flight in a vertical lift aircraft with degraded outside visual cues.
- The feasibility of integrating tactile instrument technology into military flight garments.

In a survey of 970 US Army rotary wing mishaps from 1987-1995 (Durnford *et al.* 1995, Braithwaite *et al.* 1997), 30% of the mishaps were considered to have had spatial disorientation as a major or contributory factor. On average, spatial disorientation costs the US Army 14 lives and \$58 million each year. When classifying these mishaps by phase of flight, 25% of spatial disorientation mishaps occurred during drift and/or descent in hover, which was the second largest group of all mishaps (Figure 34). Hovering flight is distinctive to vertical landing and take-off aircraft such as helicopters and the AV8B Harrier. The importance of spatial disorientation and countermeasures for this phase of flight is critical for safe operations of the next generation vertical landing and take-off aircraft, such as the Joint Strike Fighter variant for the United States Marine Corps and the Royal Air Force.

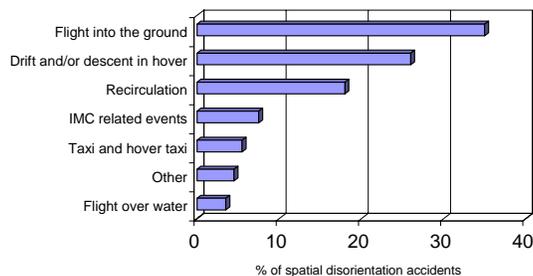


Figure 34: Types of spatial disorientation accidents (from Braithwaite *et al.* 1997).

When considering spatial disorientation mishaps in vertical landing and take-off aircraft, one must remember that instrumentation in these aircraft have come from the traditional fixed-wing aircraft. New instrumentation designed for the hover phase of flight has been restricted to the development of symbology on MFDs and HMDs. This has provided a partial solution but has not eliminated the problem of spatial disorientation in hover flight. Even though information to assist orientation during hover is presented in the integrated helmet and display sighting system (IHADSS) of the AH-64 helicopter, often it is not interpreted correctly or is even ignored (Braithwaite *et al.* 1997). There is a critical need for the development of new instrumentation to provide drift and/or descent cues during hovering flight.

The successful achievement of JSF TSAS project objectives required the use of a dual station vertical lift aircraft with associated flight test support that would allow timely completion of the project within a fixed budget. The TSAS planning team established demonstrator aircraft criteria that were used in evaluating a variety of candidate flight test aircraft. Use of these criteria resulted in the decision to use the UH-60 aircraft at United States Army Aeromedical Research Laboratory (USAARL) located at Fort Rucker, Alabama that provided a complete flight demonstration package at the lowest cost. Benefits of using the USAARL UH-60 aircraft included:

- Dual-seat capability enabling the addition of a safety pilot, who doubled as an instructor pilot, to provide real-time assistance to TSAS demonstration pilots.
- Previous integration and test experience with tactile instruments (Raj *et al.* 1998).
- Aircraft availability.
- Low integration and flying time costs.
- Testing the TSAS tactile instrument in a harsh environment.

The USAARL flight test facility also provided multiple benefits including:

- Complete on-site aircraft modification and maintenance, and avionics hardware and software test capability.
- On-site flight test planning, data collection and analysis, and reporting capability.
- The availability of United States Army helicopter pilots.
- Motion-based UH-60 simulator.

The JSF TSAS project was a true team effort involving numerous Military, Academic, and Industry organizations. The JSF TSAS project participants are listed below.

- National Aeronautics and Space Administration-Johnson Space Center provided concept origination and computer hardware.
- University of Sydney provided aeronautical engineering, flight test engineering and project management support.
- Joint Strike Fighter provided program management and fiscal support.
- Naval Aerospace Medical Research Laboratory provided TSAS laboratory testing facilities, system integration facilities, flight hardware fabrication and US Navy test pilot.
- United States Army Aeromedical Research Laboratory provided the UH-60 aircraft and US Army pilots, prepared the documentation for aircraft modification approval and flight clearances, conducted ground testing to verify flight readiness, and made available the UH-60 simulator for TSAS integration and pilot training.
- Coastal Systems Station developed the tactor laboratory hardware, provided fiscal management support, and provided all TSAS logistical support.
- University of West Florida developed TSAS software and designed and integrated the flight-worthy TSAS hardware.

- Naval Air Station Pensacola provided flight test and range support.
- Office of Naval Research provided fiscal management support.
- Jackson Foundation provided project management support.
- Princeton University provided tactile expertise.
- Massachusetts Institute of Technology and Tulane University provided expertise in helicopter handling qualities modelling and analysis.
- Carleton Technologies, under CSS contract, supplied and supported the pneumatic tactor, model 2856-A0, and the ground-based pneumatic tactor driver system.
- Engineering Acoustics Inc., under ONR SBIR contract, supplied and supported the electromagnetic tactor, AT-96.
- Audiological Engineering, under ONR contract, supplied the electromagnetic tactor, Tactaid.
- Unitech Research Inc., under CSS contract, supplied the electrical tactor, Audiotact.
- Lockheed-Martin/ Mustang Survival, under CSS contract, supplied the F-22 cooling vest.
- Boeing North American, Inc. Autonetics & Missile Systems Division, under CSS contract, supplied and supported the MIGITS II Inertial Navigation /Global Positioning System (INS/GPS).

The JSF TSAS flight demonstration project integrated an array of pneumatic vibro-tactile tactors, an F-22 cooling vest, and GPS/INS technologies into a single system in an UH-60 helicopter. A 10-event test operation was conducted to demonstrate the utility of this advanced human-machine interface for performing hover operations.

4.2 SYSTEM DESCRIPTION AND INTEGRATION

The following sections describe the test aircraft, TSAS, and integration requirements, including ground-based testing systems. The components that made up the TSAS system were integrated into the UH-60 as shown in Figure 35. The TSAS system took data from a commercial off-the-shelf (COTS) GPS/INS, as well as from the aircraft itself to calculate the helicopter velocity. This information was displayed via pneumatically driven tactors mounted in an F-22 cooling vest. The tactors were arrayed around the torso in eight columns. Location of the tactor on the torso was used to indicate direction of helicopter drift, and tactor activation pulse pattern was used to indicate magnitude of the helicopter drift. The TSAS tactor display used in this flight test was designated NP-1.

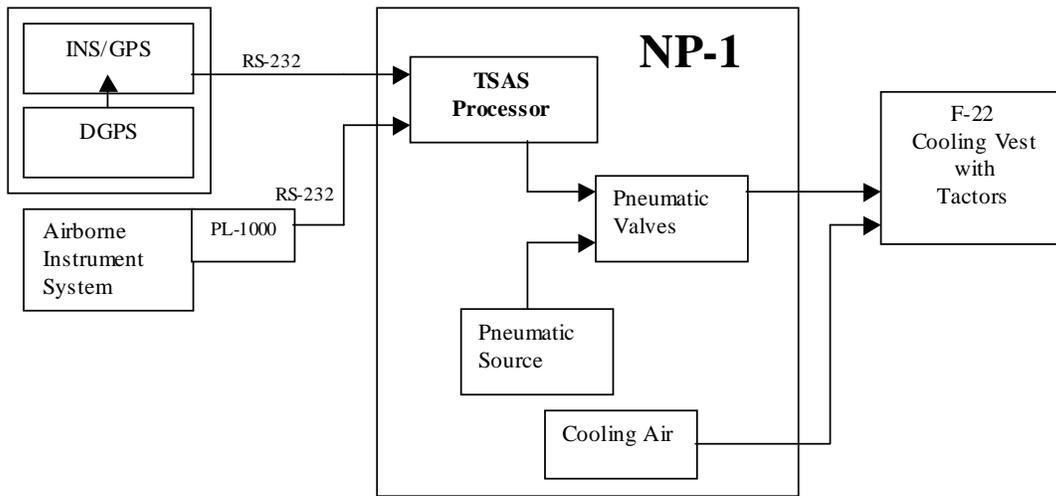


Figure 35: JSF TSAS NP-1 architecture.

UH-60 Aircraft

The USAARL UH-60 research aircraft (Figure 36) is a twin turbine engine, single rotor, semi-monocoque fuselage, rotary-wing helicopter manufactured by the Sikorsky Aircraft Company. The aircraft is designed to operate with a crew of three: pilot, co-pilot, and crew chief. In that original configuration, it can carry 11 combat equipped soldiers. The primary mission of the aircraft is the transport of troops, supplies, and equipment. Other missions include training, mobilization, concept development as well as medical evacuation and disaster relief.

The main rotor system has four blades that are constructed of titanium and fibreglass. Two T700-GE-700 engines supply propulsion. The UH-60 has a non-retractable landing gear system consisting of two main landing gears and a tail wheel. The max gross weight of the aircraft is 22,000 pounds. The pilot and co-pilot have controls for flying the aircraft. The aircraft is fully instrument rated at either pilot's station. The aircraft is equipped with an automatic flight control system (AFCS), which enhances the stability and handling qualities of the helicopter.



Figure 36: USAARL UH-60 research aircraft.

The USAARL research aircraft (Figure 36) has been fitted with a custom-made Airborne Instrumentation System (AIS). Flight parameters can be derived from the main aircraft systems to provide an indication of flying performance, and input ports are also available for monitoring physiological data from a suitably equipped pilot. The data can be recorded on-board or relayed via telemetry directly to the ground. The flight parameter data can also be converted to RS-232 data to drive on-board devices such as TSAS.

Equipment installed in the USAARL UH-60A included the:

- 115 Volt 60 Hz AC inverter that supplied power to the TSAS NP-1.
- AIS that supplied analog data from the aircraft instruments.
- PL-1000 that digitised the AIS data and transmitted these data over a serial communications port to the TSAS NP-1 computer.

Foggles

To reduce outside visual cues and simulate IMC, the TSAS demonstration pilots were required to wear "foggles." Foggles are standard Army issue aviator glasses with a semi-opaque film (Ryser Optik, St. Gallen, Switzerland ~0.1) attached to the clear glass lens. The film was attached in such a manner that the pilot's outside visual acuity was reduced to 20/200 while maintaining inside visual acuity at 20/20. To further reduce outside visual cues, the chin bubble was also covered with an opaque plastic lining (Figure 37).



Figure 37: UH-60 chin bubble with opaque plastic lining.

TSAS NP-1 Sensor

To provide aircraft performance data to the tactile display, a GPS/INS system with Differential GPS (DGPS) corrections was integrated with the UH-60 and TSAS. The GPS/INS was a Boeing-North American, Model C-MIGITS-II that was connected to a Ball Aerospace, Model AN496C passive patch antenna with a 150 mm conical ground plane. The DGPS corrections were provided by a US Coast Guard differential beacon receiver, Starlink, Inc., Model DNAV-212G with a +AMBA-4 Antenna.

Boeing North America, Inc. Autonetics and Missile Systems Division has developed the C-MIGITS-II GPS/INS Tactical System using the latest solid state inertial sensor technology integrated with advanced GPS engines. The C-MIGITS II contains a five channel, coarse/acquisition code, L1 frequency GPS engine, and a digital Quartz IMU. The two subsystems are integrated using a Kalman filter process to produce a small, lightweight, synergistic guidance, navigation and control system. These proven off-the-shelf products integrated into one package translate into affordability and low risk. C-MIGITS II provides all essential guidance, navigation and control data, including three-dimensional position and velocity, precise time, attitude, heading, angular rate, and acceleration.

Many guidance and control problems in the past have been addressed with stand-alone INS or GPS solutions: however, the inherent characteristics of each system do not provide an ideal guidance, navigation and control solution. By properly integrating the INS and GPS systems, the strengths of one can offset the

deficiencies of the other. An INS is generally characterized as a self-contained, autonomous navigator, whose position and velocity outputs will degrade over time. Alternatively, the GPS, which is generally described as a navigator relying on external satellite signals, produces high accuracy solutions and is time independent. When the two systems are combined, the GPS/INS system will limit the INS error growth, and provide a continuous navigation solution when GPS signals are not available. In addition, high-speed attitude, velocity, angular rate, and acceleration are available at accuracies not achievable by GPS alone.

The DGPS receiver, Starlink DNAV-212 contains a Starlink MRB-2A differential beacon that provides the differential corrections to the C-MIGITS II. The MRB-2A provides reliable fully automatic DGPS beacon selection. The MRB-2A beacon receiver uses two channels to ensure that the automatically selected beacon is providing reliable DGPS correction data. Channel one continuously tracks the selected beacon and outputs the correction data for the C-MIGITS II. Channel two continuously scans the beacon frequency range, measuring each of the receivable beacon signals. If and when a new signal with better performance is detected, channel one will switch to it.

DGPS works by placing a high performance GPS receiver (reference station) at a known location. Since the receiver knows its exact location, it can determine the errors in the satellite signals. It does this by measuring the ranges to each satellite using the signals received and comparing these measured ranges to the actual ranges calculated from its known position. The difference between the measured and calculated range is the total error. The error data for each tracked satellite is formatted into a correction message and transmitted to GPS users. The correction message format follows the standard established by the Radio Technical Commission for Maritime Services, Special Committee 104 (RTCM-SC 104). These differential corrections are then applied to the GPS calculations, thus removing most of the satellite signal error and improving accuracy. The level of accuracy obtained for a C-MIGITS II with DGPS is 2.5 meters for position and 0.025 meters/sec for velocity.

TSAS NP-1 Hardware

The tactor control hardware NP-1 was developed and tested in the three months prior to the flight test. This interface relied heavily on COTS components due to the short timeline. Emphasis on individual component ruggedization and electromagnetic shielding minimized system integration time for placement in the harsh environment of a rotary wing aircraft. Dr. Anil Raj (NAMRL), the NAMRL Engineering Prototype Facility, and the USAARL Biomedical Technology Fabrication Shop developed the TSAS NP-1 hardware, and Dr. Anil Raj provided material for this section. Coastal Systems Station (CSS), Panama City, Florida provided COTS component procurement support.

The TSAS controller, a Pentium-based ruggedized portable computer manufactured by Kontron Elektronik GmbH, Model IP Lite, received flight information from the UH-60 AIS and the C-MIGITS via RS-232 serial ports, and custom software determined which tactors should be activated to indicate a given velocity. The software then activated the appropriate digital lines that control the tactors via a National Instruments Model PC-DIO-96 digital I/O board. These digital instructions provide the control signals to the pneumatic control solenoid valves (Amatrix Corp., model MK 754.8XTD424.B03) via dedicated valve speed-up circuitry (Amatrix Corp., model UDB 8010). This set up allows individual solenoids to switch at up to 200 Hz. Each tactor connects to two valves, one connects to a positive pressure source, and the other connects to a negative pressure source.

The differential positive and negative pressure sources are created and maintained by a Medo USA, Inc., model VP0625UL compressor/vacuum pump connected to two accumulator/manifolds (one for high pressure, one for low pressure). A manual bleed valve attached to each accumulator/manifold controlled the airflow through the accumulator, allowing pressure levels to be set at approximately ± 13.8 kPa. Polyurethane tubing connects the manifolds to the solenoid valves for distribution to the individual tactors.

In addition, the NP-1 carried a Carleton Life Support Technologies, model 100C1183-1 blower that provides ventilation to the pilot via the Tactor Locator System (TLS). A 3 VDC battery-pack on the NP-1 provided backup power to the C-MIGITS II to maintain the last position in memory, therefore reducing

satellite acquisition time on start-up. A 115 VAC, 60 Hz power supply on the plate powered a video camcorder for flight documentation.

TSAS NP-1 Software

The UWF-IHMC was tasked with developing the TSAS software, and Mr. Niranjani Suri and Mr. Roger Carff provided material for this section. The TSAS software was implemented in C++ on a QNX real time operating system, and may be separated into four components as shown in Figure 38. The sensor modules are responsible for providing information about the real world to the TSAS controller. The TSAS controller module feeds the input to one of many algorithms. The algorithms can be selected and controlled by the operator using a graphical user interface (GUI). Based upon the input, the algorithm sends commands to the TSAS driver to activate tactors. The TSAS driver executes any commands received from the TSAS controller and generates the necessary electrical signals that feed to the TSAS hardware. The TSAS driver also receives feedback information from the TSAS electronics, which is sent back to the TSAS controller. Currently, this feedback information provides notification about tactor failures. The TSAS GUI module provides a graphical user interface to the test operator.

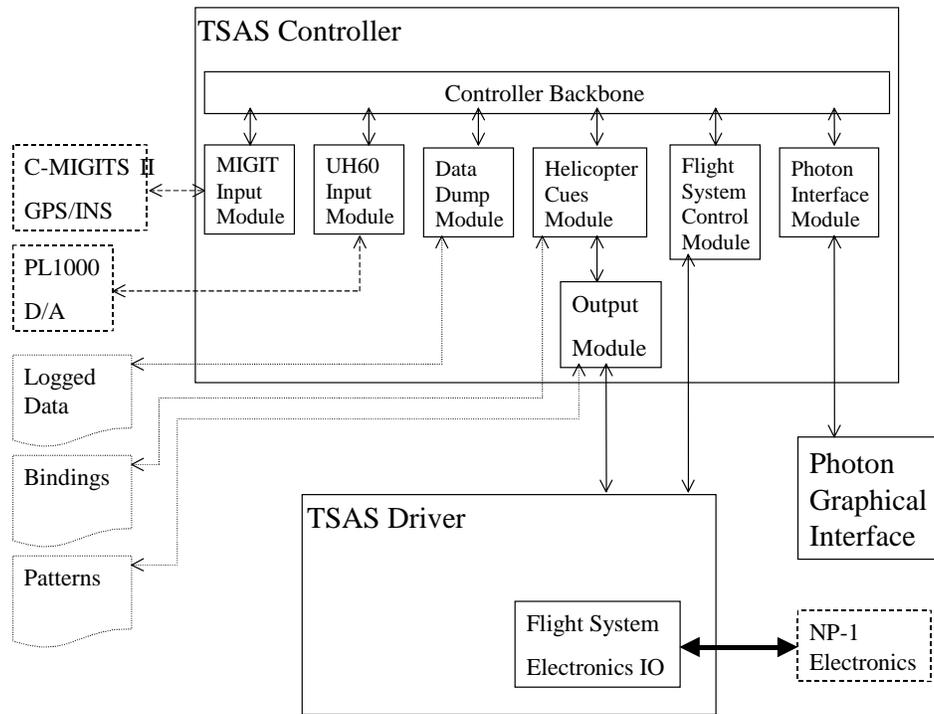


Figure 38: JSF TSAS NP-1 Software Architecture

JSF TSAS Tactor Locator System

The TLS for the JSF flight demonstration consisted of an off-the-shelf F-22 cooling-heating coverall garment assembly (Figure 39: Mustang Survival, Inc., model CMU-31/P). The garment was modified to place an array of 22 pneumatic tactors (Carleton Technologies, model 2856-A0) within its structure. Both the pneumatic tactor umbilical and the ventilation air hose terminate in quick disconnect connectors to allow rapid unencumbered egress of the pilot in case of emergency. The tactor array consists of eight columns of two tactors, plus six additional spare tactors, three on the front and three on the back. The TLS tactor columns fall on the front, front-left, left, back-left, back, back-right, right, and front-right of the subject to provide directional information in 45° increments. The TSAS TLS was worn on the torso over an undershirt, and underneath the flight suit as shown in Figure 40.

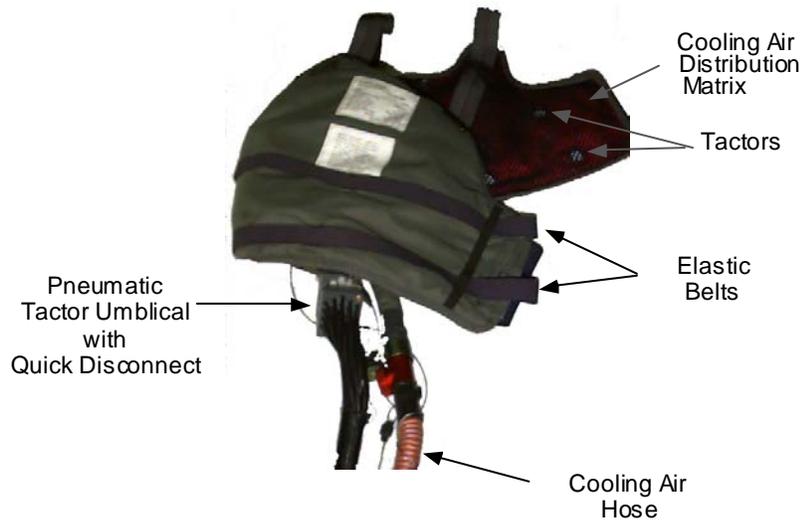


Figure 39: JSF TSAS tactor locator system.



Figure 40: TSAS demonstration pilot showing TSAS tactor locator system.

Carleton Technologies Pneumatic Tactor

The Carleton Technologies pneumatic tactor, model 2856-A0 (Figure 41) consists of a hemispherical shaped molded plastic shell with a diameter of 31mm. A latex membrane covers the concave area of the shell. The air supply tubing (2.4mm ID 4.0mm OD) attaches to the topside of the tactor. Oscillatory compressed air is driven into the tactor that forces the latex membrane to vibrate. A strong tactile sensation is achieved when the tactor membrane vibrates at 50 Hz. Tactor weight was 2g.

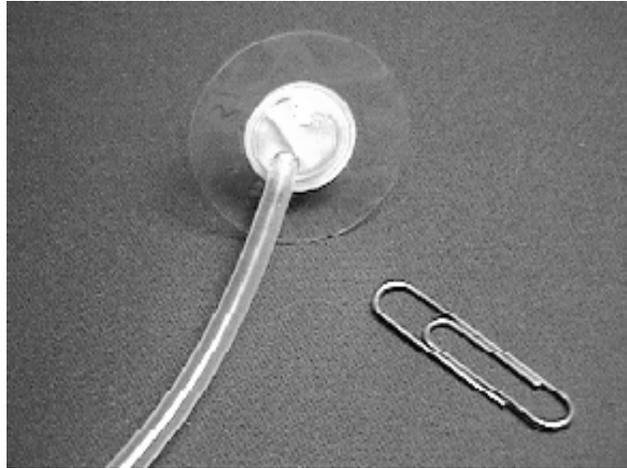


Figure 41: Carleton Technologies model 2856-A0 pneumatic tactor.

Tactor Selection

There are primarily three types of tactors available: electro-magnetic, pneumatic, and direct electrical stimulation. For this JSF TSAS flight demonstration effort, four companies were identified that were able to deliver a state-of-art tactor.

Audiological Engineering produces a vibro-mechanical tactor (Tactaid) that uses an electro-magnetic system that vibrates the entire tactor case. This produces a diffuse tactile sensation. This tactor was small and lightweight and was used extensively in laboratory testing when a high number of tactors were required. The Tactaid had been used previously in a helicopter flight demonstration, but its low intensity tactile sensation rendered it unsuitable for the JSF TSAS flight-testing.

Engineering Acoustics, Inc. (EAI) produces a vibro-mechanical electro-magnetic tactor (AT-96) with an indent button contacting the skin. This produces a localized tactile sensation. This tactor has excellent frequency and amplitude control and was used extensively in laboratory testing. However, its large individual size and high weight coupled with a low intensity tactile sensation deemed it unsuitable for actual flight-testing. Based on JSF TSAS laboratory testing feedback, EAI have produced an improved tactor (C2) that overcomes many of the limitations of the AT96. This tactor would be suitable for future flight-testing.

Unitech Research produces a direct electrical tactor (Audiotact). These tactors produce a strong intensity tactile sensation in a small lightweight tactor. However, the range between absolute threshold and pain is very small and moreover, this dynamic range of usability varies with skin environmental conditions including sweating. What feels like a strong tactile signal changes to a painful sensation due to the skin sweating. Unitech Research proposes the use of an electrolyte gel to minimize the tactile sensation variation with skin environmental conditions. The gel worked well in the laboratory, but was deemed impractical for actual flight. The electrocutaneous tactor is an emerging technology with benefits in size, weight and strength of tactile sensation but was not sufficiently mature for the JSF TSAS flight demonstration. Due to its superiority in size and weight further development to overcome the sensation range limitations is warranted.

Carleton Technologies Inc. produces a pneumatic vibro-mechanical tactor (model 2856-A0) [previously described]. These tactors are robust, lightweight and produce a strong intensity tactile sensation. Laboratory evaluation demonstrated that the pneumatic tactor was the most suitable tactor available for the JSF TSAS flight demonstration.

JSF TSAS Tactile Algorithm

Using helicopter handling qualities theory, and simulator testing described in the following section, an adequate tactile algorithm to meet project goals was developed. Tactile algorithm is defined as the tactor positions, pulse or activation patterns, carrier frequencies, waveforms and amplitudes chosen to display a particular aircraft flight parameter. Tactor pulse pattern is defined as the rate of turning the tactor on and off. It is separate from the carrier frequency, which represents the vibration frequency of the tactor when the tactor is on. For example, the pneumatic tactor has a fixed carrier frequency or vibration of 50 Hz, but the tactor can be turned on and off once per second, thus the pulse pattern is 1 Hz, separate from the carrier frequency.

The development of new instrumentation to provide drift and/or descent cues during hovering flight is required to improve the safety of flight and reduce pilot workload, especially in degraded visual conditions. When visual cues degrade, considerable additional pilot workload is required for low speed and hover tasks (Aeronautical Design Standard ADS-33D, 1994; Hoh and Mitchell, 1996). The UH-60 aircraft used for this flight demonstration, like most modern V/STOL aircraft, is equipped with an AFCS that enhances the hover stability and handling qualities. However, the pilot must still visually perceive very small drift velocities in order to perform low speed and hover flight operations (Hoh and Mitchell, 1996). In addition, mishap statistics show that for safe hover operations the critical factor is undetected drift, and this accounts for 25% of spatial disorientation mishaps in helicopters (Figure 34). Therefore, helicopter drift velocities were deemed the most important tactile cue for safe hover flight maneuvers.

Hovering is a maneuver in which the helicopter is maintained in nearly motionless flight over a reference point at a constant altitude and heading. Control corrections by the pilot need to be applied smoothly with constant pressure rather than abrupt movements. Stopping and stabilizing a helicopter requires lead-generation control inputs. For example, if the helicopter is moving right, a slight amount of left pressure on the cyclic will stop the right movement. Before the helicopter stops, left pressure must be released or the helicopter will come to a stop, and then move to the left. Failure to allow for the aircraft lag will result in over-controlling (US Department of Transportation, 1978). To determine the correct amount of pressure and to maintain lead generation on the controls during hover operations, the helicopter pilot must detect small changes in velocity. Therefore, helicopter rate of change of velocity cues was also deemed necessary to perform a stable hover. In degraded visual conditions, it is very difficult to hover over a smooth surface at night because the spatial resolution to see small changes in velocity is not available, and even the best pilots over-control and get into pilot induced oscillations.

As described earlier, the pneumatic tactor was selected due to its lightweight and strong tactile sensation. The pneumatic tactor activation was fixed at the amplitude and carrier frequency (± 13.8 kPa square wave at 50 Hz) to provide the strongest tactile sensation. The fixed tactor amplitude, waveform and frequency allowed only tactor position and pulse pattern as the tactor stimulus variables that could be used to display aircraft flight parameters.

To display the horizontal velocity vector using a tactile instrument, the components of the velocity were separated, and then displayed using the available different tactile qualities. Tactor location was used to indicate helicopter velocity direction, and tactor activation pulse pattern was used to indicate velocity vector magnitude.

For horizontal velocity direction, a tactor would be activated at a location corresponding to the velocity direction. For example, if the helicopter was moving left, two tactors on the left side would activate (Figure 42, column 7, green tactors); if the helicopter was moving forward, two tactors on the abdomen would active (Figure 42, column 1, yellow tactors); and if the helicopter was moving right and forward the two 45 degree front-right tactors would activate (Figure 42, column 2, orange tactors). Both tactors in each column fire simultaneously to provide a strong intensity tactile sensation, and to provide redundancy in the event of a tactor failure. During the T-34 TSAS flight demonstration, the “missed tactor” problem was the basis for the majority of technical problems encountered in the T-34 flight demonstration. Having redundancy at each tactor location was deemed necessary to minimize the risk of the “missed tactor” problem.

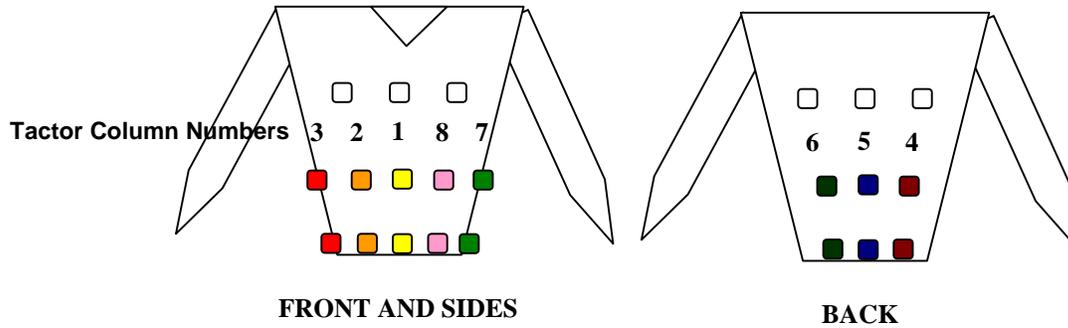


Figure 42: JSF TSAS tactile array.

Geldard (1960), and Sachs, Miller, and Grant (1980) reported that only three tactor amplitude intensities are easily determined. The T-34 TSAS flight demonstration (Chapter 3) showed that only three tactor perceived intensities are easily determined. Therefore, to display horizontal velocity magnitude, three tactor activation pulse patterns were used as shown in Figure 43. For example, if the helicopter were drifting in the range 0.3 to 0.7 m/sec, the tactor would activate at 1 pulse per second. If the helicopter were moving in the range greater than 0.7 to 2.0 m/sec, the tactor would activate at 4 pulses per second, and if the helicopter were moving greater than 2.0 m/sec, the tactor would activate at 10 pulses per second.

In summary, if the helicopter were moving at 0.5 m/sec to the left, the two tactors located on the left side of the torso would activate at 1 pulse per second.

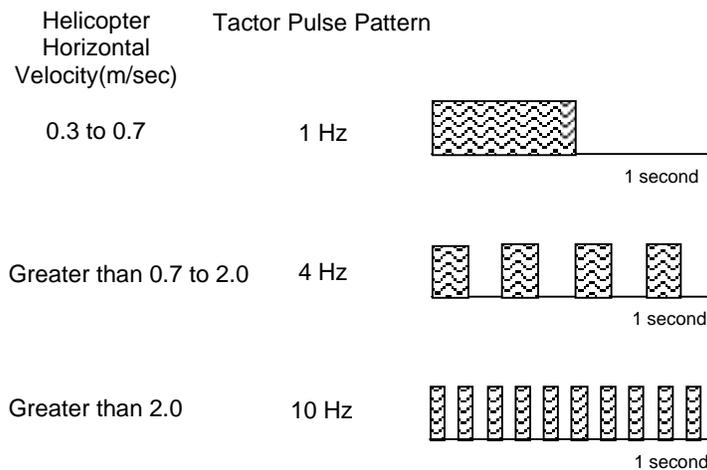


Figure 43: JSF TSAS tactor pulse pattern.

As described earlier, rate of change of velocity cues is also needed by pilots to stabilize a helicopter in degraded visual conditions. Using the tactor display algorithm described above, the pilots were able to receive rate of change of velocity cues using the tactile instrument. As perceived by the helicopter pilot, the rate of change of velocity is an important variable and in a subtle, but significant, way is different from the classical definition of acceleration. For example, if the helicopter is drifting to the left and is slowing down, the acceleration vector is directed towards the right, while the velocity vector is to the left. To maintain a stable and safe hover using the tactile instrument, the pilot needs to know that the helicopter is drifting to the left and is slowing down. Therefore tactile cues to represent velocity and rate of change of velocity should only be on the left side of the body. Displaying an acceleration cue on the right while still drifting to the left would confuse the pilot and render the tactile algorithm unintuitive.

Using the time or rate that the frequency of the tactor pulse pattern increased or decreased, the pilot was able to infer rate of change of velocity cues. For example, if no tactors were activated, and then the left

tactors were activated at 1 Hz and quickly followed by activation at 4 Hz, the pilot was able to infer that the helicopter was not only moving to the left, but also that the helicopter was accelerating. This rate of change of velocity cues was not as instantly intuitive as the velocity cues, however, all pilots learned to recognize and interpret the rate of change of velocity cues during their first UH-60 simulator session.

Simulator Testing

A series of UH-60 simulator sessions were conducted prior to the flight demonstration using the Tactor Control Laboratory System (TCLS) and the UH-60 simulator at USAARL. ; The objectives of the UH-60 simulator sessions were to:

- Develop and evaluate the tactile algorithm to meet project goals.
- Train pilots in using tactile cues in hover operations.
- Evaluate the safety of the JSF TSAS evaluation flight test plan (Table 7).

During each UH-60 simulator session, each pilot was asked to make quantitative comments related to the simulator session goals of algorithm development and flight test plan evaluation. Due to time and funding limitations set by the sponsor, Joint Strike Fighter, the simulator sessions were not intended to be a scientific optimisation of tactile displays, but a prototyping tool to achieve the goal of a successful flight demonstration. Therefore, no quantitative flight performance data were recorded from these simulator sessions.

TACTOR CONTROL LABORATORY SYSTEM

The Coastal Systems Station (CSS) was tasked to build a system capable of evaluating an exceptionally wide range of tactile stimulation devices and scenarios. It was designed for use solely in the laboratory environment of NAMRL and USAARL with maximum flexibility, minimal development time and cost, and the ability to support a variety of tactor types. Mr. Joel Peak (CSS) provided material for this section.

Functional requirements were:

- 80 tactor drive capability.
- 6 independent waveforms available.
- All tactors individually driven.
- 30 V-30 A max drive requirement.
- Local control with remote control via Ethernet interface.
- Allow future capability for diagnostic testing.
- Support real-time operating conditions.

The Tactor Control Laboratory System (TCLS) was designed to simulate potential operational scenarios in a laboratory environment and allow extensive experimentation with a broad range of stimulus characteristics and patterns. There exist a large number of conceptual approaches to tactile stimulation in aerospace conditions, and these approaches have not been exhaustively evaluated for suitability or merit. The TCLS was intended to be a laboratory tool that would allow evaluation of conceptual approaches to tactile displays, and guide the development of TSAS implementations. Specifically the TCLS would evaluate the most appropriate characteristics of the excitation waveform, such as wave shape (sine, square, triangle, etc.), amplitude, frequency, pulse pattern, and how the individual tactor excitations may be used in concert with other tactors to best convey the desired information. Consequently, the primary functions of the TCLS are to:

- Provide a powerful computer to interface with various sensor systems, process sensor input, and execute patterns of tactor excitation.
- Respond to sensor input and change tactor excitation patterns in real time.
- Allow dynamic variation of the excitation waveforms used for each tactor.
- Provide a means of visually verifying the excitation waveforms currently being used.

The TCLS is controlled by a Pentium-based computer, which is equipped with multiple special-purpose Metrabyte boards, including three waveform generators, two digital I/O cards generators, and an analog-to-digital converter generator. The computer/controller initialises the six available waveforms and defines the patterns of tactor excitation that will be used during the session. It then collects sensor input, analyses the data, determines which, if any, tactor excitation pattern is required, and sends the necessary information to the custom portion of the system. The custom components use a VME computer backplane to link various analog and digital circuitry necessary to energize individual tactors on cue.

On the Metrabyte/VME interface board, the control information is converted from the unique cabling used by the Metrabyte cards to standard cabling more readily accessible to the VME components. The control information is then passed to the logic boards, where the information is decoded to select specific waveforms and energize the tactor. Next, the driver boards amplify the signals and supply enough current to drive the tactors at optimal power levels. These amplified signals are routed through the remapping panel and the VME/TLS interface board. The high power signals leave the lab system via connectors on the front door of the rack, and traverse an umbilical cable to the TLS, where individual tactors fire according to the predetermined patterns.

Each logic/driver pair controls up to 16 tactors. The five pairs allow a maximum capability of $5 \times 16 = 80$ tactors, typically arranged with 64 tactors in an 8×8 matrix on the torso, and up to 16 auxiliary tactors located, as required, elsewhere. The output of each logic/driver pair corresponds to two rows of tactors. The TLS, on the other hand, is designed and assembled in columns, for increased reliability and ease of use. The remapping board and the associated VME/TLS interface board provide the transformation between rows and columns, such that individual rows may be included or excluded at will. This allows the system to independently drive two 40 tactor TLS's simultaneously, for even more flexibility in research. The system most readily supports tactors with a 30V-peak drive requirement but it may be used to simulate the electrical interface of other tactor types, such as pneumatic tactors. Furthermore, two basic driver types are currently available through plug-in modules on the driver boards' FET (unipolar) drivers for typical battery-powered applications, and op amp (bipolar) driver for powered and atypical battery-powered applications. The system was designed for ease of use and maximum versatility, and can readily incorporate alternative tactor types with minimal impact to the basic design.

The TCLS components were installed in a 19-inch rack on wheels. The primary components consist of the following:

Off-the-shelf hardware

- Computer/controller
- Industrial rack-mount PC
- Pentium 200 MHz processor
- SVGA video card
- Metrabyte arbitrary waveform generator, dual outputs [3 each for a total of 6 waveforms]
- Metrabyte digital I/O, 96 output [2 each for a total of 192 outputs]
- Metrabyte analog to digital converter, 64 inputs
- Rack-mount 17" monitor
- Keyboard & mouse
- Switching power supplies, 1 KW, constant current/voltage [2 each]
- UPS, 1400 VA, rack mount
- Oscilloscopes, dual channel [3 each for a total of 6 displayed channels]
- VME chassis with logic power supply

Custom Hardware Developed

- Tactor decoders, signal selectors and drivers
- Logic boards, for decoding and signal selection [5 each]
- Driver boards, for signal amplification and drive current [5 each]
- PET plug-in modules [80 each]
- Op Amp plug-in modules [80 each]
- Metrabyte/TLS interface board
- VME/TLS interface board and remapping panel

FLIGHT SIMULATOR

The UH-60 flight simulator is a six-degree-of-freedom motion-based device designed for training aviators in the use of the UH-60 Black Hawk helicopter. The device consists of a simulator compartment containing a cockpit with pilot and co-pilot stations, instructor operation (IO) station and an observer station. The simulator is equipped with a visual system that simulates natural environment surroundings. A central computer system controls the operation of the simulator complex. The simulator is used to provide training in aircraft control, cockpit pre-flight procedures, instrument flight operations, visual flight operations, sling load operations, external stores subsystems, night vision goggles training, and nap of the earth flight.

The simulator compartment houses the cockpit and IO station. Within the cockpit are all the controls, indicators, and panels located in the aircraft. Controls that are not functional are physically present to preserve the appearance of a realistic configuration. Loudspeakers are located in the simulator compartment to simulate audio cues. Each of the pilot's seats is vibrated individually to simulate both continuous and periodic oscillations and vibrations experienced by the crew during normal and emergency flight conditions and maneuvers. However, these vibrations are isolated from the IO and observer stations.

The simulator compartment is mounted on a 150 cm six degree-of-freedom motion system consisting of a moving platform assembly driven and supported from below by six identical hydraulic actuators. The motion system provides combinations of pitch, roll, yaw, lateral, longitudinal, and vertical movement. Motion of the simulator compartment can be controlled to simulate motion due to pilot inputs as well as those resulting from rotor operation, turbulence, and changes in aircraft centre-of-gravity, as well as emergency conditions and system malfunctions. All motions except pitch are washed out to the neutral position after the computed acceleration has reached zero. Pitch attitude is maintained as necessary to simulate sustained longitudinal acceleration cues. Motion can be frozen at any instant and the simulator has the ability to be programmed into a crash override mode where motion can continue despite impact with the ground or other obstacles.

The pilot and co-pilot stations are provided with forward, left, and right side window displays. The visual generation system consists of two separate functional areas. The first is the visual display system that presents the wide-angle-collimating video image to the crew. The digital image generator system is a full-colour visual display that provides imagery for day, night, and dusk scenes as well as replicating the effects of the searchlight/landing light on the visual displays.

The computer system consists of a central processing unit and five auxiliary processing units. Visual displays are controlled by digital image generator inputs that are modified by inputs from other units such as the simulator navigation/communication identification subsystem, instructional subsystem, and air vehicle subsystems. The navigation and communication identification subsystem provides position data for the aircraft the simulator is replicating. The instructional subsystem forwards information that detail the visual environment, scene lighting, and target paths through the database, target status, and landing light status. The air vehicle subsystem sends information relevant to the aircraft position rates, altitude, and attitude. All of these inputs are stored in the shared memory of the main simulator control computer.

SIMULATOR RESULTS

In the two weeks prior to the flight demonstrations, five pilots participated in 16 simulator sessions (Table 5). Four of these pilots subsequently flew the actual flight demonstrations. As shown in Table 5, the first simulator session for each pilot was used to learn how to use the tactile cues to fly the aircraft, and evaluate the JSF TSAS flight test plan. Subsequent flights were used to develop and evaluate the tactile algorithm, and provide further training using tactile cues.

Table 5. JSF TSAS Simulator Testing.

Date	Flight	Pilot	Algorithm	Flight Goals	Comments/Results
02Sep97	01	CL	0.2/0.7/2.0	TSAS Familiarization Test Plan Evaluation	Test Plan o'k
02Sep97	02	PM	0.2/0.7/2.0	TSAS Familiarization Test Plan Evaluation	Test Plan o'k
03Sep97	03	AE	0.2/0.7/2.0	TSAS Familiarization Test Plan Evaluation	Test Plan o'k Increases SA
03Sep97	04	PM	0.3/0.7/2.0	Evaluate Algorithm	Sensation of front tactors not good Prefers 0.3/0.7/2
03Sep97	05	CL	0.3/0.7/2.0	Evaluate Algorithm	Null is better
04Sep97	06	PM	0.3/0.7/2.0	Training Session	Tactor fit not good Missed forward tactors
04Sep97	07	AE	No Tactors	Test Plan Evaluation Without TSAS	No idea, Violent crash Tasks impossible on visual instruments alone
04Sep97	08	CL	0.3/0.7/2.0	Training Session	Tactors not good on right side
04Sep97	09	AE	0.3/0.7/2.0	Test Plan Evaluation With TSAS	Completed all tasks as opposed to SIM07
05Sep97	10	PM	0.3/0.7/2.0	Training Session	F/B o.k. L/R weak
05Sep97	11	CL	0.3/0.7/2.0	Training Session	
10Sep97	12	SG	0.2/0.7/2.0	TSAS Familiarization Test Plan Evaluation	Test Plan o.k.
10Sep97	13	CL	0.2/0.7/2.0	Re-check Algorithm Training Session	
11Sep97	14	SG	0.3/0.7/2.0	Training Session	
11Sep97	15	CL	0.3/0.7/2.0	Re-check Algorithm Training Session	Prefers 0.3/0.7/2
11Sep97	16	JB	0.3/0.7/2.0	TSAS Familiarization Test Plan check-out	

From these simulator sessions the tactile algorithm shown in Figures 42 and 43 was considered adequate to meet project goals, and the JSF TSAS evaluation flight test plan (Table 7) was considered a safe and realistic evaluation for the TSAS tactile display.

4.3 TEST PLAN

Four pilots, three from the US Army, and one test pilot from the US Navy, participated in the flight demonstrations, with approximately two flights per pilot. The hazard analysis completed prior to the flight test is provided in Appendix D. The series of flight tests included:

System Function Test. These two flights occurred at USAARL, Ft. Rucker, Alabama and these flights checked system integration, TSAS functionality and GPS/INS signal accuracy.

Pilot Familiarization: Three of the pilots flew a flight that acquainted them with the operation of TSAS in actual flight. The fourth pilot, who functioned as the safety pilot for all the flights and who had simulator time with TSAS, did not require a pilot familiarization flight. These flights occurred at USAARL, Ft. Rucker, Alabama.

TSAS Evaluation: These five flights occurred at NAS Pensacola, Pensacola, Florida and assessed the performance of TSAS in reducing workload and improving situation awareness in difficult flight conditions. Table 6 represents the JSF TSAS test event matrix.

Table 6. JSF TSAS Test Event Matrix.

Flight	Pilot	Purpose	Location
1	CL	System Function	USAARL
2	SG	System Function	USAARL
3	SG	Pilot Familiarization	USAARL
4	JB	Pilot Familiarization	USAARL
5	CL	Pilot Familiarization	USAARL
6	CL	TSAS Evaluation	NAS Pensacola
7	JB	TSAS Evaluation	NAS Pensacola
8	CL	TSAS Evaluation	NAS Pensacola
9	SG	TSAS Evaluation	NAS Pensacola
10	AE	TSAS Evaluation	NAS Pensacola

TSAS Evaluation

This flight consisted of typical visual meteorological conditions (VMC) and simulated instrument meteorological conditions (IMC) hover phases followed by an IMC simulated ship operations phase with TSAS on and TSAS off. Data from these flights were used to evaluate the effectiveness of TSAS.

Table 7. JSF TSAS Evaluation Flight Test Plan.

Task	Maneuver	Time	ALT (FT AGL)
A: VMC Hover Phase (TSAS ON)			
1.	Stationary In Ground Effect (IGE) Hover	120sec	10
2.	Left 180 degree hovering turn	hover 20s after	10
3.	Forward hover for 100 ft	hover 20s after	10
4.	Rearward hover for 100 ft	hover 20s after	10
5.	Left sideward hover for 50 ft	hover 20s after	10
6.	Right sideward hover for 50 ft	hover 20s after	10
7.	Ascent to Out of Ground Effect (OGE)	hover 20s after	70
8.	Stationary OGE hover	120sec	70
9.	Forward hover for 100 ft	hover 20s after	70
10.	Rearward hover for 100 ft	hover 20s after	70
11.	Right 180 degree hovering turn	hover 20s after	70
12.	Left sideward hover for 50 ft	hover 20s after	70
13.	Right sideward hover for 50 ft	hover 20s after	70
14.	Descent to IGE	hover 20s after	10
15.	Land		

Task	Maneuver	Time	ALT (FT AGL)
B: IMC Hover Phase		(“Foggles” ON, TSAS ON)	
16.	Stationary IGE Hover	120sec	10
17.	Forward hover for 100 ft	hover 20s after	10
18.	Right 180 degree hovering turn	hover 20s after	70
19.	Left sideward hover for 50 ft	hover 20s after	10
20.	Ascent to OGE	hover 20s after	70
21.	Stationary OGE hover	120sec	70
22.	Descent to IGE	hover 20s after	10
23.	Land		
C. IMC Simulated Ship Operations Phase		(“Foggles” ON, TSAS ON)	
24.	Ascent to IGE hover		10
25.	Left sideward hover for 50 ft		10
26.	Ascent to OGE hover		70
27.	Takeoff to translational flight		200
28.	Approach to OGE Hover	70	
29.	Descent to IGE hover		10
30.	Right sideward hover for 50 ft	10	
31.	IGE hover		10
32.	Land		
D. IMC Simulated Ship Operations Phase		(“Foggles” ON, TSAS OFF)	
33.	Ascent to IGE hover		10
34.	Left sideward hover for 50 ft		10
35.	Ascent to OGE hover		70
36.	Takeoff to translational flight		200
37.	Approach to OGE Hover	70	
38.	Descent to IGE hover		10
39.	Right sideward hover for 50 ft	10	
40.	IGE hover		10
41.	Land	NOTE: Safety pilot flew traffic pattern to arrive on final leg in OGE hover.	

Human Factors Metrics

SITUATION AWARENESS

Situation awareness ratings were collected as dependent variables. No situation awareness metric existed that fits the precise needs of the task of hovering a vertical lift aircraft in reduced outside visual conditions. A metric was adapted from the China Lake Situation Awareness (CLSA) scale (Adams, 1998). The modified CLSA was a criterion-driven metric that estimated subjective situation awareness and each pilot rated each phase of the flight during the flight debrief.

Table 8. Modified China Lake Situational Awareness Scale.

SITUATION AWARENESS SCALE VALUE	INTERPRETATION
Very Good 1	<ul style="list-style-type: none"> • Full Knowledge of Aircraft Energy State /Mission • Full Ability to Anticipate/Accommodate Trends
Good 2	<ul style="list-style-type: none"> • Full Knowledge of Aircraft Energy State /Mission • Partial Ability to Anticipate/ Accommodate Trends • No Task Shedding
Adequate 3	<ul style="list-style-type: none"> • Full Knowledge of Aircraft Energy State /Mission • Saturated Ability to Anticipate / Accommodate Trends • Some Shedding of Minor Tasks
Poor 4	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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

VIDEO DEBRIEF

Each pilot was debriefed via an interview after his or her TSAS effectiveness flight. Table 9 represents the interview questions

Table 9. TSAS Video Debrief Interview.

- Was the F-22 cooling suit comfortable?
- Any suggestions for improvement of the F-22 cooling suit fit?
- Could you feel the tactors?
- Was the tactor signal intensity strong enough?
- Could you comment on tactor intensity during tactical conditions?
- Was the tactile information intuitive?
- Was the tactile sensation annoying?
- Please comment on workload during IMC shipboard operations?
- Any suggestions for improvements of the tactors and/or tactile information?
- Any further comments?

Data Recording

The TSAS NP-1 computer recorded the aircraft performance data from the C-MIGITS GPS/INS, selected aircraft instruments (altimeter), and the tactor activation for all flights. Video documentation of flight activities included two internal cameras; one view over the pilot’s shoulder, and one out the front windshield. For TSAS Evaluation flights at NAS Pensacola, video from the ground was recorded and video telemetry of the over the pilot’s shoulder camera was added. The video telemetry system was added to allow visiting JSF personnel to view in-flight video of the TSAS Evaluation flights and consisted of a Broadcast Microwave Services, Inc., Model TBT-200-155T system on the aircraft and a video monitor on the ground. Audio communications between the safety pilot and the tower and from the aircrew was collected on all flights on the video recorders.

Data Reduction

Flight data reduction consisted of converting the binary data log files stored by the TSAS NP-1 processor to ASCII format. The resultant ASCII data files contained 60 channels of data, which are converted to MatLab format variables after digital filtering with a zero phase 12th order Butterworth low pass (0.5Hz) filter. GPS data required conversion from World Geodetic Survey (WGS-84) latitude and longitude to Universal Transverse Mercator (UTM) Easting and Northing (ft).

4.4 FLIGHT TEST RESULTS

Flight testing was conducted in accordance with the test plan described in Section 4.3. Phases A and B were flown with TSAS on to demonstrate the use of TSAS in VMC and IMC hover conditions. Phases C and D were simulated shipboard landings flown with TSAS on and off respectively, to evaluate the effectiveness of TSAS. Three of the four pilots flew similar flight events to enable comparison of results. For TSAS Evaluation flight FP5, the pilot did not perform phase B, IMC hover phase, and phase D, TSAS off IMC shipboard operations due to time constraints. However, FP5 test pilot did perform the TSAS on IMC shipboard operations (Phase C). Due to the incomplete data set for FP5, the situation awareness pilot ratings and flight data from FP5 are not included in this study, however workload and subjective comments are included. Flight 3 (FP3) was the official JSF TSAS flight demonstration for invited guests.

Situation Awareness

Table 10 details the results of the situation awareness metric for the TSAS Evaluation flights. All pilots reported improved situation awareness during TSAS on IMC shipboard operations (Phase C) vs. TSAS off IMC shipboard operations (Phase D).

Table 10. Situation Awareness Pilot Ratings.

Flight	Pilot	A1	A2	B1	B2	C	D
		VMC Hover		IMC Hover		Shipboard TSAS On	Shipboard TSAS Off
FP1	CL	1	1	2	2.5	2.0	5
FP2	JB	1	1	2	2	2.0	4
FP3	CL	1	1	2	2	1.5~2.0	5
FP4	SG	1	1	2	2	1.5	4

During phase D, TSAS off IMC shipboard operations, all project pilots reported either a fair or minimal knowledge of the aircraft state with saturated ability to anticipate trends. One pilot commented, “I had no idea what was happening” and another, “I would not attempt this maneuver in these conditions.” In contrast, during phase C, TSAS on IMC shipboard operations, all project pilots reported a full knowledge of the aircraft state with a partial ability to anticipate trends.

One of the pilots commented that “(I) noticed while flying simulated shipboard maneuvers that I could fly *safer*, I had more cues.” Another pilot commented “(I) noticed at the high hover I depended on the factors more due to the reduced visibility. I could feel the factors before I could detect visual cues of movement.” Both these comments reflect the importance of the addition of tactile cues to the traditional visual cues in maintaining situation awareness. All demonstration pilots reported that the maintenance of situation awareness during reduced visual conditions was enhanced with TSAS.

Workload

During the debrief, all pilots reported reduced workload during Phase C as compared to Phase D. The knowledge of aircraft velocity and rate of change of velocity without looking at a visual instrument permitted the pilot to concentrate on other instruments such as the altimeter and mission tasks, thereby reducing workload. The tactile instrument reduced pilot workload by providing the opportunity to devote

more time to other instruments and systems when flying in task saturated conditions. These effects can substantially increase mission effectiveness.

Two of the subject pilots commented “We could’ve used this in Desert Storm.” One of the subject pilots, at the JSF TSAS flight demonstration, stated that TSAS, without any further development, would be preferable to the status quo. Another commented, “I noticed that a pilot’s capability was increased with TSAS.”

The relationship between situation awareness and performance is not direct, but can be foreseen. In general, it is expected that poor performance will occur when situation awareness is incomplete or inaccurate (Endsley, 1995). With decreased pilot workload and enhanced situation awareness, TSAS increases the potential for improved performance of an aviator. Improved performance in military aircraft translates to improved survivability and mission capability.

Pilot Comments

Was the F-22 cooling suit comfortable?

All pilots reported that the F-22 cooling vest was comfortable. However, two of the pilots remarked that the vest was restrictive and that they had difficulty taking a deep breath.

Any suggestions for improvement of the F-22 cooling suit fit?

The addition of an adjustable elastic panel on both sides of the vest would permit a greater range of chest movement

Could you feel the tactors?

All pilots reported that they could feel the tactors all the time.

Was the tactor intensity of signal strong enough?

All pilots reported tactor intensity strong enough in the vibration environment of a helicopter.

Could you comment on tactor intensity during tactical conditions?

One pilot responded, “In high stress environment, where there is sensory overload, or with high threat situations, stronger tactile sensations would be more appropriate. Even stronger tactile sensations for critical altitude alert signals would be very important.”

Another commented “I see that in Army tactical situations, personally hovering over snow, where helicopter drift is very hard to detect, that the TSAS suit would make flight safer and easier to fly. The TSAS vest could be the difference between success and a mishap.”

“Tactically, when using Night Vision Goggles (NVG) and hovering over an oil rig, over a catwalk. Since Blackhawk is 65 ft wingtip to wingtip, I sit 20 ft behind that, and troops are 10 ft behind me. Very important to know helicopter movement while troops are rappelling, jumping off, getting on. Crew chief in the back can say move forward and with the vest I can tell if I move forward.”

“In combat, while firing mini-guns, the flash is blinding, NVG goggles turn off and I have a loss of vision. The suit could let me know if I am drifting, and which direction that I am moving.”

“In combat, while taking incoming fire flying or hovering low to the ground, flash from missile blast, explosions gunfire and loss of vision is present. The suit could again let me know what the helicopter is doing all this time in relation to the ground or hazards.”

Was the tactile information intuitive?

All pilots responded that the tactile information was very intuitive. Comments included: “No thinking.”

“I didn’t have to think.”

“(TSAS) design gave ‘solid indications’ of drift.”

“Frequency signal strength variations to identify the amount of helicopter drift was very helpful.”

Was the tactile sensation annoying?

All pilots responded that the tactile sensation was not annoying or distracting.

Please comment on workload during IMC shipboard operations?

All pilots responded that workload was reduced.

Any suggestions for improvements of the tactors and/or tactile information?

1. Position Cue:

“I would add the ability to pinpoint my location at will. Then I can tell if there are changes from that personally set point. Pinpointing is very important for control (of) the helicopter, while rappelling, hoisting or hovering over water.”

“I would like to add that with the TSAS suit aircraft position is known (communicated) without verbally saying it between pilots and crew chief could be in the loop as well”.

“Have a pinpoint set control, set at will. While hovering, set it then I can use that point as a reference point for off loading troops via repelling, fast roping, or egress.”

2. Altitude Information:

“I would suggest adding something to give altitude information. Maybe on the left arm - controls of collective position. (1) rate of descent, (2) rate of ascent, (3) change in descent, (4) change in ascent and (5) altitude. While flying following terrain. Keeping above obstacles, but not over 100 feet where threats are.”

“Altitude control tactor, while flying with a minimum and a maximum attitude on approach on arm and identifying drift up or down.”

Any further comments?

Other comments included:

“In multi-flight scenario, fatigue sets in, air crew co-ordination is decreased, minor task capability is reduced, the suit would counteract this. Especially cases of NVG flights, over water, or while shipboard hovering.”

“In training with NVG, student is flying all by themselves. Instructor with the suit on can monitor correctness of the flight path of the student (following directions, drift, etc.) while checking the radio or other instruments.”

“Student can tell what direction they are moving while flying.”

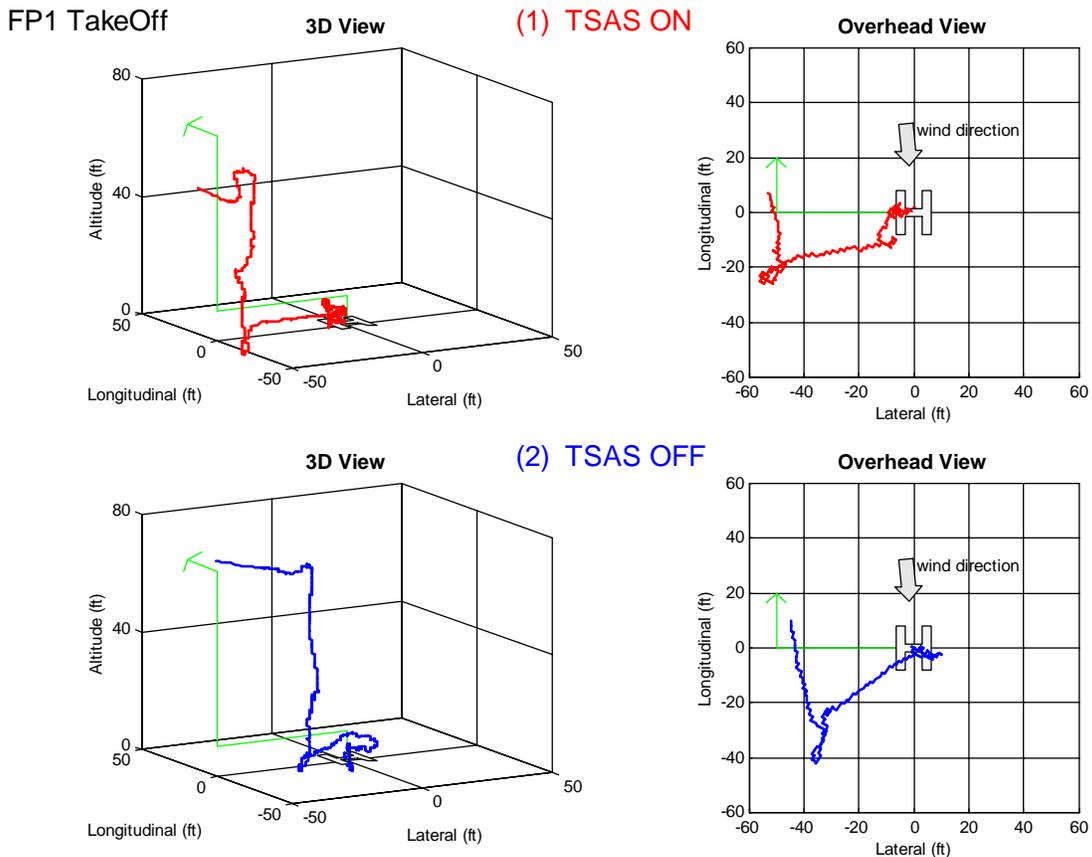
“Administratively or in a controlled environment, non-verbal communication with the crew is possible (i.e. buzzing each other to report all ready, or wait or emergency.)”

Flight Data

Using TSAS, pilots demonstrated improved control of aircraft during complex flight maneuvers. The awareness of aircraft velocity over the ground or “drift” without looking at a visual instrument was the biggest advantage of TSAS. This is illustrated in Figures 44 through 51, which contain data for the four pilots. Looking at the top of the flight data figures (Figures 44 through 51), there are two **red** plots that show the aircraft path with TSAS ON (Phase C), the top left is a 3D view and the top right is an overhead view. At the bottom of the flight data figures (Figures 44 through 51), there are two **blue** plots that show the aircraft path with TSAS OFF (phase D) in both 3D and overhead views. The orientation of the helipad

icon (H) indicates the heading of the helicopter at the beginning of the maneuver. For the 3D view, the helicopter is facing away from the reader, and in the overhead view the nose of the helicopter is orientated to the top of the page. Wind direction is shown as a grey arrow. The maneuver for the simulated shipboard take-off is described above, and consists of an ascent to IGE hover, followed by a left sideward hover for 50ft, then ascent to OGE hover and transition to forward flight. The maneuver for the simulated shipboard landing is described above, and consists of a descent from OGE to IGE hover, followed by a left sideward hover for 50ft, stabilize at an IGE hover and then land. The safety pilot was responsible for verbally instructing the subject pilot on the sequence of maneuvers. The intended maneuver is shown as a dashed green arrow in the overhead and 3D views.

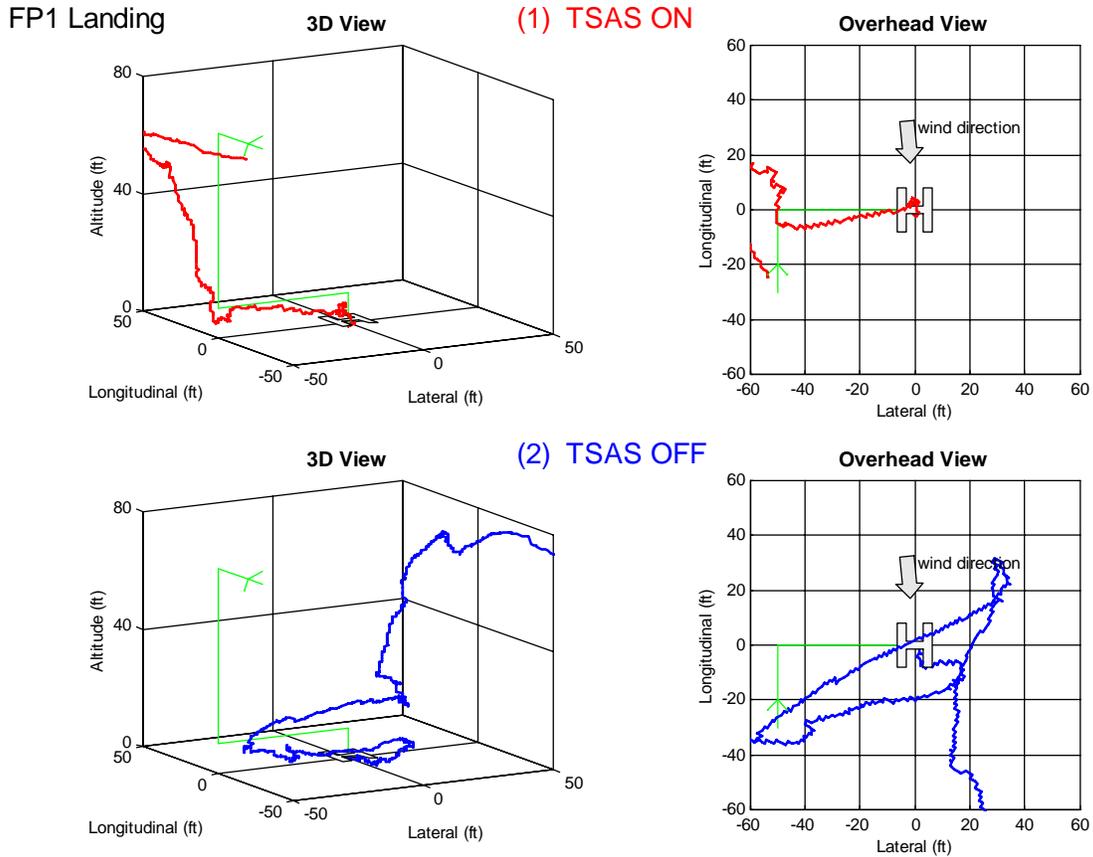
Figure 44 displays the data for the simulated shipboard take-off with TSAS ON and TSAS OFF for evaluation flight, FP1. Looking at Figure 44, the pilot during TSAS ON initially drifts rearward during ascent to IGE hover. Aware of this drift the pilot stops the rearward drift during the IGE hover and then moves leftward in the correct direction to the OGE hover. Minimal horizontal drift of less than 10ft occurs during the OGE hover and the pilot departs on the correct takeoff heading. With TSAS OFF, the aircraft initially drifts to the right during the ascent to IGE, and then drifts rearward during the leftward hover, and during the ascent to OGE. These drifts are undetected and uncorrected by the pilot and the aircraft ends up 40 ft behind the correct takeoff point.



Wind: 10 kts @ 210 deg.

Figure 44: FP1 Simulated shipboard take-off (Phase C and D).

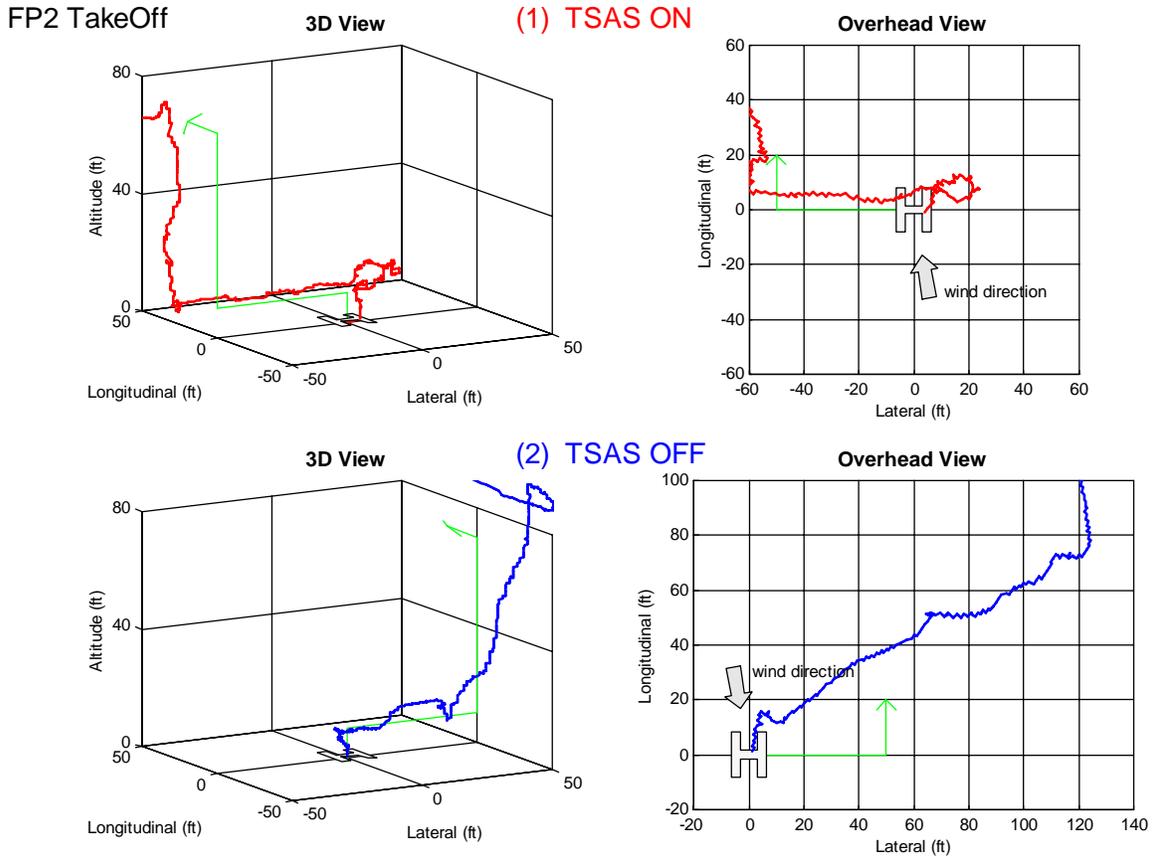
Figure 45 displays the data for the simulated shipboard landing with TSAS ON and TSAS OFF for FP1 evaluation flight. With TSAS ON, the pilot performs a safe correct landing under the guidance of the safety pilot (Figure 45, red plots). With TSAS OFF, the pilot does not perform a safe landing and the safety pilot takes control of the aircraft during this maneuver (Figure 45, blue plots).



Wind: 10 kts @ 210 deg.

Figure 45: FP1 Simulated shipboard landing (Phase C and D).

Figure 46 displays the data for the simulated shipboard take-off with TSAS ON and TSAS OFF for evaluation flight, FP2. Looking at the red plots in Figure 46, the pilot with TSAS ON initially drifts right while ascending to IGE hover. Aware of this drift, the pilot compensates for the right drift and moves left the correct amount to clear the simulated deck. No horizontal drift occurs during the OGE hover and the pilot departs on the correct takeoff heading. With TSAS ON, the pilot performs a safe, correct shipboard take-off. With TSAS OFF, the aircraft drifts forward during the ascent to IGE hover, the rightward hover, and during the ascent to OGE hover. Also the helicopter drifts right during the ascent to OGE hover. These drifts are undetected and uncorrected by the pilot and the aircraft ends up 70 ft to the right and 70 ft in front of the correct takeoff location. The pilot in FP2 does not perform a safe, correct shipboard take-off with TSAS OFF.

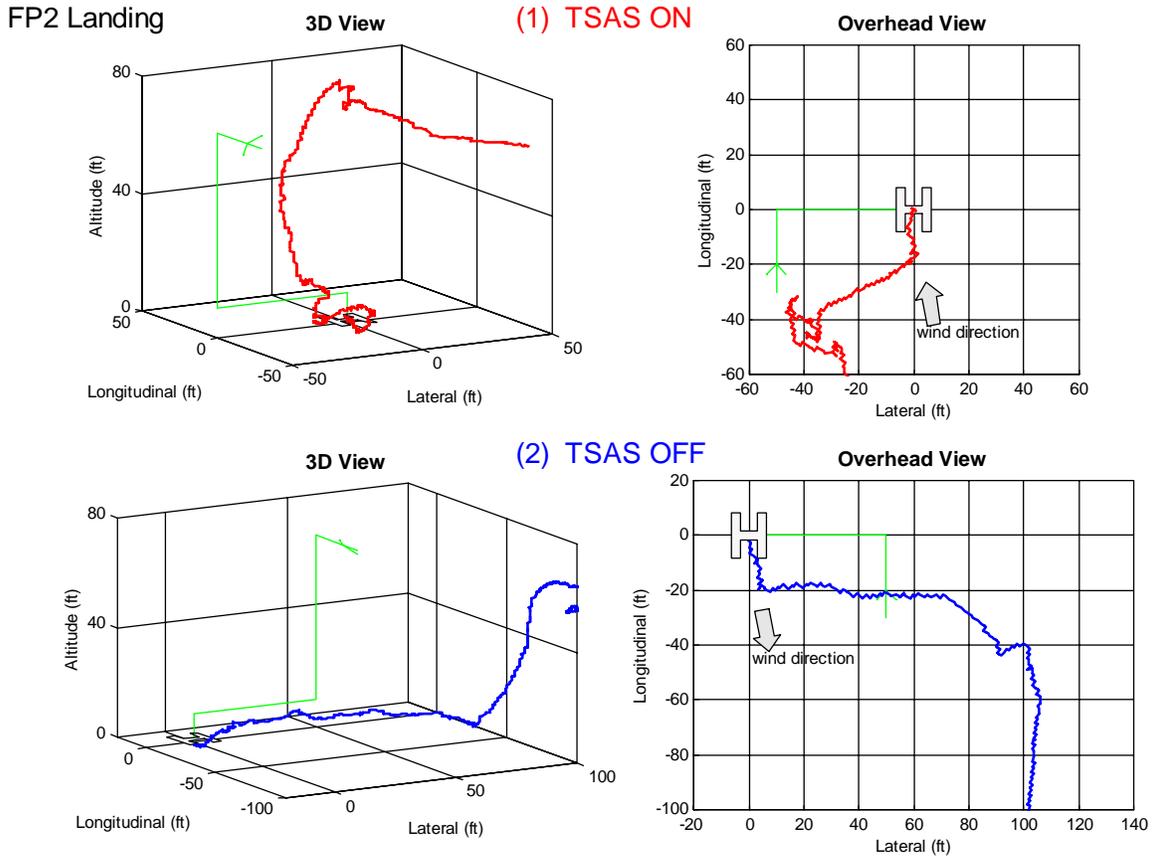


Wind: 12 kts @ 210 deg.

Figure 46: FP2 Simulated shipboard take-off (Phase C and D).

Note that the heading direction was changed from TSAS ON to TSAS OFF so that the take-off and landing were into the wind.

Figure 47 displays the data for the simulated shipboard landing with TSAS ON and TSAS OFF for FP2 evaluation flight. With TSAS ON, the pilot performs a safe landing following the guidance of the safety pilot (Figure 47, red plots). The descent to IGE hover is vertical with horizontal drifts of approximately 10 ft. With TSAS OFF, the pilot does not detect the forward drift during descent from OGE to IGE and during the IGE hover before the leftward hover. This undetected and uncorrected forward drift is approximately 50 ft.

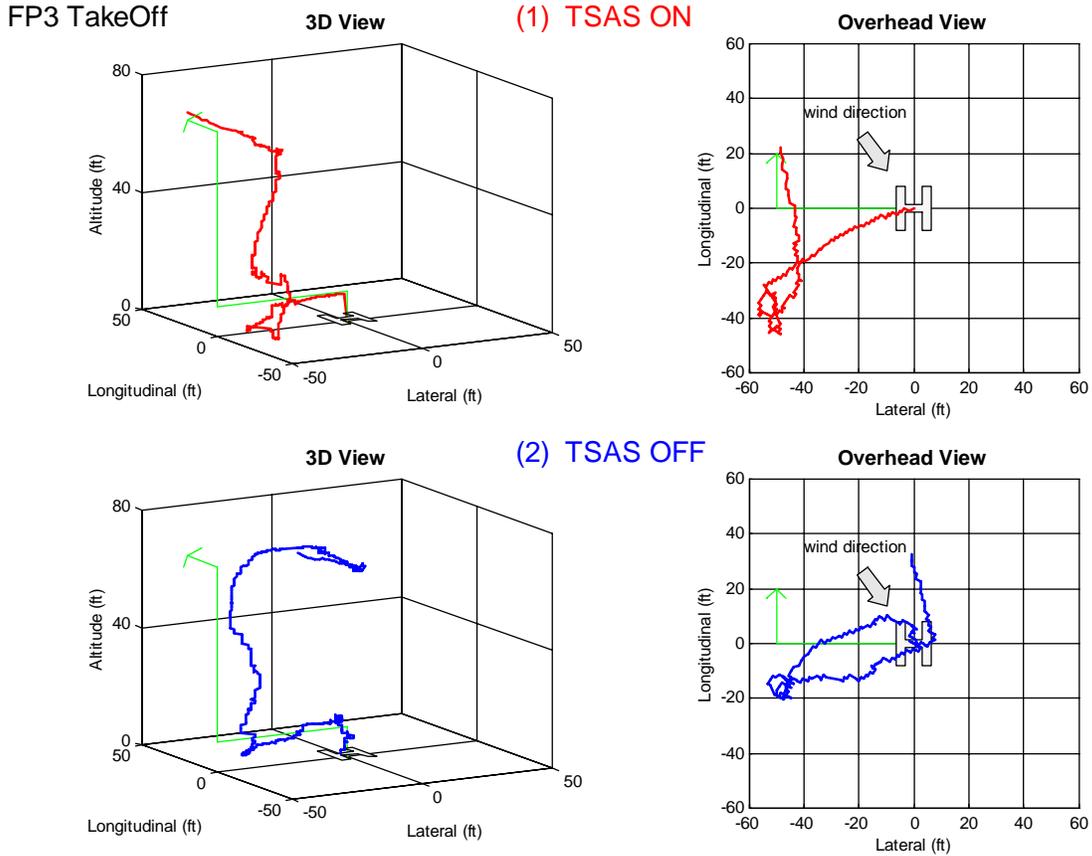


Wind: 12 kts @ 210 deg.

Figure 47: FP2 Simulated shipboard landing (Phase C and D).

Note that the heading direction was changed from TSAS ON to TSAS OFF so that the take-off and landing were into the wind.

Figure 48 displays the data for the simulated shipboard take-off with TSAS ON and TSAS OFF for evaluation flight, FP3. The TSAS ON takeoff is qualitatively the least accurate of the TSAS ON take-offs. However, the pilot is aware of a rearward drift and performs the leftward hover of 50 ft to achieve a safe clearance from the simulated deck. A safe transition to forward flight is achieved. With TSAS OFF, the pilot performs a fairly accurate maneuver until the aircraft drifts right 50 ft during the OGE hover. This undetected rightward drift prior to the transition to forward flight results in inadequate lateral clearance from the simulated deck, and in a real shipboard situation would result in a mishap.

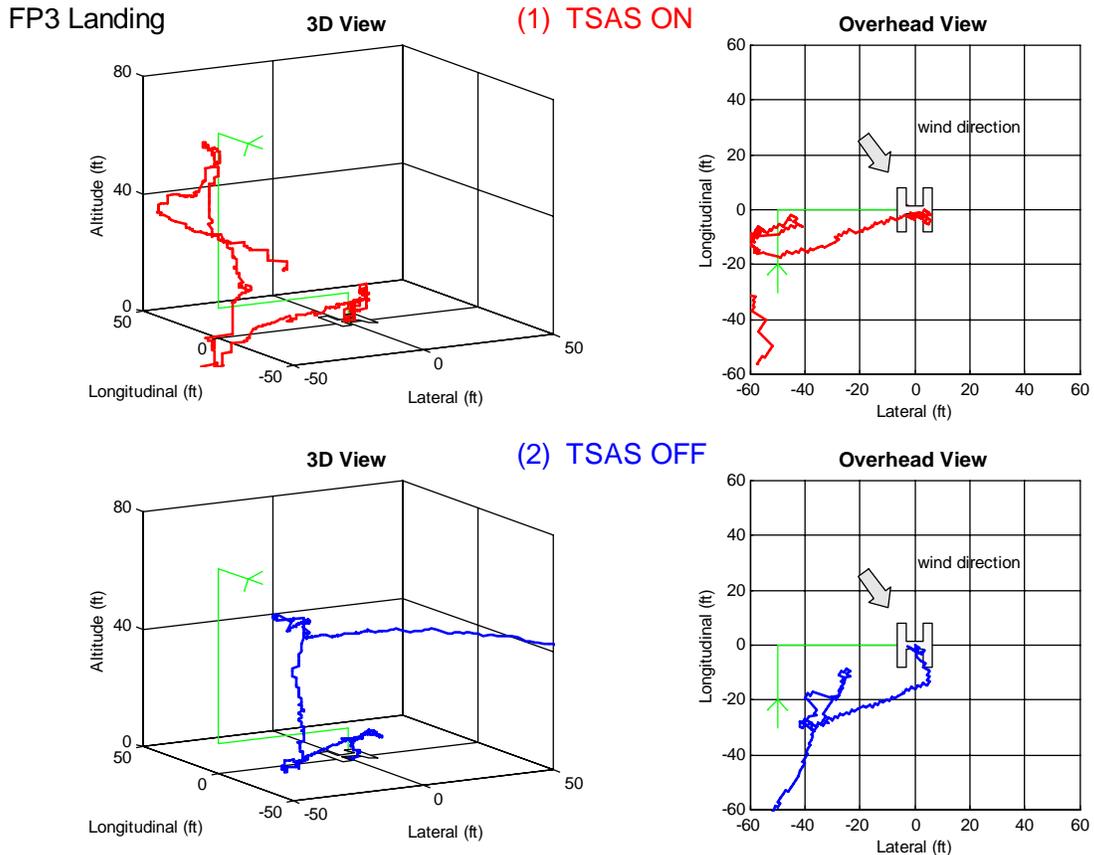


Wind: 10 kts @ 170 deg. (gusty)

Figure 48: FP3 Simulated shipboard take-off (Phase C and D).

The pilot in FP3 does not perform a safe, correct shipboard take-off with TSAS OFF. Knowledge of the aircraft drift during hovering is critical for safe flight.

Figure 49 displays the data for the simulated shipboard landing with TSAS ON and TSAS OFF for FP3 evaluation flight.



Wind: 10 kts @ 170 deg.

Figure 49: FP3 Simulated shipboard landing (Phase C and D).

With TSAS ON, the pilot performs a safe landing following the guidance of the safety pilot (Figure 49, red plots). The descent to IGE hover is vertical with a leftward drift followed by a correction to the right. A straight rightward hover in IGE completes the landing. With TSAS OFF, the pilot does not detect a rearward drift of approximately 20 ft during the OGE hover. As seen in other landings, when TSAS was OFF, undetected drifts occurred.

Figure 50 displays data from the simulated shipboard take-off for TSAS Evaluation flight, FP4, for both TSAS ON and TSAS OFF. For both TSAS ON and OFF, the pilot initially drifts right while ascending to IGE hover. With TSAS OFF, this drift is neither sensed nor corrected and increases to approximately 20ft (Figure 50, blue plot bottom right). The pilot then performs the left sideward hover. With TSAS OFF, the left sideward hover is in the correct direction, however the undetected rightward drift prior to the left hover results in inadequate lateral clearance from the simulated deck. In addition, with TSAS OFF the aircraft drifts aft during ascent to OGE, undetected by the pilot. With TSAS OFF, the pilot does not perform a safe correct shipboard take-off. With TSAS ON, the pilot performs the left hover but drifts rearward, however, aware of this backward drift, the pilot corrects by moving forward on the ascent to OGE hover (Figure 50, red plot top right). While maintaining the OGE hover the pilot drifts to the right, however, aware of this rightward drift, the pilot departs in a forward and leftward direction (Figure 50 top right). Similar to the pilot in FP1, FP2 and FP3 with TSAS ON, the pilot performed a safe, correct shipboard take-off.

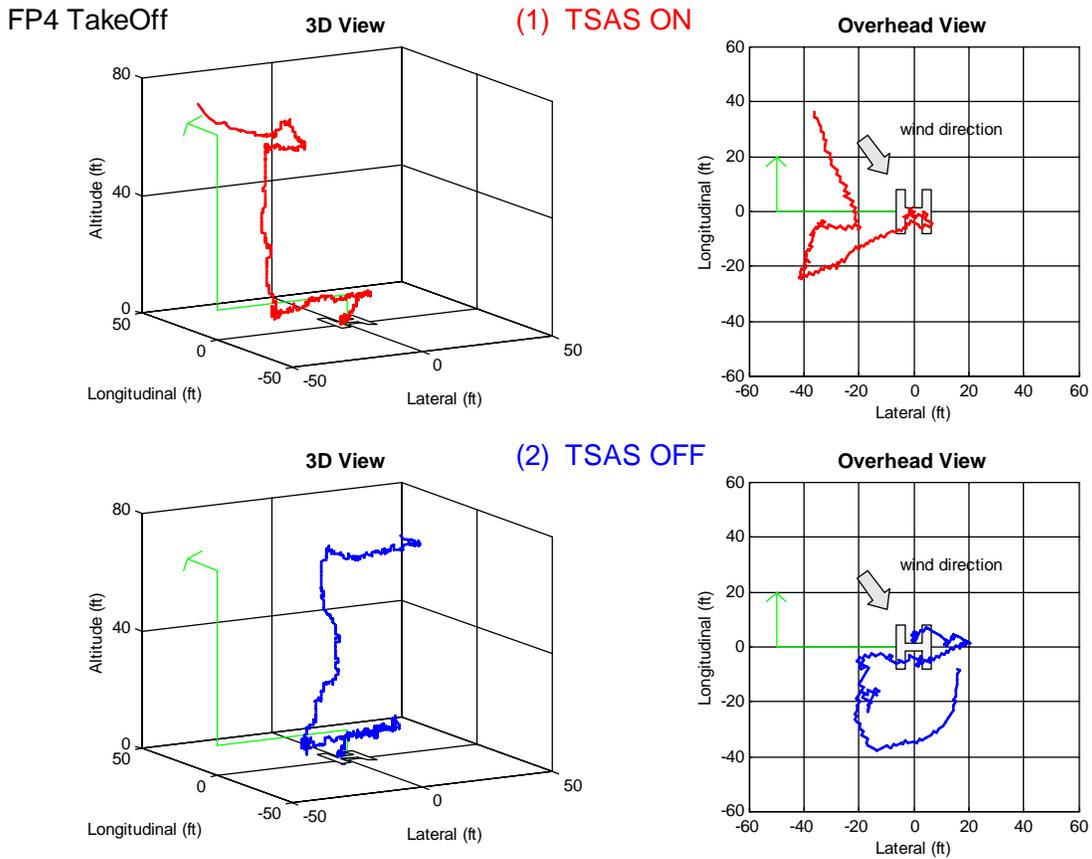
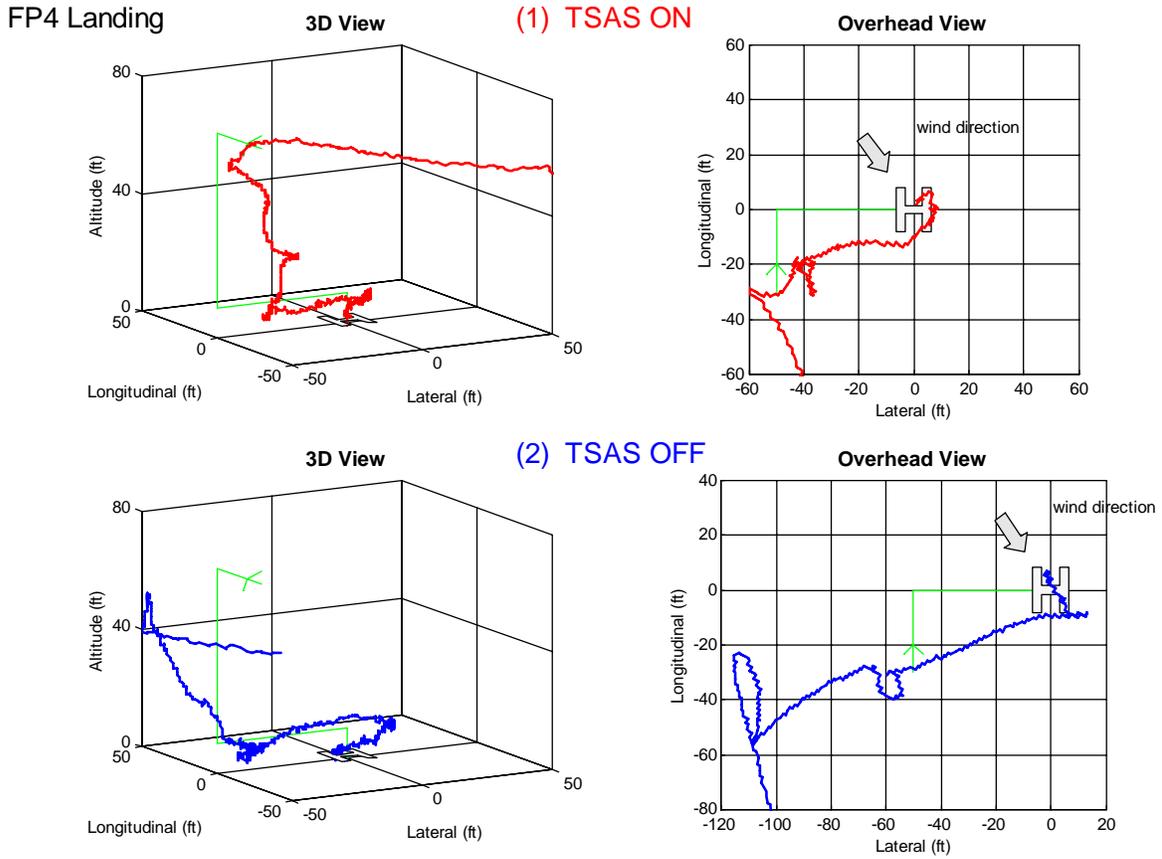


Figure 50: FP4 Simulated shipboard take-off (Phase C and D).

Figure 51 displays the data for the simulated shipboard landing with TSAS ON and TSAS OFF for FP4 evaluation flight. Similar to the FP2 flight, the pilot with TSAS ON performs a safe landing following the guidance of the safety pilot (Figure 51, red plots). The descent to IGE hover is vertical with horizontal drifts approximately 10 ft. With TSAS OFF, the pilot does not detect the rightward drift during descent from OGE to IGE and during the IGE hover before the rightward hover. This undetected and uncorrected rightward drift is approximately 60 ft.



Wind: 10 kts @ 190 deg.

Figure 51: FP4 Simulated shipboard landing (Phase C and D).

4.5 DISCUSSION

The JSF TSAS flight demonstration fulfilled project test objectives and demonstrated that a tactile instrument could provide increased mission effectiveness and survivability in V/STOL strike aircraft. Results from the JSF TSAS flight demonstration have shown that TSAS technologies have the potential to increase pilot situation awareness and reduce pilot workload, especially during complex flight conditions in poor visibility. Using TSAS, pilots demonstrated enhanced control of hover maneuvers, relying on tactile cues for the necessary information.

The awareness of aircraft movement over the ground or “drift” without looking at a visual instrument was the most important feature of the JSF TSAS tactile instrument. An undetected drift of a helicopter or V/STOL aircraft whilst hovering can lead to a spatial disorientation mishap resulting in a serious and costly problem in terms of lives lost, aircraft lost and mission failure. With the increasing use of night vision devices the problem will only increase in magnitude. The JSF TSAS tactile instrument using an F-22 cooling vest and lightweight pneumatic tactor was optimised for hover conditions in poor visibility. By providing horizontal drift information, the pilots were able to spend more time visually attending to other displays, including the altimeter for altitude control. This ability to spend more time visually on other displays and use the tactile instrument for horizontal drift resulted in reports of increased situation awareness and reduced workload. During IGE hover in VMC, the pilots used the tactile cues as a secondary source of drift information, again resulting in reports of increased situation awareness and reduced workload. During OGE hover in VMC, the visual detection of drift became harder due to the loss of visual cues, and the tactile display was able to provide the necessary drift information that allowed the pilot to spend more time visually on other instruments and outside the cockpit. The TSAS tactile display permitted the pilot to concentrate on mission tasks, thereby reducing workload. These effects can increase mission effectiveness.

With the tactile cues provided by TSAS tactile instrument, pilots were able to demonstrate improved control of aircraft during complex flight conditions in VMC and IMC conditions. Even though the flight demonstrations were very successful in showing that tactile instruments can solve operational problems, one must be cautioned in overusing the tactile instrument to provide too much information, thus diminishing the capability of the display. This is especially important with the current tactor and TLS technology. When the pilot felt a tactile sensation with the JSF TSAS hover display, only one aircraft variable was being communicated (velocity) and the position on the body corresponded to the direction of that velocity, and the intensity of the sensation corresponded to the magnitude. This was a simple, easy-to-interpret tactile algorithm that used current tactor and TLS technology to solve a critical aviation problem and improve the safety of flight.

These results confirm the idea seen in the T-34 flight demonstration in that a tactile display provides excellent warning of deviation from a desired state or null condition. By using the appropriate tactile algorithm (tactor location with maximal separation and strong tactile intensity) intuitive 3D direction and magnitude information can be provided.

A few technical problems related to the sensor hardware were encountered during the test program. As mentioned previously, strong emphasis was placed on the use of COTS equipment, which led to the selection of civilian GPS and DGPS units. The GPS unit had strict antenna requirements, which precluded the use of the installed military aircraft GPS antenna. The DGPS unit received US Coast Guard beacon signals from Mobile, Alabama that proved intermittent at Ft. Rucker, Alabama. Utilizing a dedicated passive civilian GPS antenna and moving closer to Mobile (NAS Pensacola) solved these two problems, but the use of a military GPS unit with P-Code (as would be the case in a fleet deployed TSAS) would also eliminate those two problems. No other significant technical difficulties were encountered during the flight test program.

Chapter 5

If you are looking for perfect safety, you will do well to sit on a fence and watch the birds; but if you really wish to learn, you must mount a machine and become acquainted with its tricks by actual trial.

--Wilbur Wright, 1901

Commentary

The goal of this thesis was to demonstrate that aviators in actual fixed-wing forward flight and rotary-wing hover flight could use a tactile instrument to receive situation awareness information. This was the first time that a tactile instrument was developed and flown in actual military aircraft, resulting in engineering and scientific decisions being made without having an extensive body of knowledge to build on. The successful flight test demonstrations, favourable pilot subjective comments, and JSF TSAS quantitative data have justified these decisions, raised numerous issues, and have laid the groundwork for future development.

The requirement of actual flight demonstration was the primary driving force for all engineering, scientific, and political/economic decisions. The “real world” of the aircraft cockpit is a demanding, complex, high workload environment that is noisy, often hot, and with an inherent high vibration. This environment precluded the use of the majority of the tactile display technology that had been developed for use in visual or audio sensory substitution tactile displays. For example, no commercially available tactor had a strong enough intensity to be easily felt in a T-34 or an UH-60 cockpit. If a tactor cannot be felt then a tactile instrument provides no information, just as a visual display provides no information if it is not being looked at. Since the primary feature of a tactile instrument is to provide information even when one is not focusing or “looking” at the display, tactor intensity becomes the most critical design parameter. This necessitated the development of the modified vibrating pager motor for the T-34 project, and subsequently, the pneumatic tactor for the JSF project. The T-34 TSAS project did not compromise on tactor intensity so even though the “pager motor” tactor was heavy, causing problems in the implementation of the tactor algorithm, other tactors were not used. Understanding the environment in which the tactile instrument must operate, and never compromising on the role of the tactile instrument was critical in the successful completion of the flight demonstration programs.

TSAS design decisions were made using both a top down and bottom up process. The principal investigator and program manager/aerospace engineer determined overall project goals and theoretical concepts. For all design decisions on critical details, such as number of tactors, placement of tactors, and tactor algorithms, the pilots who would wear the tactile display and fly the demonstrations were included in the decision process. In circumstances when pilot concerns/ideas clashed with scientific or engineering concerns, final decisions by the program manager/aerospace engineer were always weighted towards the pilot. Listening to the end-user and balancing their requests with engineering and scientific requirements was instrumental in the successful completion of the flight demonstrations and the receipt of favourable subjective ratings from the pilots.

The TSAS tactile instrument was successfully flown in two flight demonstrations presented in chapters 3 and 4, T-34 TSAS and JSF TSAS, respectively. By using tactors located on the torso, an adequate intensity tactor, and an easy-to-learn intuitive tactile algorithm for the presentation of information, the TSAS tactile

instrument overcame limitations of previous attempts to develop tactile displays for aviation. Over the previous 40 years, a number of aviation tactile displays had been published, and none of this work progressed farther than the design or laboratory phase. This work represents the first successful flight demonstrations of a tactile instrument for military aviation. Without the successful completion of the T-34 TSAS and JSF TSAS flight test demonstrations, the TSAS tactile instrument may also have been allocated to the shelves of “nice ideas,” and the development of an aviation tactile instrument be delayed and/or completely cancelled. However, due to the completion of the flight demonstrations, the following research and development programs have been funded to continue work on aviation tactile instrument technology:

- NASA Ames Research Center has funded a basic scientific study on the effects of workload and tactile instruments during hover operations in a civilian tilt rotor.
- United States Air Force Special Operations Command (AFSOC) has sponsored a program to further develop the JSF TSAS hover display for operation use, including adding the capability to provide attitude information in addition to the existing hover drift information.
- NASA Johnson Space Center has funded a program to develop a tactile display to provide orientation information during Space Shuttle landing.

All of these research programs will attempt to address scientific, engineering and end-user limitations of the current aviation tactile instrument technology.

TSAS has the capability of providing a wide variety of flight parameter information, such as attitude, altitude, velocity, navigation, targets etc. The T-34 TSAS flight demonstration has shown that a pilot can maintain control of a fixed wing aircraft using only tactile cues, while the JSF flight demonstration has shown that a tactile instrument can enhance performance, reduce workload, and enhance spatial awareness in a rotary wing aircraft during poor visibility flight conditions.

As a solution to the critical problem of losing situation awareness while hovering a V/STOL aircraft in poor visibility conditions (IMC or using NVDs), the TSAS NP-1 tactile instrument has shown great potential. The ability to provide drift information via the sense of touch allowed the pilots to use their vision for other critical tasks, including maintaining altitude. One pilot even commented that if he were required to fly combat sorties again, he would want the prototype TSAS NP-1 tactile display as is. Such remarks are very encouraging for the potential of tactile instruments, and further engineering development of the tactile instrument is required to reduce the size and weight of the auxiliary equipment and improve reliability, maintainability and affordability. To maximize the potential of the hover NP-1 tactile instrument, extra capability is required with the following two items deemed the most important next steps:

- 1) Provide altitude information on the arms. Many accidents occur because the helicopter drifts into the ground. The ability to provide drift information via the sense of touch allowed the pilots to use their vision for other tasks, including maintaining altitude, but extensive research needs to be done to see if altitude information can be provided via the sense of touch.
- 2) The ability to provide attitude information as shown in the T-34 flight program. This feature is required to expand the use of the tactile instrument to the critical area of hover transition to forward flight. This requires presenting attitude (pitch and roll) information.

One must be cautioned in using the tactile display to provide too much information. When the pilot perceived a tactile sensation with the JSF TSAS hover display, only aircraft velocity was been communicated, with the position on the body corresponding to the direction of that velocity, and the intensity of the sensation corresponding to the magnitude. This was a simple, easy-to-interpret tactile algorithm that used tactor and TLS technology to improve the safety of flight. In contrast, the T-34 TSAS tactile instrument presented two variables simultaneously (pitch and roll) and the tactor position on the body, coupled with the perceived intensity of the tactors indicated the magnitude of the variables. This tactile algorithm was implemented primarily due to limitations of the tactor available. Flight performance during climbing and descending turns showed that there were problems when two tactors were activated simultaneously (Figure 28). The test pilot for the T-34 TSAS flight demonstration claimed he was able to use the tactile instrument most effectively when the tactors were activated from the off or null condition. He often had problems distinguishing between tactors that were located physically close to each other. This was in part due to tactor technology, and also to limitations of the sensory system detecting different sites on the body in high workload environments. The UH-60 TSAS flight demonstration project showed that a

tactile display could overload the pilot (McGrath *et al.* 1998), just as some visual displays can provide too much information and cause a problem.

TSAS flight demonstrations have shown that presenting two or more different types of information simultaneously and in close proximity when using the similar tactors makes the tactile instrument system non-intuitive and difficult to use. This is due in part to limitations of current tactor technology. For example, using the T-34 fine algorithm, if the aircraft was pitched down 9 degrees and rolled right 18 degrees, the lower tactor on the front (Figure 24; tactor 1) would activate at 10 pulses per second, and the middle tactor on the right side (Figure 24; tactor 10) would activate at 4 pulses per second. It is hypothesized that the two tactors firing simultaneously at different pulse patterns required cognitive information processing to indicate aircraft attitude. Since a pilot's information processing capacity is limited (Fracker, 1989), "information overload" can occur with tactile instruments that require cognitive information processing. The limit of information processing can occur rather quickly in the complex aviation environment. This problem of "information overload" is also seen in visual and audio displays. To implement the features described above to improve tactile instrument performance, the development of the following issues are necessary:

1. The need for improved tactors. The prototype (T-34) and first generation (JSF) tactors used in the flight demonstrations could only be turned on and off. The amplitude, carrier frequency, and stimulus type (vibration, stroking) could not be controlled in these tactor systems. This is analogous to a black and white versus a colour visual display. A "richer" tactile sensation that could convey more information can be achieved with improved tactors.
2. Incorporating the absolute minimum number of tactors into existing flight garments. Today's aviator is asked to wear an ever-increasing amount of equipment. A tactile instrument that has a minimum number of tactors that still provides the necessary information will be lighter, more robust, and easier to maintain than a tactile instrument with a large number of tactors.
3. Keeping the tactile instrument intuitive and easy to understand. A tactile instrument will be of little or no use if the tactile instrument requires the pilot to "focus" on the tactile stimuli, and then relate this stimuli to a piece of information by cognitive "thinking." For example, a Morse code type algorithm for displaying pitch and roll magnitude would require extensive training and "thinking," and would not be acceptable due to the increase in workload.
4. Expanded coverage Tactor Locator System. To provide attitude information, a minimum of three rows and eight columns of tactors are required on the torso. To achieve this a TLS that covers more of the upper torso is required. The current TLS provides excellent coverage of the mid/lower torso region but lacks coverage in the upper torso where tactors for attitude would be required.

Improved Tactors

To achieve goal 1 of an improved aviation tactor, the aviation tactor should have the following requirements. It is worth noting that the requirements for an aviation tactor in 1999 are identical to the ten desirable characteristics for a tactile transducer to be used as a tactile aid for deaf people as detailed by Sherrick (1984). Given the modest research budgets for tactor development, it is not surprising that tactors with the following characteristics have not been developed in the past 15 years.

1. Small Size
To achieve aviator confidence, the tactor needs to be integrated into flight garments worn by aviators. The tactor needs to be small enough to facilitate this integration without producing bulges or causing discomfort due to a large size.
2. Low Mass
This is a critical parameter for the aviation tactile instrument if more than 20 transducers are required. The use of multiple tactors in high G environments causes the total weight of the tactile instrument to be prohibitively heavy if the individual tactor is not of low mass.
3. High Efficiency

A high efficiency factor is required to keep power usage low, especially for multiple factor displays. This requirement is even more important for battery operated tactile displays.

4. Appropriate Frequency Response

The threshold for perception of mechanical vibration for a sinusoidal wave over the range of 50-500 Hz is a U-shaped curve with a minimum near 200 to 300 Hz (Sherrick and Craig, 1982). For a rectangular wave, the threshold curve is approximately flat across the 50-500 Hz region (Geldard, Sherrick, and Cholewiak, 1981). For aviation tactile instruments, providing three levels of frequency to achieve a variation in perceived intensity is desirable to convey urgency to the primary information. Therefore, tactors used in aviation tactile instruments should have a flat and consistent operation across the 50 – 500 Hz range. This is not a trivial design goal. The majority of tactors use the qualities of mechanical resonance to multiply the force/displacement output, which tends to give an optimal operating frequency for that tactor and not a flat response across a range of frequencies.

5. Low Radiation of Acoustic Energy

Noise is not as critical for the aviation tactile display as compared to other tactile displays because of the inherent background noise in an aircraft cockpit. Nonetheless, the tactor should not emit acoustic energy such that it distracts or interferes with the pilot's audio function.

6. Insensitivity to contact pressure

In the rapidly changing force environment of flight, it is difficult to ensure a constant coupling of the tactor and skin. Therefore, the static loading of the tactor should have minimal impact on the dynamic force output.

7. Low distortion

The tactor must provide a reliable and reproducible stimulus to the skin over the operating range of the tactor free of amplitude, frequency, and phase distortions.

8. Large dynamic range

A desirable dynamic range for a tactor is 40 dB (von Békésy, 1959), and for an aviation tactor one could argue that a higher range is desirable. The T-34 test pilot commented, "I would rather be bruised than miss a tactor." If the information to be presented tactually is critical and life threatening, a robust tactile stimulus needs to be presented to avoid the possibility of the pilot "missing" the tactile stimuli.

9. Little long term discomfort

After sitting in a cramped and uncomfortable cockpit for long periods of time, a pilot does not need to be prodded or poked by a poorly designed and annoying tactile instrument.

10. Reliability

The aviation tactile display is an aircraft instrument. The tactors must be reliable to ensure pilot confidence in the tactile display, and they must work in a harsh and complex working environment (aircraft carrier, combat conditions). Tactors used in aviation need a system error feedback capability or failure mode to alert the pilot that a tactor is not working correctly.

To the above list first presented by Sherrick (1984), the following items are added for an aviation tactor required for the new millennium.

11. Maintainability

The tactor display system must be maintainable in the harsh working environment of military aviation (aircraft carrier, combat conditions).

12. Low radiation of Electro-Magnetic Energy

To avoid interference with other cockpit instrumentation, the aviation tactor must emit a low electro-magnetic signature. The tactor must also be resistant to interference from external electro-magnetic energy.

13. Cost

Economic and political needs require that tactor costs be kept down, especially in systems that require multiple tactors.

Aggressive, well-funded research and development of tactors is required to develop operational tactile instruments that will save lives in aviation. Commercial spin-off benefits from this military aviation development will be the improvement of tactile communication aids for the visual, hearing and balance impaired and other tactile displays.

The tactors used in this thesis were an electro-magnetic (T-34) and pneumatic low-pressure standing wave (JSF) vibrating tactors. Both of these tactors use vibro-mechanical transduction to produce a tactile sensation on the skin. Different forms of mechanical stimulation, including standard perpendicular vibration, parallel scratching, and pinching need to be more thoroughly investigated and developed. Current technology for mechanical transduction tactors have a low efficiency and to generate an adequate intensity of signal a reasonably heavy tactor with large power consumption is required. For multiple tactor tactile displays, individual tactor weight is very critical and a heavy tactor is unacceptable.

Another type of tactor that uses direct electrical contact to stimulate sensory endings in the skin was evaluated for the JSF TSAS flight demonstration. Current electrocutaneous tactor technology was not suitable for the flight test, but the technology shows great promise and should be further investigated. Electrocutaneous tactors stimulate some cutaneous receptors and fibres of the afferent nervous system by means of a small electric charge applied to the skin. Electrocutaneous stimulation affects receptors that are within range. Thus the quality of the sensation can vary, depending on several parameters, including electrode configuration, skin hydration, and body site. The quality of the sensation can also change with stimulation strength and if strong enough, it will be painful (Kaczmarek *et al.* 1991).

Minimum Number of Tactors

To achieve a minimum number of tactors in a tactile instrument that requires multiple tactors, there are tactile illusions that possibly can be used. These tactile illusions use psychophysical properties of the somatosensory system to change the perceived intensity, location, or motion of the tactile stimulus. When two tactile stimuli of equal intensity are presented simultaneously to adjacent locations on the skin, the resulting sensation is not two separate tactile sensations, but rather the stimuli combine to form a sensation midway between the two tactors. This illusion is called the “Phantom sensation” (Von Békésy, 1957; Gescheider, 1965; Alles, 1970, Verrillo and Gescheider, 1975), and could be used to generate “virtual tactors” located between physical tactors, thereby reducing the number of tactors required in an operational tactile instrument. The phantom sensation is dependent upon the physical separation of the stimuli, the amplitude, and the timing of the stimuli.

Intuitive Tactile Display

To keep the tactile display intuitive, easy to understand, and minimize the number of tactors (goals 2 and 3), the concept of developing intelligent software that presents the most critical piece of information when needed is required. This is similar to the “page” concept of state-of-the-art visual displays. A page presents certain specific information on the visual display (about engines, aircraft attitude, radar etc.). For example, during a helicopter instrument take-off, pitch attitude, positive rate of climb, and heading are of prime concern, whereas at cruise altitude, navigation information is important. When and how to transition from one mode to another is an important development for a tactile instrument. The software system would allow different types of information to be displayed through automatic, rule-based mode switching.

Intelligent knowledge-based software is a computer program that enables a computer to make a decision that is normally made by a human with special expertise. This is also termed expert system software. The architecture of intelligent knowledge-based software is based on human cognitive structures and processes. The first part of human cognitive processing is a long-term memory of facts, structures, and rules that represent expert knowledge about the area of expertise. The analogous structure in intelligent knowledge-based software is called the knowledge base. The second part of human cognitive processing is a method of reasoning that can use the expert knowledge to solve problems. The part of intelligent knowledge-based software that carries out the reasoning function is called the inference engine. In this analogy, the inference engine mimics thinking, while knowledge is contained in the knowledge base (McGrath *et al.* 1998).

A rule-based inference engine centres on the use of IF THEN statements. For example:

1. If the helicopter forward ground speed is less than 20 knots, then the helicopter is hovering.
2. If the helicopter is hovering and the helicopter pitch and roll attitude is less than 15 degrees then the tactile instrument should provide hovering information.

When the current problem situation satisfies or matches the IF part of a rule, the action specified by the THEN part of the rule is performed. Because intelligent knowledge-based software is dealing with fast moving data, rules offer the opportunity to examine the state of the data at each step and react appropriately. The use of rules also simplifies the job of explaining what the program did or how it reached a particular conclusion.

The architecture for the intelligent knowledge-based software under development for the TSAS project is shown in Figure 52. The software system is comprised of the following major components:

1. Input modules that provide information on aircraft state, aircraft performance data, pilot inputs, and pilot procedures.
2. Model modules that provide theoretical information about the aircraft and pilot to the knowledge base.
3. The knowledge base interacts with the inference engine and organizes and stores all available information.
4. Rule-based inference engine which interacts with the input modules, model modules and the knowledge base and then determines the right information to be displayed in a particular situation.

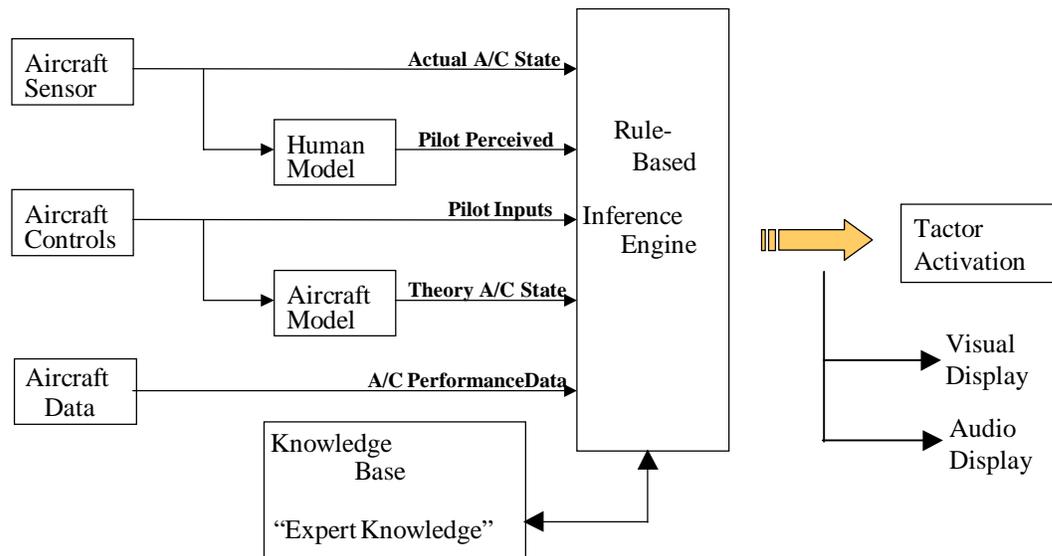


Figure 52: TSAS Intelligent knowledge-based software architecture
(from McGrath *et al.* 1998)

Aircraft Sensor Module is an *input* module to the knowledge base and provides the actual state of the aircraft (air speed, attitude etc.) and the actual state of aircraft systems (engine temperature, rpm, etc.).

Aircraft Controls Module is an *input* module that provides the actual pilot inputs on the controls (throttle, cyclic, etc.)

Aircraft Data Module is an *input* module that provides aircraft performance data. These data are typically empirical in nature and are supplied by the aircraft manufacturer.

Human Model Module is a *predictive* module that contains a model of the perceived human orientation. The input to this model is data from the aircraft sensor module. This model uses observer theory techniques to estimate the perceived orientation of the pilot. The observer theory model of human orientation was described by Oman (1982), and subsequently enhanced by Borah, Young, and Curry (1988), and Pommellet (1990). In the inference engine, data from this module, estimated pilot perception of orientation, is compared to actual pilot and aircraft orientation, and an estimate of the potential for spatial disorientation is predicted. Tactor activation together with visual and auditory displays are modified when a spatial disorientation situation is predicted. One possible implementation of this concept is to increase the magnitude of the tactile sensation during periods of high probability spatial disorientation situations.

Aircraft Model Module is predictive model of the actual aircraft. The input to this model is data from the aircraft control module. This model uses a computer motion model of the aircraft to estimate the state of the aircraft. In the inference engine, data from this module, estimated aircraft state, is compared to actual aircraft state and an estimate of a potential aircraft sensor failure or unusual meteorological condition is predicted.

The Knowledge Base contains "expert knowledge" of aircrew procedures in different situations. For example, an instrument takeoff in a SH60 requires the following procedure (Naval Air Training and Operating Procedures Standardization - NATOPS - 13.1.1.402.c):

- c. At 50 KIAS, as the AFCS (Automatic Flight Control System) switches to airspeed hold, level the wings, place feet on the pedals and centre the ball if required. Accelerate to 100 KIAS and establish a minimum of 500 FPM ROC (Rate of Climb). Take up a heading to account for drift.

Information like this is provided to the rule-based inference engine by the knowledge base. The knowledge base organizes and stores all available information.

The Rule-Based Inference Engine determines the right information to be displayed in a particular situation. As described earlier, the rule-based inference engine makes extensive use of IF THEN statements. When the current problem situation satisfies or matches the IF part of a rule, the action specified by the THEN part of the rule is performed.

The intelligent knowledge-based software described above controls the tactile presentation of information. This software must be adaptive, and "smart" about which information to provide, and how, when, what, and where to provide that information.

How to provide tactile information?

The presentation of tactile information should be intuitive and easy to interpret. It should be neither annoying nor something that the pilot habituates to. Additionally, information concerning threats or warnings must be clearly and easily differentiated from routine information.

When to provide tactile information?

The software system must monitor a variety of flight parameters, pilot inputs, and model estimates and prioritises the information depending on the current context. Some examples of "when" to provide tactile information may include:

- Continuously provide orientation information to help the pilot maintain spatial awareness.
- When aircraft is in autopilot mode and during transition between autopilot and pilot control.
- When there is a threat from hostile aircraft.

- When the input and predictive modules indicate that the aircraft might soon be at risk or that the pilot may be experiencing spatial disorientation.

What information to provide?

There is a wide range of information that can be provided via the sense of touch, however, flight demonstrations have shown that pilots using the current limited prototype display can only usefully accommodate a subset of this total. Some examples of "what" information to provide the pilot via tactile input might include:

- Roll and pitch information.
- Helicopter or V/STOL aircraft drift information.
- Navigation information.
- Relative location of hostile aircraft.
- Spatial disorientation episode recovery information.
- Instrument landing information.

Where to provide tactile information?

The factors must be located to achieve the goal of intuitive and easy to interpret tactile information. Some examples of "where" to provide information might include:

- Attitude information on the torso during fixed-wing flight situations.
- Helicopter altitude information on the collective arm.

Intelligent knowledge-based software will be an essential and complex component of a tactile instrument system that provides critical information to the pilot in a non-visual manner. Intelligent knowledge-based software that uses mode-switching software mechanisms developed for the tactile instrument will facilitate the eventual integration of visual, audio, and tactile displays into a single synergistic situation awareness display. The switching software must be adaptive, and "smart" about which information to provide, and how, when, what, and where to provide that information. The situation awareness display will provide the right combination of information at the right time by the right sensory channel(s).

As an example (Figure 53) the following algorithm is currently being implemented for the AFSOC sponsored program to develop a tactile instrument with hover and transition to forward flight capabilities.

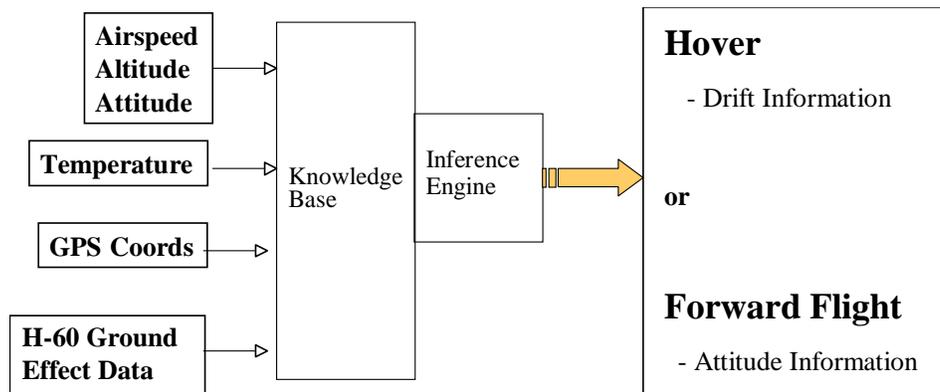


Figure 53: TSAS intelligent software architecture for helicopter transition.

F-22 Cooling Vest

One of the major breakthroughs of the JSF TSAS project was the use of the F-22 cooling vest as the TLS. The F-22 cooling vest solved both engineering and human factors/acceptability concerns for a TLS. First, the F-22 cooling vest TLS was lightweight and snug fitting when properly worn, and when connected to the cooling air, inflated slightly, which ensured a constant contact pressure of the pneumatic factors on the torso. Coupled with the reduced weight of the pneumatic factor compared to the "pager motor" factor, the

pilots did not report any lost factor sensation as we saw in the T-34 program. Two of the larger pilots commented that additional elastic would improve the comfort even more. From a human factor perspective, the F-22 vest was exceptional because the pilots wanted to wear it. The cooling air climate control was appreciated by all pilots and was instrumental in overcoming the very important aviator culture criticism that “I don’t want to wear another piece of equipment.” This is a very real problem as depicted in Figure 54, as the modern aviator is tasked to carry/wear a large amount of equipment. Without aviator acceptance, the tactile instrument will be limited in its development.

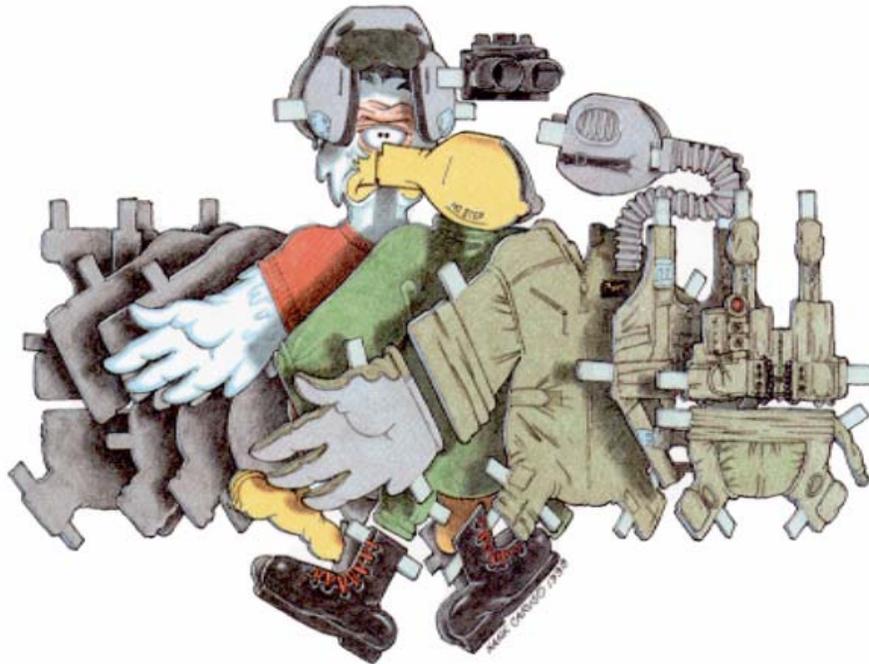


Figure 54: The overloaded aviator (Hank Caruso, 1998).

The F-22 cooling suit was a vest (Figure 40) that provided a good fit around the torso. This coverage of the torso was more than adequate for the presentation of helicopter horizontal velocity. It allowed the placement of two factors in each direction, thus providing increased stimulation and redundancy – a very critical feature in aviation. To expand the role of the vest to include orientation information during forward flight presented as a single factor or a collection of factors in the direction of down, an expanded coverage vest is required to include the upper torso region. The current vest does not provide a snug fit in the upper torso (chest and back) that is required to maintain factor contact with the body.

Future Research Developments

Expanding upon the static “virtual factor” concept described earlier, the phantom sensation can also produce the perception of the tactile sensation dynamically moving between the factors. By controlling the relative intensities of adjacent factors, one can move the location of the sensation to a point intermediate between the two stimulators. The separation of the factors, the relative amplitudes, and the relative timing of the factor activation (Figure 55) affect this phantom sensation. For example, by decreasing the intensity of one factor, whilst simultaneously increasing the intensity of another factor at a different point, one can interpret this as a tactile sensation moving gradually from one factor to the other (Von Békésy, 1957; Alles, 1970; Kirman, 1974). Therefore two tactile stimuli presented at different locations will feel as a single moving point. Using this illusion, it is possible to create motion perceptions using a minimal number of factors.

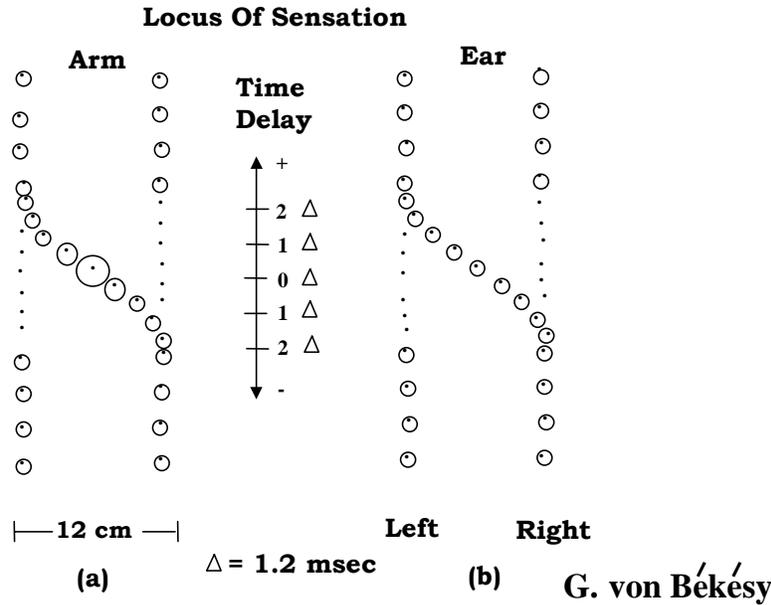


Figure 55: Localization as a function of interstimulus onset interval (from von Békésy, 1957).

Another related tactile illusion known as the sensory saltation has possible applications for an aviation tactile instrument. This illusion is more commonly known as the cutaneous rabbit and corresponds fairly closely to visual animation (Cholewiak, 1976; Geldard, 1977). To produce the classic cutaneous rabbit illusion, three tactors are placed at equal distances on the forearm. Five brief tactile pulses are delivered at the first tactor near the wrist, followed by five tactile pulses at the middle tactor, followed by five pulses at the third tactor near the elbow for a total of fifteen pulses at 3 separate locations. Instead of perceiving five pulses at the three tactor locations, one perceives the tactile sensation to be a continuous stream distributed with approximately equal spacing from the site of the first tactor to that of the third. The tactile sensation is characteristically described as if a tiny rabbit was hopping up the arm from wrist to elbow (Geldard, 1977).

Tan and Pentland (1997) developed a tactile display for wearable computers that used a two-dimensional rabbit illusion to provide directional cues. The tactile display is a 3x3 matrix of tactors located on the back, and by using the rabbit illusion the display can provide movement sensation in a particular direction (up, down, left, right, ± 45 degree incline).

Implementing the dynamic phantom tactile illusion and the cutaneous rabbit illusion in an aviation tactile instrument would allow research to be conducted to evaluate the robustness of these illusions in the air environment, and their suitability in presenting movement or “flow” information. Preliminary work during the T-34 flight demonstration showed that the vibro-tactile sensation generated by the rotating eccentric weight of the pager motor could not be accurately controlled in time and also produced a diffuse sensation. The inaccurate time control was primarily due to the time lag required to spin-up the motor. Because of the inaccurate time control and the non-localized sensation, the pager motor tactor was not able to produce the rabbit illusion. Tactors with a better time control and a more discrete or “sharper” output are needed to reliably produce the tactile illusions noted here.

TSAS Benefits

As stated previously, the goal of this project was to fly a tactile instrument in military aircraft. Along the way, a number of anecdotal findings were obtained from the TSAS demonstration pilots that warrant further investigation.

The first anecdotal report that was noted was a possible reduction in simulator sickness symptoms for the person who was wearing the tactile display. Symptoms resembling motion sickness (nausea, stomach awareness, fatigue, lethargy, sweating) and asthenopia (eyestrain, difficulty in focusing, blurred vision) have been reported in pilots following training sessions in flight simulators (Gower, Lilienthal, Kennedy, Fowlkes, and Baltzley, 1987; Gower, Fowlkes, 1989a,b; and Gower, Fowlkes, and Baltzley, 1989). The symptom constellation has been called simulator sickness. Twenty-five percent of aviators experienced significant symptoms that lasted more than an hour after a training session, and 8% reported symptoms lasting for more than six hours post training (Baltzley, Berbaum, Lilienthal, and Gower, 1989).

Full motion based simulator sessions for the JSF TSAS project lasting 8 hours were conducted for tactile algorithm development and flight test plan evaluation. . During these sessions, the program manager/aerospace engineer and the simulator operator reported simulator sickness symptoms. Conversely the test pilot reported that he felt OK. This report is possibly an isolated incident based on individual susceptibility to simulator sickness, however further investigation is warranted.

The second finding was related to the effects of the tactile instrument on training. Two of the pilots for the JSF TSAS flight demonstration project had been flight instructors. They commented that the vest would be very beneficial for training novice pilots how to hover. The additional cues on drift provided by the tactile vest would supplement and augment the visuals and help the novice pilot learn how to hover. Both instructor pilots believed that the vest would reduce the time needed to train a pilot how to hover, and in this time of cost reduction budgets this may be an important use of the tactile instrument.

Also the use of the vest would help in the safety of training pilots. One of the pilots was also a Night Vision Device (NVD) instructor. This NVD instructor pilot commented that while the novice NVD pilot was flying on NVDs for the first time, the instructor pilot would have to periodically focus on an auxiliary flying task (navigation, equipment status, communication). At this point the NVD instructor pilot was relying on the novice pilot to “fly” the aircraft. This can be stressful and potentially dangerous given the inherent problems of flying with NVDs even for experienced NVD pilots. The instructor commented that having the TSAS vest would be very helpful because he would be aware of what is happening with regard to drifting even if he were momentarily distracted.

Another benefit of the tactile instrument is in the area of training in simulators. If a tactile instrument is worn in the simulator, the tactile sensation experienced by the pilot is identical to the tactile sensation produced by an operational tactile instrument, thus potentially improving the training transfer from simulator to real world. A TSAS tactile instrument used in the simulator would be a slightly modified version of the operational TSAS display. The only modification would be to accept the simulated sensor data as opposed to real sensor data (i.e. helicopter drift). The actual operational TLS would be used in the simulator. Duplicating, rather than simulating, the tactile information in an aircraft simulator would enhance the rehearsal and training capabilities of the aircraft simulator.

One must remember that the tactile instrument is most needed during the worst of flight conditions. If there is a good visual horizon and low workload (simple navigation task, no equipment failure) then visual maintenance of spatial orientation and situation awareness is adequate and the need for a tactile instrument is minimized. However, when the pilot is flying in IMC with high workload (complex navigation task, equipment failure), or in combat situations, then critical information must be provided to the pilot in ways other than visual. Using the sense of touch to provide critical information by activating the tactile instrument allows the pilot to receive the critical information, even if the pilot is visually distracted. With the tactile cues provided by the TSAS tactile instrument, pilots were able to demonstrate improved control of aircraft during complex flight conditions in VMC and simulated IMC conditions. The JSF TSAS flight demonstration was successful in showing that a tactile instrument can solve operational problems.

Chapter 6

There is only one duty, only one safe course, and that is to try to be right.

Winston Churchill

Conclusion

The TSAS flight demonstrations have shown that tactile instruments can play an important role in decreasing spatial disorientation and improving situation awareness in modern aircraft. The TSAS flight demonstrations were the first time tactile instruments were successfully flown in military aircraft, and these demonstrations showed that TSAS has the potential to save lives and increase mission effectiveness. The T-34 flight test demonstration program has shown that a tactile instrument can be used in normal flight regimes (straight and level flight, standard rate turns, ground-controlled approaches and unusual attitude recoveries), and acrobatic flight regimes (loops, aileron rolls) in a fixed wing aircraft. The subsequent JSF flight test demonstration program showed the effectiveness of a tactile instrument in hover flight regimes in rotary wing and V/STOL aircraft. Overall, TSAS flight demonstrations have shown that a tactile instrument can decrease pilot workload and enhance pilot situation awareness. These effects can increase survivability and mission effectiveness.

To achieve a complete solution to the problem of spatial awareness mishaps, tactile instruments must be integrated with advanced visual displays and audio systems into a synergistic situation awareness instrument. This integrated solution represents the basis for the next-generation human-machine interface for military and commercial aircraft. Development of mode-switching software mechanisms for the tactile instrument will also be applicable to advanced HMD and 3D audio displays. The mode-switching software must be adaptive, and "smart" about which information to present; and how, when, what, and where to provide that information. The switching software will facilitate the eventual integration of visual, audio, and tactile displays into a situation awareness display that will provide the right combination of information at the right time by the right sensory channel(s).

To fully realize the potential of TSAS, the further development, testing, and evaluation of the following technology areas and the human factors implications need to be pursued:

- Integration of tactile instruments with Helmet Mounted Displays and 3D audio displays.
- Significant improvement in tactor technology.
- Tactor integration with flight garments.
- Miniaturization of all TSAS components.
- Improve JSF hover tactile algorithm to include altitude and position cues.
- Development of "smart" software to enable intelligent switching between various modes of situation awareness information.

Non-Military Uses of the TSAS

This thesis has focused on the application of TSAS for military aviation. However, TSAS has many very important commercial applications and has the potential to save lives and improve performance in a number of areas. Examples of the areas in which the TSAS tactile instrument could be used include:

1. Civilian Aviation

Spatial disorientation is not only a military problem. Sixteen percent of all fatal general aviation mishaps are attributable to spatial disorientation (Kirkham *et al.* 1978). TSAS could be used in civilian aviation to reduce spatial disorientation mishaps.

2. Air traffic controllers and dispatchers.

TSAS technology can be used for the spatial localization of targets by directing attention towards any target that is on sonar, radar, or being electronically tracked via a tactile cue. The target presented on a 2-D radar screen requires visual attention and cognitive processing of the information before a course of action is undertaken. Air traffic controllers can be cued to the location of targets using a 3-D tactile instrument quickly and intuitively, thus improving performance.

3. Space Applications

In space, the only sensory indication of orientation is currently provided by vision and astronauts are denied any sensory reference to indicate down. TSAS could be interfaced with an inertial reference system to give astronauts a continuous perception of down. In Extra Vehicular Activities (EVA), TSAS could improve safety and performance by presenting a constant point of reference, such as the airlock of the international space station and/or a companion astronaut. Not knowing the direction of an airlock, especially in an emergency, or a collision with another astronaut could have fatal consequences. TSAS also offers a countermeasure to the sensory-motor disorders associated with adaptation to “zero G” in space and re-adaptation to 1 G on returning to earth (Rupert *et al.* 1994).

4. Medical Applications

Research and development of tactile displays for military aviation will lead to better factors and improved understanding and methods of presenting tactile information. This will directly impact and improve tactile displays for providing visual information for blind people, hearing information for deaf people, and as a vestibular prosthesis for people with balance disorders.

Many people with balance disorders will benefit from treatment, but there is a significant number for whom treatment is not beneficial or who only obtain partial relief of their symptoms. Thus, in the long term, there remain many that could benefit in some way from a balance prosthesis. A tactile display could provide a balance prostheses that will re-supply motion information to those who have lost it because of inner ear disease.

A tactile display can also be used for balance rehabilitation applications. The tactile display can be used to provide tactile biofeedback as part of the NeuroCom Balance Master™ (NeuroCom International, Clackmas, Oregon) rehabilitation products. The tactile display would be especially helpful to some older patients who would have difficulty processing the visual biofeedback information.

In conclusion, TSAS has the potential to save lives and increase performance in many different areas. Further research and development is warranted to fully realize the potential of this novel and intuitive display technology.

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APPENDIX C: T-34 TSAS Hazard Analysis

HAZARD ANALYSIS RATINGS

HAZARD SERVERITY		MISHAP PROBABILITY	
I	CATASTROPHIC	A	LIKELY TO OCCUR IMMEDIATELY OR WITHIN A SHORT PERIOD OF TIME
II	CRITICAL	B	PROBABLY WILL OCCUR IN TIME
III	MARGINAL	C	MAY OCCUR IN TIME
IV	NEGLIGIBLE	D	UNLIKELY TO OCCUR

HAZARD ANALYSIS

ITEM	HAZARDOUS CONDITIONS	CAUSE	EFFECT	LEVEL	ASSESSMENT	RECOMMENDATION
T-34c aircraft	Aircraft departs controlled flight during maneuvers	VTOS-N1 system malfunction or pilot error	Uncontrollable aircraft	II/C	All maneuvers will be performed within NATOPS limits. Safety pilot takes control when flight information is predicting uncontrolled conditions. "T" connector designed to prevent the N1 system signals from going back into the aircraft system.	Brief this during each prebrief
VTOS-N1 system suit	Subject pilot is restrained during egress	Suit connector does not breakaway from cable connector	Subject pilot cannot egress from aircraft	I/D	Crew systems evaluate breakaway connectors as part of the pink sheet process. Double check connectors after hookup and prior to flight.	Brief this during each prebrief
VTOS-N1 system suit	Subject pilot receiving burns	VTOS-N1 suit fire	Burning of the subject pilot	II/D	N1 system suit is constructed of an approved fire resistant material. The N1 system will have a power switch on the Badger computer. The N1 suit will have quick disconnect.	Brief this during each prebrief
VTOS-N1 system suit	Subject pilot receiving electrical shock	VTOS-N1 system malfunction	Electric shock to subject pilot	IV/D	The N1 system is powered by 9-volt battery and will have a power switch on the Badger computer. The N1 system does not use capacitors for power storage.	Brief this during each prebrief
T-34c aircraft	T-34 gyro signal is interfered or lost	VTOS-N1 system malfunction interfering with aircraft instruments	Loss of primary flight information	II/D	NATOPS emergency procedures. Testing will be conducted under VMC conditions. "T" connector will prevent the N1 system signals from going back into the aircraft system.	Brief this during each prebrief

APPENDIX D: JSF TSAS Hazard Analysis

HAZARD ANALYSIS RATINGS

HAZARD SERVERITY		MISHAP PROBABILITY	
I	CATASTROPHIC	A	LIKELY TO OCCUR IMMEDIATELY OR WITHIN A SHORT PERIOD OF TIME
II	CRITICAL	B	PROBABLY WILL OCCUR IN TIME
III	MARGINAL	C	MAY OCCUR IN TIME
IV	NEGLIGIBLE	D	UNLIKELY TO OCCUR

HAZARD ANALYSIS

ITEM	HAZARDOUS CONDITIONS	CAUSE	EFFECT	LEVEL	ASSESSMENT	RECOMMEND
UH-60 aircraft	Aircraft departs controlled flight during maneuvers	TSAS-NP1 system malfunction or pilot error	Uncontrollable aircraft	II/C	All maneuvers will be performed within limits. Safety pilot takes control when flight information is predicting uncontrolled conditions..	Brief this during each prebrief
TSAS-NP1 system suit	Subject pilot is restrained during egress	TSAS-NP1 connector does not breakaway from cable connector	Subject pilot cannot egress from aircraft	I/D	Crew systems evaluate breakaway connectors as part of the pink sheet process. Double check connectors after hookup and prior to flight.	Brief this during each prebrief
UH-60 aircraft	Subject pilot receiving burns	UH-60 aircraft fire	Burning of the subject pilot	II/D	TSAS-NP1 system vest is constructed of an approved fire resistant material..	Brief this during each prebrief
UH-60 aircraft	UH-60 aircraft signals are interfered or lost	TSAS-NP1 system malfunction interfering with aircraft instruments	Loss of primary flight information	II/D	TSAS-NP1 operates independently of the aircraft system. Except through the AIS. AIS is designed to isolate data to NP-1 and aircraft	Brief this during each prebrief

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14. ABSTRACT Spatial disorientation and the subsequent loss of situation awareness account for a significant percentage of fatal mishaps in aviation. In the aviation environment, the vestibular and somatosensory sensations currently do not provide accurate orientation information. The only reliable source of orientation is vision; when this information is compromised, disorientation occurs. The Tactile Situation Awareness System (TSAS) is an advanced flight instrument that uses the sensory channel of touch to provide situation awareness information to pilots above and beyond visual cues. The TSAS system accepts data from various aircraft sensors and presents this information via tactile stimulators or "tactors" integrated into flight garments. TSAS has the capability of presenting a variety of flight parameter information, including attitude, altitude, velocity, navigation, acceleration, threat location, and / or target location. This report documents a series of flight demonstrations in various aircraft conducted to demonstrate the capabilities of the TSAS systems during flight operations. TSAS, integrated with visual displays and audio systems into a synergistic situation awareness instrument, represents the basis for the next generation human-machine interface for military and commercial aircraft.

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