A Tool to Maintain Spatial Orientation and Situation Awareness for Operators of Manned and Unmanned Aerial Vehicles and other Military Motion Platforms

Angus H. Rupert, Braden J. McGrath
Naval Aerospace Medical
Research Laboratory
51 Hovey Road
Pensacola, FL 32508-1046
USA

Matt Griffin
18th Flight Test Squadron
320 Tully Street
Hurlburt Field, FL 32544
USA

The Naval Aerospace Medical Research Laboratory has developed a Tactile Situation Awareness System (TSAS) that intuitively provides spatial orientation, navigation and threat/targeting information to operators of various military platforms. The TSAS consists of tactile stimulators (tactors) on the torso and limbs of the body that relay processed information from a variety of sensors to the operator.

Since 1992, the advantages of TSAS have been demonstrated in several applications including helicopters, fixed-wing, Unmanned Aerial Vehicles (UAVs), High-Altitude High-Opening (HAHO) parachuting, undersea, and land (1-5). Before any piece of hardware becomes part of the military inventory, the user community conducts operational test and evaluation (OPTEVEVAL) and Operational Utility Evaluations (OUE) to identify strengths, weaknesses, and suitability in a wide variety of operational conditions. These tests also serve to develop concepts of operation.

In the first section of this paper, we will present some of the data collected during an Operational Assessment (OA) of TSAS conducted by the 18th Flight Test of the USAF at Hurlburt Field. In the second portion, we address some of the strengths and weaknesses of TSAS technologies and the improvements made over the past decade.

PART ONE. 18TH FLIGHT TEST DATA

BACKGROUND

TSAS Concept

The TSAS uses the sense of touch to provide spatial orientation and situational awareness (SA) information to pilots and crew members. The system reads data from current aircraft systems, processes it, and then relays designated information using miniature tactile stimulators called tactors. Two types of tactors are currently available: pneumatic and electromagnetic. The pneumatic tactors are comprised of plastic bodies with latex bladders. Air is pulsed through the tactor and felt as a distinct tapping when placed against the body. The electromagnetic tactors have a magnet and electrical coil and, when energized, produce a unique tapping sensation that "feels" different than the pneumatic tactors. The pneumatic tactors are located in a cooling vest; the electromagnetic tactors are located under the thighs and on top of the shoulders.

Hardware

The NP-3 system is comprised of five main subelements: a processor unit, two pneumatic valve sets, an interface control unit, a compressed air source, and two vests. The TSAS processor is a PC-104 computer system in a custom enclosure. The processor interprets the aircraft's 1553 data bus information and generates signals for the pneumatic valves and the electromagnetic tactors. For this test, the processor unit was mounted on an instrumentation rack. The valve sets regulate compressed airflow to the tactors. For

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

the flight, one valve set was mounted on the right-hand seat. For the simulator sessions, valve sets were mounted on the pilot, copilot, and flight engineer seats. The interface unit is a commercial off-the-shelf (COTS) Panasonic ruggedized computer used to control various TSAS mode functions. While the final configuration for an air source in aircraft has not been determined, for this test, a COTS SCUBA tank was used. Both the interface unit and the compressed air source were mounted on an instrumentation rack. The vests are YF-22 cooling vests modified with 24 pneumatic tactors and 4 electromagnetic tactors each. Figures 1 and 2 show an early prototype of the TSAS vest. The pneumatic tactor-line umbilical, electromagnetic umbilical, and ventilation air hose terminate in quick-disconnect connectors.

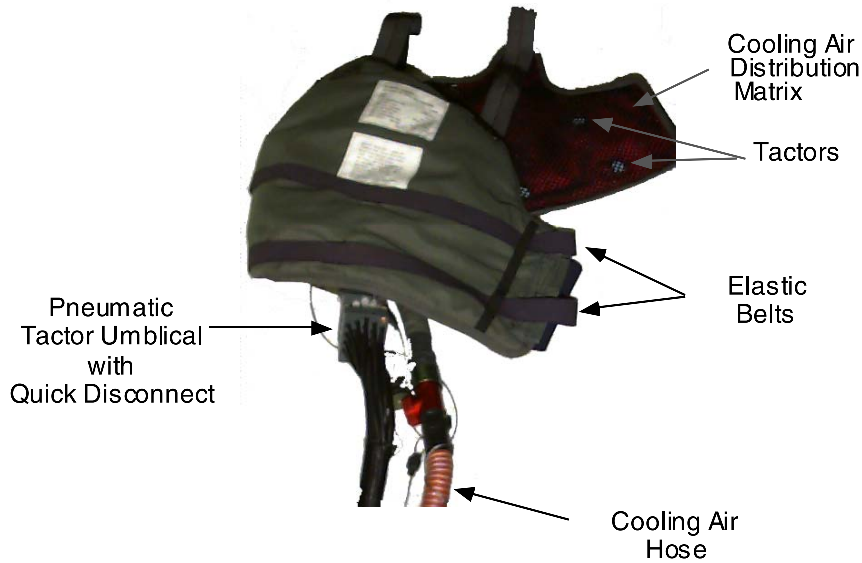

Figure 1. TSAS Vest

Figure 2. Wearing the TSAS Vest

The TSAS is designed to enhance SA by providing cues to the pilots. Current applications include hover cues and terrain following/terrain avoidance (TF/TA) climb, dive, and steering cues. The crew can follow the TSAS directions or refer back to the aircraft instruments. The system can be set up to provide hover cues automatically below a set airspeed. In this configuration, the system provides indications of lateral, longitudinal, and vertical deviations during a hover. The hover configuration frees the crew to operate other aircraft systems rather than visually monitoring aircraft hover cues. During TF/TA operations, the TSAS echoes the climb/dive command cues the crews receive on current instruments. The TF/TA configuration allows the crews to focus on other tasks. Additional applications include lateral steering, flight director guidance, and threat warning indications. While the system was demonstrated to work independently of existing aircraft visual instruments, it is not intended to entirely replace visual stimuli.

METHOD

The TSAS prototype was tested using the CV-22 simulator and flight testing in an MH-53M helicopter. Testing in the simulator compared flight performance with and without TSAS. Time constraints caused the test team to eliminate vertical cues from this portion of the test. Therefore, to maintain consistency in results, vertical cues are not presented in this report. Lateral and longitudinal velocity errors were combined to produce a single velocity error. Most suitability issues were addressed by discussions with aircrews on integrating the TSAS with aircraft systems and missions. Due to aircraft availability and the bulkiness of the new body armor, TSAS was not tested in flight with body armor. The TSAS was tested for 25 simulation hours on 8-9 Jun, 8-10 Aug, and 12-13 Oct 2000 at the CV-22 simulator at Bell Helicopter Plant 1, Hurst, Texas. MH-53M flight tests were limited to three missions, and were flown at Hurlburt Field and Eglin Range on 16, 17, and 22 Nov 2000 for 6.9 flight hours.

Simulator Testing

TSAS was integrated into the CV-22 simulator at Bell Helicopter Plant. Aircrews used TSAS in the fixed-point mode and general hover modes. For fixed-point mode, the tactile cues keyed the pilots to fly the aircraft within a box around a specific geo-referenced point based on aircraft position. To evaluate this mode, the crew flew a simulated fast rope insertion to a specific point on the ground. For the general hover mode, TSAS provided hover cues based solely on aircraft velocities to establish a good hover regardless of location. In hover mode, the crew duplicated the maneuvers found in Table 1 during day and night visual meteorological conditions. The TSAS processor unit, which monitors the aircraft navigation system, recorded flight information for post-mission analysis. A direct comparison was made between errors with and without TSAS. The crew was also surveyed to evaluate and comment on the effectiveness/ compatibility of using TSAS during hover operations with good hover cues (day) and limited hover cues (night). The survey used a scale from 1 (very ineffective) to 4 (very effective). The test team measured the percentage of positive responses (a score of 3 or 4). When time permitted, aircrews also evaluated other applications of TSAS such as TF climb/dive commands, lateral steering cues, and flight director guidance for instrument approaches. Initial simulator testing was not successful in capturing quantitative data. Subsequent simulator tests included very little time on controlled hover operations like those in Table 1, focusing instead on more realistic missions. During testing, aircrew members quickly adapted to the lateral and longitudinal cues from the vest, but they took additional time to learn the vertical cues. Also, only the general hover mode was analyzed due to difficulties in data retrieval. Unlike the flight data, which compared "TSAS Off, Hover Displays On" to "TSAS On, Hover Displays Off," the simulator data are presented as "TSAS On" versus "TSAS Off" for both visual situations (On and Off). The difference is due to the lack of additional motion and extra visual cues in the real world that are not available in the simulator.

Table 1. Standard Hover Maneuvers

Task	Maneuver	Time[a]	AGL[b] (ft)
1	Stationary in ground effect (IGE) hover	120 s	10
2	Left 180° hovering turn	Hover 20s after	10
3	Longitudinal 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	Stationary out-of-ground effect (OGE) hover	120 s	100
8	Longitudinal hover for 100 ft	Hover 20s after	100
9	Rearward hover for 100 ft	Hover 20s after	100
10	Right 180° hovering turn	Hover 20s after	100
11	Left sideward hover for 50 ft	Hover 20s after	100
12	Right sideward hover for 50 ft	Hover 20s after	100
13	Stationary hover	20 s	10
14	Land		

[a] Amount of time to maintain stable hover after completion of maneuver
[b] Above Ground Level

Flight Test

During the flight test, pilot and copilot duplicated the hover maneuvers from the CV-22 simulator portion of the test (Table 1). Due to safety considerations, all tasks were performed at 100 ft above ground level (AGL) rather than those listed in the Table. The simulated shipboard takeoff was not tested because of time constraints and aircraft availability. The first and second flights were flown during daylight over water 5 miles off shore to minimize outside visual cues. The third flight occurred over land at night using night vision goggles. The test environment had minimal to no outside visual cues, especially at night. The TSAS processor unit, which acquires 1553 bus data, recorded flight information for post-mission analysis. A direct comparison was made between errors with and without the TSAS. The crew also completed surveys to evaluate and comment on the effectiveness/compatibility of using TSAS during hover operations. The survey uses a scale from 1 (very ineffective) to 4 (very effective). The test team measured the percentage of positive responses (a score of 3 or 4). All quantitative data were reviewed after each mission; however, only the data from Table 1, tasks 1 and 7 were used for performance measures. Test conditions involved "TSAS Off, Hover Displays On," which is the current method of flight, and "TSAS On, Hover Displays Off." The latter method tests a worst-case scenario for TSAS in which TSAS and outside visual cues were the only input the pilot had to maintain a stable hover. The "displays" refer to the hover cues available on visual instruments. The lateral and longitudinal velocity errors were averaged to produce a combined velocity error.

RESULTS

The USAF 18th Flight Test (FLTS) was tasked to perform an Operational Assessment to answer a critical operational issue: Does TSAS show the potential to improve aircrew performance?

Critical Operational Issue

The answer to the question, “Does the Tactile Situational Awareness System show the potential to improve aircrew performance?” is YES. Three out of three measures of effectiveness (MOEs) met criteria. TSAS was evaluated during three different sessions at the CV-22 simulator and on three flights on an MH-53M. In both cases, analysis of hover errors (measured in velocity) improved with TSAS usage. Additionally, aircrew ratings indicated TSAS was effective in reducing aircrew workload and increasing SA. Aircrew members who used TSAS agreed it was effective in the applications tested.

Measures of Effectiveness 1

Aircrew Hover Performance in Flight and Perceived SA. Criteria: Both performance and SA must improve with TSAS usage. MET CRITERIA. One out of four measures of performance (MOPs) met criteria, while the remaining three MOPs had no significantly measurable evaluation criteria. Quantitative data recorded during flight showed hover performance, measured as drift velocity, improved significantly with TSAS usage. Aircrew members agreed unanimously that TSAS was effective, and it reduced workload and improved SA.

Vertical, Lateral, and Longitudinal Errors During Hover Maneuvers Measured in Distance and Velocity. Criteria: Hover performance (holding a stable hover) improves with TSAS usage. MET CRITERIA. The average hover performance improved with TSAS usage as shown in Table 2. The fourth pilot in Table 2 did not show a significant difference with TSAS on or off during the initial hover checks. The test team did observe that pilot 4 became fatigued after an hour of hovering. Thus, pilot 4’s performance diminished without TSAS but improved with TSAS. This result warrants further investigation into the benefits of TSAS during long missions. Overall, pilots using TSAS were able to spend more time “outside the cockpit,” thus improving their overall SA. The quantitative data presented in Table 2 are for the 2-min stabilized hover from Table 1, tasks 1 and 7. Figure 3 shows a summary of the average velocity errors for each pilot and an overall average.

Table 2. Flight Test Velocity Errors

Pilot	TSAS On, Displays Off			TSAS Off, Displays On			Significantly Different?
	Mean	Stdev	N	Mean	Stdev	n	
Overall[a]	2.3109	1.2352	657	2.4762	1.5014	679	Yes
Pilot 1	2.0861	1.1293	140	2.5213	1.2917	140	Yes
Pilot 2	1.9509	1.0517	279		no data		N/A
Pilot 3	2.7314	1.2728	255	2.9512	1.7557	274	Yes
Pilot 4	2.0218	1.1380	262	1.9613	1.1052	265	No

[a] Does not include pilot 2

Aircrew Ratings of TSAS Effectiveness. Criteria: None. Sample size does not allow for statistically significant results. Five aircrew members evaluated TSAS effectiveness over the course of three flights. All rated the system as 4 (very effective). Several pilots commented that the cues were accurate, timely, and easy to interpret.

Aircrew Rating of TSAS’ Ability to Reduce Workload. Criteria: None. Sample size does not allow for statistically significant results. Five aircrew members rated the ability of TSAS to reduce workload as 4 (very effective). One pilot wrote, "the system definitely helped to reduce workload. The TSAS allowed me to divert my attention to other tasks." Another added, "[TSAS] reduced my workload tremendously!! TSAS enabled me to decrease my cockpit scan to altitude and heading control only. Felt like second nature to rely on drift corrections from TSAS."

Aircrew Rating of TSAS' Ability to Improve SA. Criteria: None. Sample size does not allow for statistically significant results. Five pilots evaluated TSAS' effectiveness over the course of three flights. All rated the system as 4 (very effective) for improving SA. One pilot commented that he "would get TSAS inputs before [he] could recognize drift visually."

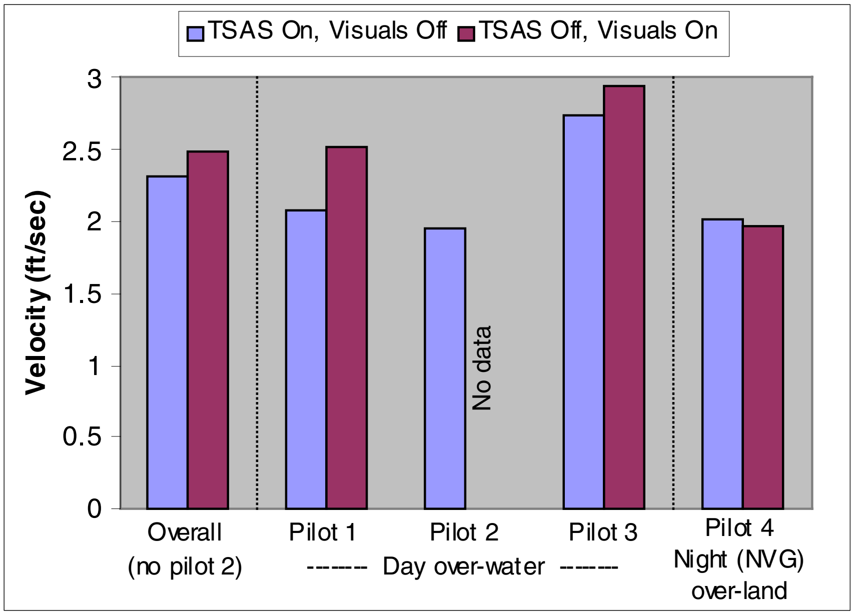

Figure 3. Flight Test Velocity Errors

Note: The average value does not include pilot 2 because all data could not be collected for that pilot due to an aircraft malfunction.

Table 3. Simulator Velocity Errors – Hover Displays On

Pilot	TSAS On			TSAS Off			Significantly Different?
	Mean	Stdev	n	Mean	Stdev	n	
IGE (10 ft)							
Overall*	0.7824	0.4367	8004	0.9650	0.6298	8004	Yes
Pilot 1	0.8536	0.4837	2001	1.5387	0.6546	2001	Yes
Pilot 2	0.6980	0.2569	2001	0.9213	0.4332	2001	Yes
Pilot 3	0.6386	0.3357	2001	0.7680	0.6156	2001	Yes
Pilot 4	0.9393	0.5414	2001	0.6320	0.3335	2001	Yes
OGE (100 ft)							
Overall	1.0620	0.6825	14007	1.2386	0.9687	14007	Yes
Pilot 1	1.1861	0.7923	2001	1.4428	0.9436	2001	Yes
Pilot 2	0.9795	0.4419	2001	1.3642	1.0852	2001	Yes
Pilot 3	0.8200	0.3308	2001	0.8201	0.4042	2001	No
Pilot 4	1.0412	0.6067	2001	1.3228	0.7604	2001	Yes
Pilot 5	0.8127	0.3100	2001	0.8203	0.3560	2001	No
Pilot 6	0.8998	0.4355	2001	0.7904	0.4342	2001	Yes
Pilot 7	1.6950	1.0513	2001	2.1099	1.4391	2001	Yes

Note: Table 3 lists the average, standard deviation (Stdev), and sample size of velocity errors (n) for both test conditions.

Measures of Effectiveness 2

Aircrew Hover Performance in the CV-22 Simulator. Criteria: Hover performance must improve with TSAS usage. MET CRITERIA. Two out of two MOPs met criteria. Quantitative data recorded during simulator sessions suggest hover performance measured as drift velocity improved significantly with TSAS usage. Additionally, qualitative data based on survey responses showed aircrew members agreed unanimously that TSAS was effective for improving hover performance.

Vertical, Lateral, and Longitudinal Errors During Hover Maneuvers Measured in Distance and Velocity. Criteria: Hover performance (holding a stable hover) improves with TSAS usage. MET CRITERIA. Overall, hover performance improved in all four test conditions. Tables 2 and 3 list the detailed values producing the figures. Figures 4 and 5 show a summary of the average velocity errors for each pilot (right side) and an overall average (left side) for both test conditions. The data show TSAS improved hover performance in seven-of-nine scenarios with "Hover Displays On" (Table 3 and Figure 4) and four-of-four scenarios with "Hover Displays Off" (Table 4 and Figure 5).

Table 4. Simulator Velocity Errors – Hover Displays Off

Pilot Performance	TSAS On			TSAS Off			Significantly Different?
	Mean	Stdev	n	Mean	Stdev	n	
IGE (10 ft)							
Overall	1.1256	0.6950	6003	1.5220	0.9767	6003	Yes
Pilot 1	1.5623	0.7686	2001	1.5485	0.8268	2001	No
Pilot 2	1.1668	0.5683	2001	2.2061	1.0441	2001	Yes
Pilot 3	0.6478	0.3390	2001	0.8112	0.3382	2001	Yes
OGE (100 ft)							
Overall	2.4035	1.3363	6003	2.6162	1.4274	6003	Yes
Pilot 1	3.0624	1.2424	2001	3.3093	1.8058	2001	Yes
Pilot 2	2.7573	1.3784	2001	2.7876	1.0638	2001	No
Pilot 3	1.3909	0.5740	2001	1.7517	0.6811	2001	Yes

Note: Each table lists the average, Stdev, and number of velocity errors (n) for both test conditions.

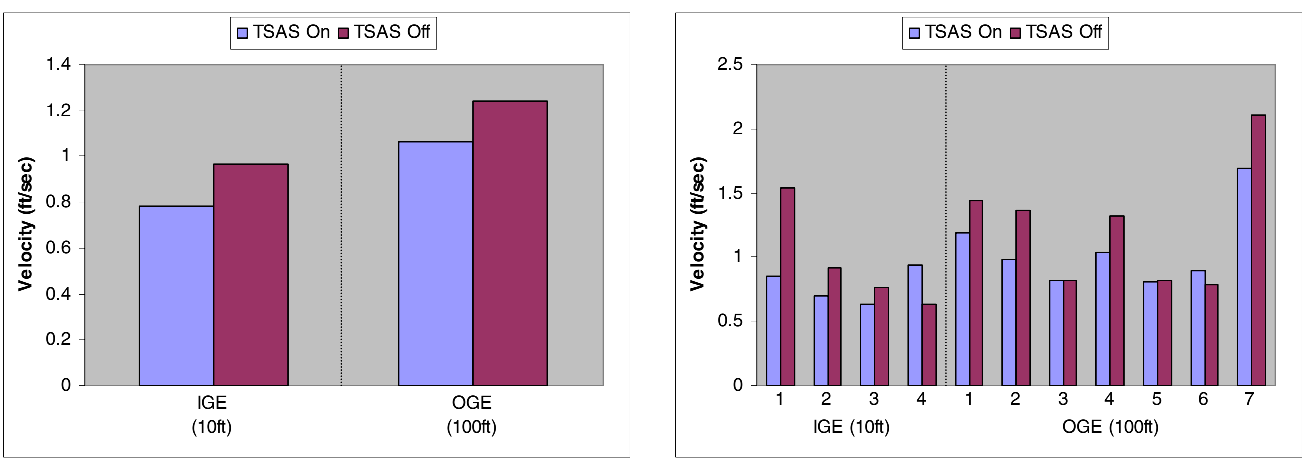

Figure 4. Simulator Velocity Errors – Hover Displays On

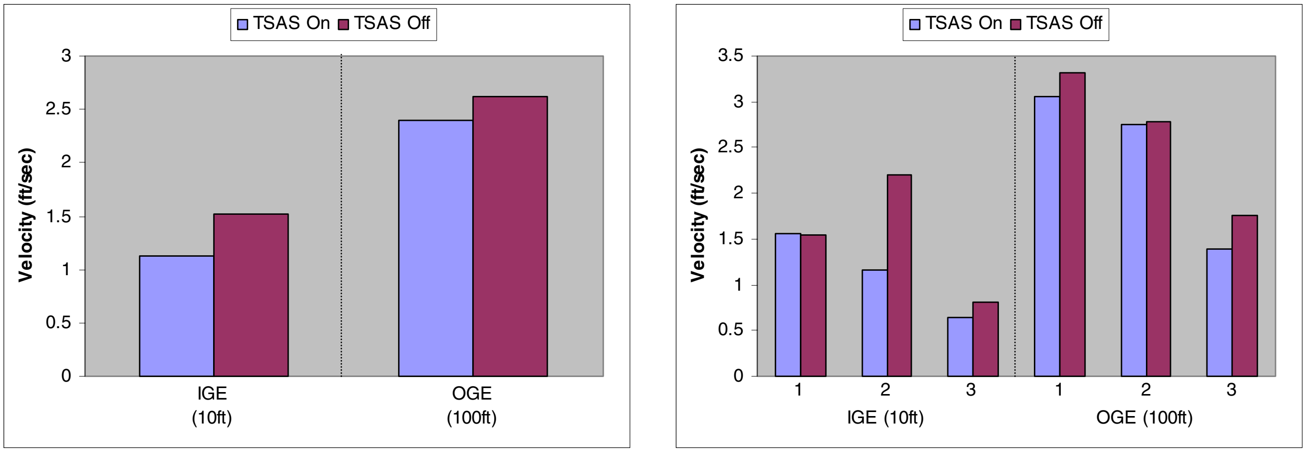

Figure 5. Simulator Velocity Errors – Hover Displays Off

Aircrew Ratings of TSAS' Effectiveness. Criteria: Eighty percent responses must be rated 3 (effective) or better. MET CRITERIA. A total of nine pilots and three flight engineers evaluated TSAS' effectiveness over the course of three sessions at the CV-22 simulator (some of the pilots attended more than one session). All rated the system as 3 (effective). Several pilots commented that the cues were accurate, timely, and easy to interpret. Pilot 5 stated, "even though the inputs were the opposite of what was expected, a comfort level was obtained within 15 minutes." Despite the positive ratings, the majority of pilots said they did not like the shoulder cues, which indicated the aircraft was above a set altitude. Vertical cueing consisted of electromagnetic tactors placed on the pilot's shoulders for down vertical cueing and under the thighs for up vertical cueing. If the aircraft were higher or lower than set altitudes, the tactors would activate telling the pilot to move the aircraft up or down. No crewmembers liked the down vertical cueing, but most liked the up vertical cueing. Further TSAS testing was recommended using vertical cueing to see if there is added value for using this feature

<u>**Measures of Effectiveness 3**</u>

Aircrew Ratings of TSAS' Potential for Use in Other Aspects of the CV-22 Mission. MET CRITERIA. Three out of four MOPs met criteria. During the second two simulator sessions, TSAS was used to provide cues for TF climb/dive commands, tactical lateral steering guidance, flight director guidance for instrument approaches, and threat information. With the exception of tactical lateral steering guidance, aircrew members considered all TSAS modes effective. They particularly liked the threat information.

Aircrew Rating of TSAS' Effectiveness for Cueing TF Climb/Dive Commands. Criteria: Eighty percent of the responses must be rated 3 (effective) or better. MET CRITERIA. Cueing for TF climb/dive commands was only evaluated in the last two simulator sessions. There were seven pilots and three flight engineers, with two of the pilots attending both sessions for a total of 12 responses. Only one pilot rated the system 2 (ineffective). All others (92%) rated the TF climb/dive commands as 3 (effective) or better. The one pilot who disagreed rated the system as effective during the first simulator session but did not like the dive cue; however, the pilot did state, "TF climb cue is very effective." In the second session, this pilot said the TSAS cues were a triple redundant input already provided by visual and audio cues. The majority of other aircrew members had similar comments about climb versus dive, but they seemed to like the cues. The flight engineers in particular liked the system because it "allows heads down CDU/EICAS (Control Display Unit/Engine Indication and Crew Alert System) work." They recommended that further TSAS testing with threat awareness information be conducted due to the high potential for timely crew threat information. Another flight test recommendation was for each aircrew position to have independent TSAS controls and settings for sensitivity/mode/frequency. Each aircrew position should be configured when the pilots are planning flight/mission profiles. These data should be down loaded to the mission computer and controlled through the CDU for further changes as the mission progresses.

Aircrew Rating of TSAS Effectiveness for Cueing Lateral Steering Guidance Back to Course. Criteria: Eighty percent of the responses must be rated 3 (effective) or better. DID NOT MEET CRITERIA. Cueing for lateral steering guidance was evaluated in the last two simulator sessions. There were 7 pilots and 3 flight engineers, with 2 pilots attending both sessions for a total of 12 surveys, but only 7 evaluated lateral steering guidance. Of the seven surveys, five (71%) rated the lateral steering guidance as 3 (effective). One of the two surveys stating the guidance was ineffective came from pilot 1 who said it was effective in the first simulator session. Even those who said the cues were effective commented they were not needed. Further TSAS testing was recommended for cueing lateral steering guidance back to course to see if there is added value for this feature.

Aircrew Rating of TSAS' Effectiveness for Cueing Flight Director Guidance (ILS/VOR). Criteria: Eighty percent of the responses must be rated 3 (effective) or better. MET CRITERIA. Cueing for flight director guidance was only evaluated in the last two simulator sessions. There were 7 pilots and 3 flight engineers, with 2 pilots attending both sessions for a total of 12 surveys, but only 7 evaluated flight director guidance. Only one pilot rated the system as 2 (ineffective). All others (86%) rated the flight director guidance (ILS/VOR) commands as 3 (effective) or better. Aircrew members liked the cueing for flight director guidance and rated it an "excellent tool for ILS approach" and "excellent for IMC approaches." The flight test recommended TSAS cueing be used for all aircrew during all phases of hover/flight so the crew will not be confused between cues and command guidance. Cueing is defined as aircraft trend information (tap on left indicates aircraft is moving left), command guidance tells the aircrew where to move the flight control (tap on left, move flight control to the left).

Aircrew Rating Of TSAS' Potential for Providing Other 1553 Data Bus Information via the Sense of Touch. Criteria: Eighty percent of the responses must be rated 3 (effective) or better. MET CRITERIA. A total of nine pilots and three flight engineers evaluated TSAS effectiveness over the course of three sessions at the CV-22 simulator (some pilots attended more than one session). All pilots rated the system as 3 (effective) or better for providing 1553 data bus information. By far, the most common suggestion was to include threat information with TSAS. This was tested during the second simulator session with great success. The flight test recommended further exploration of the data on the 1553 data bus that can be used by the TSAS to enhance aircrew SA.

ADDITIONAL FINDINGS AND RECOMMENDATIONS

TSAS has the potential to provide noncockpit crewmembers on the MH-53M with threat awareness information and aircraft position. This could be provided with electromagnetic tactors receiving a signal from a wireless data link from the processor unit. We recommend using TSAS for noncockpit crewmembers on the MH-53M for threat awareness information and aircraft position.

TSAS has the potential to provide air-conditioned and heated air for aircrew comfort. Our recommendation is that air-conditioned and heated air be used in the TSAS vest for pilot comfort and to reduce fatigue over long missions.

TSAS has the potential to assist Special Tactics Forces during air and ground navigation. We recommend a modified self-contained version of TSAS for night operations during high-altitude low-opening/high-altitude high-opening (HALO/HAHO) under canopy navigation and ground navigation for Special Tactics Forces.

Unmanned aerial vehicle (UAV) operators maintain SA by referencing monitor displays on a ground control station or an individual control unit. Relevant platform telemetry data and a forward look-ahead view from the platform are depicted while a second display shows payload perspective. When in manual control of the platform, the ability to sense platform movements or irregularities in flight is visual, making approaches and landings challenging. A TSAS interoperability test with UAVs could be conducted to gather human factors for the necessary sensory inputs during crucial phases of flight information with future UAV systems. We believe that future testing should be conducted on TSAS for interoperability with UAV operators and related systems.

TACTICAL CONSIDERATIONS

The TSAS can be programmed to relay any information on the 1553 data bus to the crew via the sense of touch. New tactics may be needed to take advantage of the TSAS. One example is changing the instrument scan pattern for the aircrew. Because TSAS provides the same information as the instruments, the crew can spend more time looking outside the aircraft or performing other duties and only referring back to instruments when TSAS indicates the aircraft has deviated from the intended position or course. Potential application for TSAS includes steering cues, TF/TA, land/water rescue, missile warning/tracking, target tracking, low-altitude warning, and ground collision avoidance system.

CONCLUSIONS AND RECOMMENDATIONS FROM 18th FLIGHT TEST

TSAS improves aircrew SA, reduces aircrew workload, and demonstrates potential suitability for the AFSOC mission. The prototype TSAS, in its conception phase, is not operationally suitable for the AFSOC mission; however, with further refinement and continued testing, it can become an effective aircrew aid during critical phases of flight.

Specific Enhancing Characteristics

Some of the TSAS' potential applications were explored in the CV-22 simulator during tactical mission profiles. One of the most promising uses for TSAS involves missile warning/tracking cues combined with TF climb/dive inputs. The missile warning inputs came from the missile-warning receiver. The TSAS vest provided excellent threat SA to the crew through the use of variable frequency directional inputs. Search radar would induce a very low frequency directional tactile input to the crew while changes to higher threat lethality states resulted in higher frequency inputs. A missile launch indication would give the crew a very high frequency "buzz," indicating immediate action required. Combined with the vertical cueing from the TF radar, missile warning cues gave the crew excellent SA on the threat situation as well as excellent terrain awareness.

Specific Deficiencies

None

SPECIFIC RECOMMENDATIONS

Recommend further TSAS testing using vertical cueing to see if there is added value for using this feature.

Recommend further TSAS testing with threat awareness information due to the high potential for timely crew threat information.

Recommend each aircrew position have independent TSAS controls and settings for sensitivity/mode/frequency. Each aircrew position should be configured when the pilots are planning flight/mission profiles. These data should be downloaded to the mission computer and controlled through the CDU for further changes as the mission progresses

Recommend further TSAS testing for cueing lateral steering guidance back to course to see if this feature adds value.

Recommend TSAS cueing be used for all aircrew during all phases of hover/flight so the crew will not be confused between cues and command guidance. Cueing is defined as aircraft trend information (tap on left indicates aircraft is moving left), command guidance tells the aircrew where to move the flight control (tap on left, move flight control to the left).

Recommend further exploration of the data on the 1553 data bus that can be used by the TSAS to enhance aircrew SA.

PART TWO. TSAS TECHNOLOGY & APPLICATIONS UPDATE

The TSAS has been tested in a wide variety of applications and environments since 1991. Each successive version resulted in further refinements to produce a system that is now ready for use by military and civilian communities. The advances have been made in five areas: Tactile Stimulators (Tactors), Power Source(s), Tactor Locator System(s) (TLS), Software Control Systems, and Devices to Test Integration.

The presentation of tactile information has varied from simple, point-source single tactors, to complex collections of tactors to provide two or more types of information simultaneously or to provide "flow" information over large portions of the torso and limbs. An example of problems encountered during testing with an early prototype that has resulted in improvements is that of flow sensations. The presentation of flow requires several tactors activated in specific patterns. We first used flow to provide the sensations of whole-body rotation or moving linearly (horizontally or vertically) at various velocities when the 8 x 5 matrix in a torso suit became available in 1991. When the rings were activated sequentially, this suit could provide sensations of "up" or "down" movement. The value of this sensation was later tested on the H-60 motion-based simulator at the US Army Aeromedical Research Laboratory in Ft Rucker Alabama. Although the test pilots approved the vertical flow sensation as an effective means to nonvisually maintain altitude, it was not possible to present other information at the same time and thus not used in-flight. This testing however, revealed several deficiencies in the state of the art, as it existed in 1995, including the need for several things: tactor locator systems that could provide a larger array of improved tactors, held at the optimal pressure against the skin; a control system that had minimal delays to permit real time user interaction with motion based platforms or simulators; and perhaps most importantly, tactors that could be controlled accurately in the frequency, amplitude and waveform dimensions and which were instrumented to provide feedback of the stimulus parameters delivered to the skin. Although flow patterns were impossible to demonstrate, meaningful tactile research was futile without full awareness and control of the tactile stimulus. The advances made over the past 10 years have now provided the current TSAS laboratory system with the required controls and feedback.

TACTILE STIMULATORS

The first tactors used for TSAS tests were COTS products such as Tactaids, small vibrators and miniature speakers. The primary weakness of these early tactors was an inadequate stimulus amplitude to produce a robust sensation in the noisy, high-vibration environment found in aircraft.

In 1995, the US Navy sponsored--under a combination of the Advanced Technology Demonstration program and the Small Business Innovative Research (SBIR) program--several companies to advance the development of a wide variety of novel tactors. Tactor development suffered from an inability to compare the effectiveness of one tactor with another due to a lack of standard psychophysical measures for touch sensation. Initially, one commercially available tactor was picked as a "standard" against which to compare other tactors until the Navy established an in-house psychophysics laboratory to evaluate new tactors as they were developed.

The ideal tactor can be controlled in frequency, amplitude, and waveform over the biological useful ranges. It should be small, rugged, waterproof, and lightweight and provide indentation and tangential "stroke" stimuli. It is instrumented to provide feedback, has no electromagnetic or acoustic signature, requires little power, and is inexpensive. Unfortunately, it does not yet exist. The tactors used for a given application must be selected from what is currently available, or a customized new design is required.

An SBIR-developed waterproof electromechanical tactor that we used for underwater applications was found to provide excellent stimuli for diving applications. Unfortunately, for obvious reasons, the Explosive Ordinance Demolition (EOD) community could not use a tactor with appreciable acoustic or magnetic signatures. This tactor in the nonwaterproof form has, however, found application in the aviation community.

The pneumatic tactor developed under a request from the Joint Strike Fighter Program has proven to be very rugged, relatively cheap, and lightweight. It has a small acoustic but no magnetic signature, produces a wide range of frequency and amplitude stimuli, and is the best all-round tactor for aviation applications currently available. This tactor has been used by NAMRL for the past 6 years. A weakness in this pneumatic tactor for laboratory applications is related to the use of air, a compressible gas, which results in a lack of fidelity of transmission of the stimulus parameters delivered at the pump compared to the stimulus reaching the skin. Many of these difficulties are resolved with our in-house hydraulic tactors.

Another solution to the problem of defining the stimulus delivered to the skin is the use of instrumented tactors or placing a pressure sensor on the skin close to the tactor which records the transmitted energy the tactor is providing. The cost and complexity of instrumented tactors make large arrays very expensive.

Considerable room exists to improve tactors, and the field is wide open for a tactor that will provide a well-controlled, tangential "stroking" stimulus.

Power Sources

Power sources were designed for both laboratory investigation systems as well as smaller, more robust systems for mobile platforms. The development of power sources for tactors was complicated by the need to accommodate more than one type of tactor simultaneously. For example the current lab system drives large combinations of 96 pneumatic, hydraulic, and electrical tactors simultaneously.

An in-house developed motor is used to drive the laboratory pneumatic and hydraulic systems. The mobile pneumatic system, such as the unit described in Part One, used compressed air bottles as the power source and a series of valves to control individual tactors.

Software Controls

The NAMRL TSAS laboratory systems are designed to provide maximal control of the tactile stimulus for scientists to develop algorithms used in the optimization of the stimulus pattern for a given application. Each of the 96 tactors is under separate frequency, amplitude, and waveform control. It is important for closed-loop control of dynamic platforms that the combination of software controls and power sources has minimal delay between sensor information and the time the stimulus providing the sensor information is relayed to the skin. In visual systems, 50-ms delays are annoying and detract from performance. The NAMRL TSAS system was designed to have no more than 1-ms delay in delivery of electromechanical stimuli and 2 ms for pneumatic and hydraulic stimuli. These delays are so minimal as to be lost in the "noise" of the biological system.

The Graphical User Interface (GUI) is important especially when there are large numbers of tactors, each of which can be controlled in frequency, amplitude, and waveform. The GUI includes a visual display of the body and limbs with each tactor represented and user-selected groupings of tactors to facilitate use of the TSAS lab system by researchers not fluent in C programming.

Tactor Locator System

Perhaps the most difficult technical challenge for the TSAS engineering team has been developing a garment that will maintain a large variety of tactors with different pressure requirements for optimal performance against the skin with the correct pressure(s) while the user is in motion. The initial prototypes used thin diving wet suits or other snug-fitting sport garments made of Lycra type materials with additional straps to maintain tactors in the appropriate location with the optimal loading characteristics. Flight-capable systems, even for testing of prototypes, had to be constructed of fire-retardant stretch Nomex to meet safety requirements.

An early breakthrough was the F-22 prototype cooling garment. This snug-fitting heating/cooling vest proved to be the ideal flight-approved garment that, in addition to providing the appropriate pressures to a restricted area of the torso, also serendipitously offered climate control of the skin as well as lumbar support for pilots. The primary drawback of the F-22 vest is that it cannot be modified to apply tactors on the upper torso and/or proximal limb. Full-torso coverage is necessary to provide the most intuitive awareness of targeting and complete pitch-and-roll coverage for fixed-wing applications including remote control of unmanned vehicles operating in three dimensions.

Through a combination of in-house development and SBIRs, we now have a variety of prototype suits with full torso and proximal limb coverage, in which it is possible to selectively control the pressures the tactors exert against the skin. NAMRL has developed a suit evaluation box (SEB) to measure the variables of concern in prototype suits. The variables include humidity and temperature in more than one area and pressure in 12 locations.

Another technical problem to be addressed for military applications is the need for TSAS compatibility with the current suits that provide chemical and biological warfare (CBW) protection. Integration of electromechanical tactors with CBW suits does not pose a problem, but the complexities of interfaces with pneumatic and hydraulic tactors will require further engineering development.

Test Devices

In early stages of TSAS development in 1989, we recognized that a collection of man-rated acceleration devices would be required to optimally integrate the tactile display system with other sensory information systems including visual displays and 3-D sound displays. Visual and aural perceptual illusions of target location occur when humans are exposed to significant linear or angular acceleration as occur on current aviation platforms. Research on visual, tactile, or 3-D sound systems can be conducted virtually anywhere, but to investigate the effects of sensory interaction in acceleration environments requires man-rated devices capable of providing linear and or angular acceleration and the appropriate visual/tactile/aural cues. To that end, the Navy Bureau of Medicine has built the Visual Vestibular Sphere Device (VVSD) (Figure 6).

The VVSD is a 12-foot diameter sphere capable of rotating up to 30 RPM about any axis between the earth vertical and horizontal. The occupant can be stationary or rotated independently about an axis collinear with the sphere in the same or opposite direction. The VVSD is being used to investigate the interaction of tactile stimuli with visual and aural displays in a dynamic angular motion environment. Other NAMRL devices with less compelling visual displays are available when it is necessary to conduct sensory integration tests requiring linear or combined linear and angular acceleration (6).

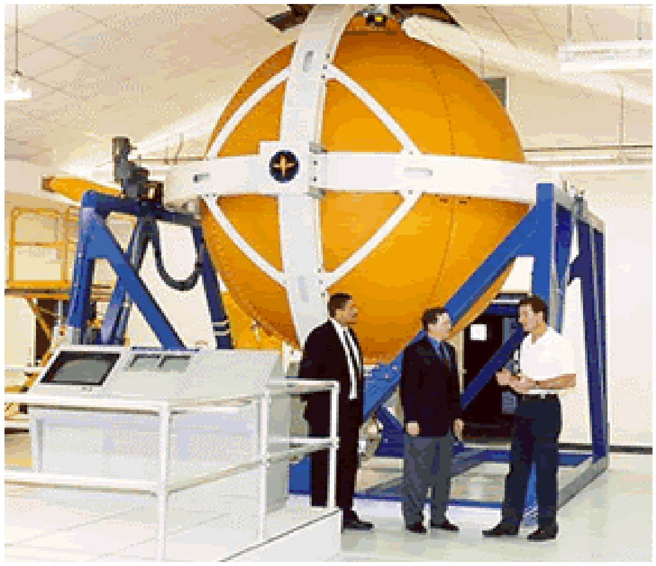

Figure 6. Visual Vestibular Sphere Device (VVSD)

APPLICATONS

The original military requirements pushing the development of TSAS were the loss of SA and disorientation problems experienced most dramatically in aerospace and diving communities and secondarily in ground forces. Spatial disorientation occurs in the aviation environment, in large part, due to false information provided by the inner ear and skin-muscle-joint systems as to the direction “down.” In space, there is no “down” nor sense of down provided by the proprioceptive systems. On the ground, the information is generally accurate except in the case of sensory compromised individuals, especially the aged. TSAS can serve as a prosthesis in all these conditions.

From a theoretical perspective, the most difficult of the above sensory conditions for which to provide a solution is the aviation environment. In this condition, not only is the sensory information provided by vestibular and somatosensory systems frequently wrong, it is also concordant between these systems, and hence the orientation illusions are most compelling when visual clues are lost due to distraction or diversion of visual attention of the operator from visual orientation cues. In space, there is simply an absence of information, and on the ground the sensory information is usually merely degraded. For these reasons, validation of TSAS as a balance prosthesis in the aviation environment where the sensory condition is most challenged, argues well for its value to counter the relatively easy sensory deficit condition in space and the trivial condition of clinical terrestrial imbalance.

We have used TSAS successfully as a balance prosthesis in the aviation and terrestrial environments. Multiple test flights in a variety of platforms by all the services have demonstrated TSAS effectiveness. On the ground, NAMRL researchers have effectively used TSAS to provide subjects with an intuitive prosthesis to maintain balance during laboratory-induced acute vestibular defects. Although the aviation prosthesis was the most challenging from a sensory perspective, it was the easiest from a technical point of view because reliable, accurate sensors already exist (i.e., aircraft attitude instruments), and the platform (plane or helicopter) is relatively stable. Alternatively, the theoretical trivial terrestrial sensory condition poses a most difficult technical problem, namely designing a sensor and algorithm that will consistently provide fall prediction with very few errors in a highly unstable platform (human). The penalty for design error would be a fall that in the elderly frequently leads to a broken hip and subsequent demise.

CONCLUSIONS

1. TSAS is an effective prosthesis for sensory compromised individuals whether they are pilots, astronauts or patients suffering balance disorders.

2. As shown by operational assessment, TSAS is an effective tool for improving situation awareness and reducing workload in the high tempo military environment.

3. TSAS should be incorporated into helicopter platforms to reduce brownout and whiteout mishaps.

4. Improvements to TSAS should be focused on (a) the development of new tactors to include stroking tangential tactile stimulators and (b) garment technologies that will provide consistent tactor contact over the full torso and proximal limbs.

REFERENCES

1. Rupert AH, Guedry FE, Reshke MF (1994, 18-22 Oct) *The Use of a Tactile Interface to Convey Position And Motion Perceptions. In Virtual Interfaces: Research And Applications.* Lisbon, Portugal. AGARD CP-541, Neuilly Sur Seine, France: Advisory Group for Aerospace Research and Development, pp. 20-11 to 20-75.

2. Rupert AH, Mateczun AJ, Guedry FE (1990) Maintaining Spatial Orientation Awareness. In *Situation Awareness In Aerospace Operations,* Copenhagen, Denmark, AGARD CP-478. Neuilly Sur Seine, France: Advisory Group for Aerospace Research and Development Conference Proceedings, 478:2-1 to 2-15.

3. Rupert AH (2000, Mar-Apr) An Instrumentation Solution for Reducing Spatial Disorientation Mishaps. *IEEE Engineering in Medicine and Biology,* 19 (2), 71-80.

4. Chiasson, J, McGrath BJ & Rupert AH (2002, 15-17 Apr) *Enhanced Situational Awareness In Sea, Air And Land Environments.* Paper presented at Human Factors & Medicine Panel Symposium on Spatial Disorientation In Military Vehicles Causes, Consequences and Cures in La Coruña, Spain.

5. Rupert AH, McTrusty TJ & Peak J (1999) Haptic Interface Enhancements for Navy Divers. *Proceedings of the International Society for Optical Engineering (SPIE):* Information Systems for Navy Divers and Autonomous Underwater Vehicles Operating in Very Shallow Water and Surf Zone Regions. Vol. 3711, pp. 246-252.

6. Rupert AH & Gadolin RE (1993) *Motion and Spatial Disorientation Systems: Special Research Capabilities*. NAMRL Special Report 93-1, Naval Aerospace Medical Research, Pensacola, FL.

This page has been deliberately left blank

Page intentionnellement blanche