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A SPATIAL DISORIENTATION PREDICTOR DEVICE TO ENHANCE PILOT SITUATIONAL AWARENESS REGARDING AIRCRAFT ATTITUDE

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Abstract

An effort has been initiated at the AAMRL to investigate the improvement of the situational awareness of a pilot with respect to his aircraft's spatial orientation. This study has as an end product a device to alert a pilot to potentially disorienting situations. Much like a Ground Collision Avoidance System (GCAS) is used in fighter aircraft to alert the pilot to "pull up" when dangerous flight paths are predicted, this device would warn the pilot to put a higher priority on attention to the orientation instruments. A Kalman filter has been developed which estimates the pilot's perceived position and orientation. The input to the Kalman filter consists of two classes of data. The first class of data are the result of passing the aircraft flight trajectory through a set of models including those representing visual, vestibular, kinesthetic, and tactile senses. The second class of data consists of noise parameters (indicating parameter uncertainty), conflict signals (e.g. vestibular and kinesthetic signal disagreement), and some nonlinear effects. The Kalman filter's perceived estimates are now the sum of both Class I data (good information) and Class II data (distorted information). When the estimated perceived position or orientation is significantly different from the actual position or orientation, the pilot will be alerted.

Introduction

When Orville Wright piloted his aircraft for the first time, he flew in a rich sensory environment. He had an excellent field of view, could sense the vibrations, sounds, smells of flying and could feel the wind in his face. Any altitude or attitude changes in the Wright Flyer were sensed immediately, either visually or through some other sensory modality. The modern aircraft pilot flies an immensely more sophisticated machine, but is somewhat at a disadvantage compared to the first aviator. Although the flying machine has become much more agile and responsive, the modern pilot has lost many of the sensory inputs of flying. He or she must interpret digital displays, decipher the numbers, and translate the information to its flight meaning. The modern pilot must operate in a cockpit environment where there are fewer discriminatory cues and there is less time to dwell on them due to the high workload environment (Malcolm, 1987). The pilot cannot hear or feel the wind, cannot (at times) see out-the-window visual cues, and cannot perceive mechanical feedback due to fly-by-wire control systems. Pilots may become disoriented in such environments, lose attitude awareness, and unknowingly pilot $35M aircraft into terrain or water. Spatial disorientation costs the Air Force 8-10 pilots a year and up to $100M a year in lost aircraft and pilot training dollars (Freeman, 1989).

Air Force Experience

Spatial disorientation (SD) is the number one human factors problem facing the Tactical Air Force (DeHart, 1986). SD has been attributed as a contributing factor in 77 Class A mishaps in the Air Force since 1980 (Freeman, 1990). A Class A mishap has been defined as damage to the aircraft over $500,000 or death of the pilot. As of 1990, the value definition has been increased to $1 million (Lyons, 1990). Figure 1 depicts the distribution of SD mishaps over years and across aircraft types.

There has been a high incidence of F-16 Class A mishaps attributed to SD. Of 20 Class A mishaps in the F-16 between 1982 and 1988, 12 were found to have SD as a definite or suspected contributor to the mishap. (McCarthy, 1988)

SD is a silent killer because in many instances, the pilot is never aware that he is disoriented. In many of these Class A mishaps, the pilot has been distracted while flying by a warning light, a missed communication, or changing radio channels. While the pilot is distracted, the aircraft can roll at an imperceptible rate. When the pilot's attention is again directed towards piloting, he or she may discover that the aircraft in an unexpected attitude. If this occurs in total darkness, or in weather where there are no out-the-window visual cues, the pilot can become disoriented. A cross check of the aircraft instruments can correct this situation, but if the pilot's attention is focused out of the cockpit, such as during formation flying or while observing bomb damage over a range, he or she may rely on sensory information to determine spatial orientation.

There are three types of SD recognized by the Air Force Inspection and Safety Center (Marlowe, 1987). Type I is called unrecognized SD. This is the "insidious" type wherein the pilot loses attitude awareness unknowingly. In many cases, the pilot is distracted by a warning light or involved with selecting a radio frequency. While the pilot is distracted with this lower priority task, the aircraft may have rolled or lost altitude.

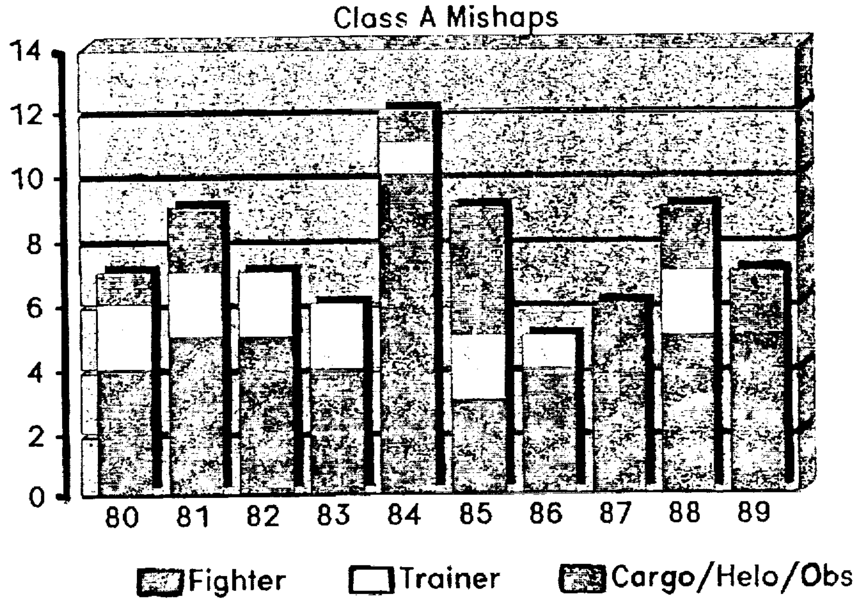

Figure 1: SPATIAL DISORIENTATION MISHAPS. The data above show Class A flight mishaps where the investigating Flight Surgeon found spatial disorientation as a definite or suspected contributor to the mishap. (Freeman, 1990)

At low altitudes, this can result in collision with the ground. Type II disorientation is called classic vertigo. The pilot is disoriented and knows it. He or she realizes there is a sensory conflict and becomes aware that they must transition attention to the aircraft instruments. In many instances, the pilot is able to resolve this conflict and provide adequate guidance of the aircraft. Type III is very rare and is an incapacitating SD. In this example, the pilot simply fails to cope with the aircraft condition, such as a violent spin. During high levels of angular acceleration vestibular inputs can cause the eyes to reflexively move uncontrollably, thus making instrument reading impossible.

There are three human factors problems generally associated with spatial disorientation (Marlowe, 1987). First, there is often a distraction source associated with the SD. The pilot tends to focus on a low priority task that absorbs his or her attention, as described in the previous example.

The second human factors problem is that humans are poor time analyzers. Pilots can become distracted while flying and ignore the instrument panel for extended periods of time. If they are not routinely performing the "T cross check" (checking the T-shaped pattern of round dials on the instrument panel), they can miss important attitude and altitude information.

The third human factors problem is the illusion element. When there are no visual cues present, the human tends to transition to somatic (tactile) and vestibular cues. These are not always reliable and frequently may be in conflict with the instruments.

In a 1987 survey conducted by the Air Force Inspection and Safety Center (AFISC), questionnaires were sent to Air Force pilots concerning their experience with spatial disorientation. From the 1500 returned questionnaires, the pilots indicated that they could become disoriented just as likely in daytime as nighttime. Most respondees noted that when they flew in formation, they expected to become disoriented when flying "on the wing". The survey also indicated that Type II disorientation was most likely to occur when pilot attention was focused on attitude changing maneuvers. Regarding SD and the F-16 specifically, seventy percent of the F-16 pilots' responses indicated problems with canopy reflections and human factors problems with head down CRTs on the instrument panel.

Human factors specialists agree that the F-16 head down displays are poorly placed and overly complex to use. In addition, HUD symbology is confusing and difficult to decipher (Taylor, 1987). These difficulties, combined with the high forward seating of the pilot, all contribute to the high incidence of SD mishaps in the F-16 fighter aircraft.

Common Challenges

NASA Space Shuttle pilots and future National Aerospace Plane pilots face similar orientational challenges to those of high performance Air Force pilots. During ascent and re-entry, sustained G forces are experienced that can result in illusions similar to those experienced during takeoff and landing. The important distinction is the potential for extended exposure to zero G while in orbit. This extends the range of consideration to include vestibular and kinesthetic illusions that are unique to a gravity free environment. In addition, consideration must be given to the effects of microgravity adaptation and space motion sickness. Future protective and alarm devices must account for the unique challenges of long term orbital flight trajectories.

Vestibular Function

The vestibular system contains mechanoreceptors specialized to detect changes in both the motion and position of the head. The receptors are part of the *vestibular apparatus* which is located in the bony channels of the inner ear, one on each side of the head. The vestibular apparatus is a membranous sac within a bony tunnel in the temporal bone of the skull. It forms three *semicircular canals* and a slight bulge for the *utricle* and *saccule* as shown in Figure 2. (Vander, Sherman, and Luciano, 1975)

The three semicircular canals on each side of the skull are arranged approximately at right angles to each other. The actual receptors of the semicircular canals are hair cells which sit at the ends of the nerve cells. The sensory hairs are closely ensheathed by a gelatinous mass which blocks the channel of the canal at that point.

The receptor system in the semicircular canals works in the following way. Whenever the head is moved, the bony tunnel wall, its enclosed membranous semicircular canal, and the attached bodies of the hair cells, of course, turn with it. The fluid filling the membranous semicircular canal, however, is neither attached to the skull nor necessarily pulled with it. The fluid tends to lag behind. As the bodies of the hair cells move with the skull, the hairs are pulled against the relatively stationary column of fluid and are bent. The speed and magnitude of the movement of the head determine the degree to which the hairs are bent and thus the hair cell stimulation. As the inertia is overcome, the hairs slowly return to their resting position. The hair cells are stimulated only during *changes* in rate of motion, i.e. during acceleration of the head. During motion at a constant speed, stimulation of the hair cells ceases.

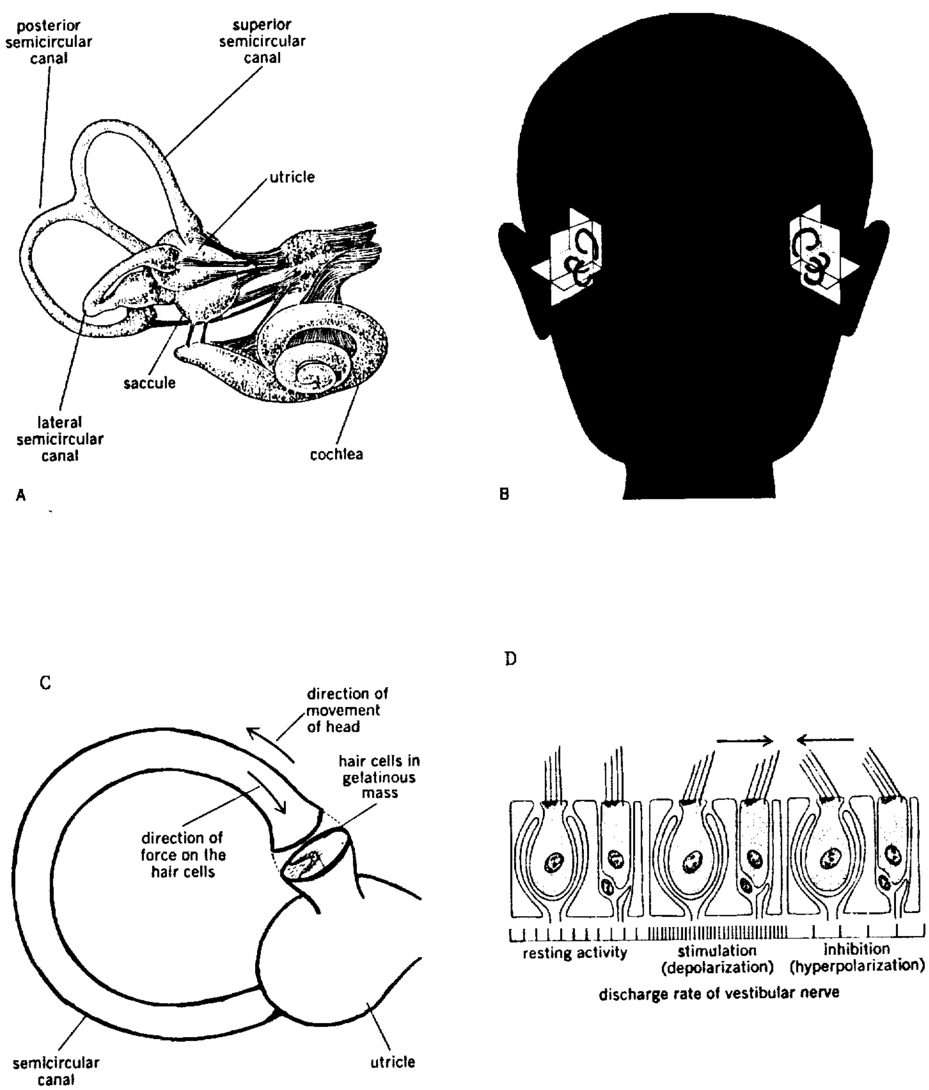

Figure 2: A. The vestibular apparatus. B. Relationship of the two sets of semicircular canals. C. Diagram of a semicircular canal. D. Relation between position of hairs and activity in the nerve. (Vander et. al, 1975)

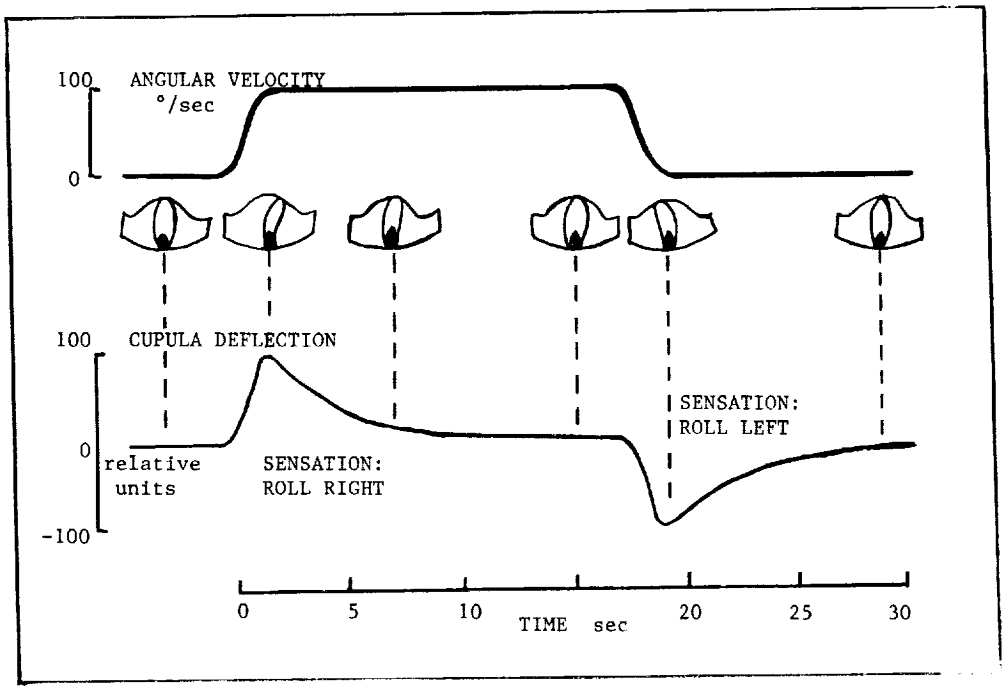

Figure 3: Response of semicircular canal and sensations of turning during and on recovery from sustained rotation. The upper graph shows the speed of rotation; the lower graph shows the deflection of the cupula of a semicircular canal stimulated by angular acceleration in the plane of the canal. (Benson, 1988)

Whereas the semicircular canals signal the rate of change of motion of the head, the otolith organs, the *utricle* and *saccule*, contain the receptors which provide information about the position of the head relative to the direction of gravity. These organs also have mechanoreceptors sensitive to the movement of projecting hairs. The hairs of the hair cells protrude into a gelatinous substance that has calcium carbonate crystals in it, thus making it more dense than the surrounding fluid. When the head is tipped, the heavy gelatinous material slides toward the downward vector and pulls on the hairs. This shearing displacement bends the hair cells and thus stimulates the receptor cells. As the head is tilted further and further, the relative displacement of hair cell body and hair changes. Some hairs may be stimulated while others are inhibited depending on the direction in which the resting hair was biased. This creates a pattern of stimulation across the surface of each organ that can be interpreted and recognized as an amount of tilt relative to gravity.

The information from the vestibular apparatus is used primarily for two purposes. The first is to control the muscles which move the eyes such that the eyes can remain fixed on an object in spite of the head moving. As the head is turned to the left, the balance of input from the vestibular apparatus on each side is altered. Impulses from the vestibular processing centers activate the ocular muscles, which turn the eyes to the right and inhibit their antagonists. Similar responses can be seen for nodding of the head. The second important use of vestibular information is reflex mechanisms for maintaining upright posture and balance. People with a defective vestibular apparatus have a reduced stability while trying to stand or walk with their eyes closed. (Howard, 1986)

Illusions of the Vestibular System

When a pilot's head is moving in a straight line at a constant velocity, the fluid in the semicircular canals remains at rest. When the head is accelerated (i.e. changes speed or direction) the fluid in the canals lags behind the movement of the canal walls due to its non-rigid inertia. After a period of time under constant angular acceleration, the fluid catches up with the walls and there is no longer any stimulus or any sensation of turning. When the head is decelerated, the fluid's inertia will carry it past the walls of the canal creating deflection of the sensing structure in the opposite direction. This causes a sense of rotation in the opposite direction as shown in Figure 3. Upon recovery from a prolonged spin, a pilot can feel as if he or she is spinning in the opposite direction. Attempts to correct for this will put the airplane into a spiral in the direction of the original spin. This is called the somatogyral illusion. (Gillingham & Wolfe, 1986)

Another dangerous illusion of the semicircular canals is known as the Coriolis phenomenon which is the result of head movement while the aircraft is in a prolonged turn. A strong illusion of turning or accelerating in a completely different axis may be created. The pilot may maneuver the aircraft into an inappropriate attitude or may even progress to a onset of dizziness and nausea.

The otolith organs can also give rise to dangerous illusions, especially in the absence of overwhelming visual cues. An abrupt forward acceleration will lead to the illusion of a much steeper climb than is actually the case, known as the somatogravic illusion. This effect has been particularly noted following takeoff, especially when visual reference is inadequate.

The pilot will input a forward motion of the control stick to reduce the aircraft's pitch angle and thereby cause the aircraft to descend. If altitude is low, such as immediately after takeoff, this can be a grave mistake.

While pulling a prolonged coordinated turn, pilots often must look out the cockpit to find another aircraft or survey a target. By tilting the head while under excess gravity, the sensation of head movement is exaggerated and the pilot can sense the aircraft has rolled out of the turn by a few degrees. Upon correction, the aircraft can become overbanked and lose altitude. If the pilot continues to look outside the cockpit at low altitude, the plane can slice downward with fatal speed.

Spatial Disorientation Detector (SDD)

To assist in the study of spatial disorientation, a special tool is being developed at the AAMRL. It consists of a set of electronic elements that will monitor the aircraft's accelerations and predict the possibility that the accelerations have created an illusion for the pilot. This tool consists of a Kalman filter (an unbiased, linear, least squares estimator) that processes the accelerations through a model of the human vestibular and somatic sensory perceptions and estimates the human's perceived attitude and position. If this value does not correlate with the actual attitude and position of the aircraft, the device will activate an audio or visual display to warn the pilot that the potential for spatial disorientation is high. Pilots should then increase their instrument check concentration and vigilance.

The Kalman filter model of the human sensory perception is presently built on an analog computer at the AAMRL as depicted in Figure 4. The six inputs into the device are the three linear acceleration vectors and the three angular acceleration vectors which are the accelerations experienced at a point in the head center coordinate system. One output of the SDD describes the true position and orientation of the aircraft. The second output describes the perceived position and orientation of the pilot. When the error between these two signals becomes large, the device will activate the alarm display to the pilot.

The crucial element of the SDD is the internal model that is used to produce the estimate of perceived orientation. Fortunately, the Kalman filter lends itself to an expanding design where simple vestibular models can be used and then, as more accurate models become available, the system can be enhanced. Many physiological studies have provided data for these models, and there is current research in the aerospace community that will expand the reliability and range of these models. Improved methods are continuously being developed to reduce the false positives of a Kalman filter. (Repperger, 1976, Borah et. al., 1988)

As with any avionics warning system, pilots are concerned about the annoyance of false positive alarms. The consensus among aviators and workload experts is that such a device would routinely be turned off if there is a significant number of false alarms. The Kalman filter approach was selected because of its ability to estimate in spite of signal noise and erroneous sensor information. This rigorous approach has been demonstrated to effectively predict human perception with a low occurrence of false positives or false negatives (Young, Curry, & Albery, 1976, Borah, Albery, & Fiore, 1976, Borah, Young, & Curry, 1988). The SDD would prove to be a valuable lifesaver.

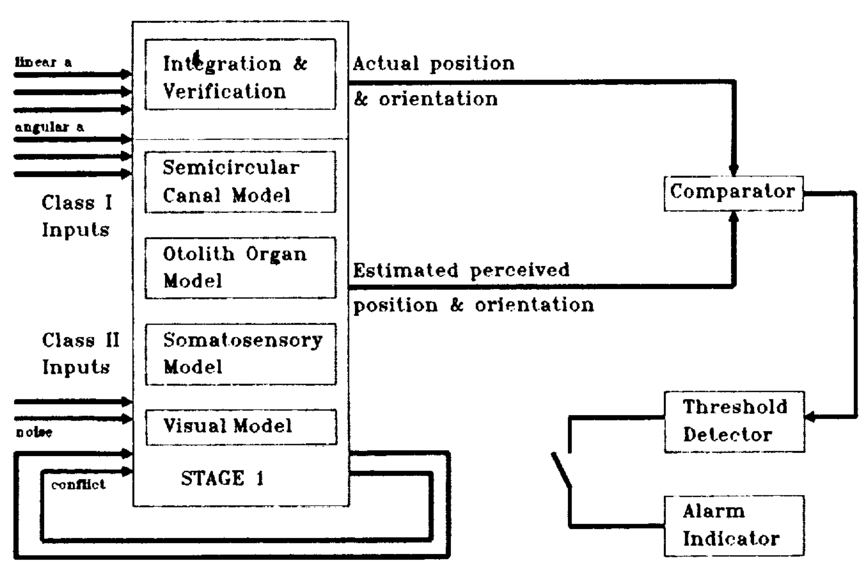

Figure 4: SDD Overview

The Bottom Line

From Flying Safety, IFC Approach, April 1989:

> "Thirty five seconds later, lead called as he passed the IP starting his bomb run. Thirty two second after that, the wingman echoed the call commencing his bomb run. Seventeen seconds later, the wingman impacted the ground in a right 35 to 40 degree bank, with a 3 degree descent, and between 500 and 540 knots."...
>
> "Overwhelming evidence indicates that the crew fell victim to Type I, or unrecognized spatial disorientation, which resulted in this mishap. Relaxed and unaware of their situation, the pilot was intent on keeping the leader in sight during the spacing maneuver, while the Weapons System Officer was preparing for the upcoming bomb run."
>
> " Having flown a completely successful first sortie and almost 20 minutes comfortable at "lead's altitude" when directed to take spacing, the crew expected nothing to change except the distance between aircraft. They did not have any idea the flight environment would be so conducive to illusions, spatial disorientation, or insidious weather conditions."

Although the predictive ability of the Spatial Disorientation Detector may not be perfect, neither is the perceptive power of the human. In the case above, the SDD would most likely have processed the positive acceleration occurring during the bomb run to generate a significant error between its estimate of pilot perception (level coordinated turn) and the actual aircraft attitude (descending turn) and thus alerted the pilot.

References

1. Benson, A.J., "Spatial Disorientation," AVIATION MEDICINE, Second Ed., Butterworths, London, England, 1988, Chaps 20 and 21.

2. Borah J., Albery, W.B., and Fiore, M.D. "Human Motion and Force Sensory Mechanism Modeling," Proceedings of the National Electronics Conference, 1978, Vol 32, pp 204.

3. Borah J., Young L., Curry R. "Optimal Estimator Model for Human Spatial Orientation," Annuals of the New York Academy of Sciences, 1988, Volume 545, New York, NY.

4. DeHart R., 1986. "Human Factors Problems in the Tactical Air Command," Aviation, Space and Environmental Medicine, July 86, 57:725.

5. Freeman J., 1989. Personal letter from Air Force Inspection and Safety Center to W.B. Albery re: Low-altitude Class A Mishaps, dtd 10 Mar 89.

6. Freeman J., 1990. Personal letter from Air Force Inspection and Safety Center to T.L. Chelette re: Spatial Disorientation Mishaps, dtd 11 May 90

7. Gillingham K., Wolfe J., 1986. "Spatial Orientation in Flight," USAFSAM-TR-85-31, School of Aerospace Medicine, Brooks AFB, San Antonio, TX, Dec 86.

8. Howard, I.P., "The Vestibular System," HANDBOOK OF PERCEPTION AND HUMAN PERFORMANCE, John Wiley and Sons, New York, 1986

9. Lyons, T.J., Freeman, J.E., "Spatial Disorientation (SD) Mishaps in the U. S. Air Force - 1988," Presented at the 61st Annual Meeting of the Aerospace Medical Association, May 13th, 1990, New Orleans, La.

10. Malcolm R., 1987. "How the Brain and Perceptual System Work," Presented at the 58th Annual Scientific Meeting of the Aerospace Medicine Association, May 10-14, 1987, Las Vegas, Hilton Hotel.

11. Marlowe B., 1987. "Spatial Disorientation and Loss of Attitude Awareness: Impact on the USAF," Presented at the 58th Annual Scientific Meeting of the Aerospace Medicine Association, May 10-14, 1987, Las Vegas, Hilton Hotel.

12. McCarthy G. W., 1988. "Human Factors in F-16 Aircraft Accidents," Presented at the 59th Annual Scientific Meeting of the Aerospace Medical Association, May 1988, New Orleans, La.

13. Repperger, D.W. "A Study of Identification Methods and Structural Modeling Techniques on Empirical Data From A Motion Study," The 1977 IEEE Conference on Systems, Man, and Cybernetics.

14. Taylor R., 1987. "HUD Pitch Scale Design and Evaluation," Presented at the 58th Annual Scientific Meeting of the Aerospace Medicine Association, May 10-14, 1987, Las Vegas, Hilton Hotel.

15. Vander, A.J., Sherman, J.H., Luciano, D.S., "Coordinated Body Functions," HUMAN PHYSIOLOGY; THE MECHANISMS OF BODY FUNCTION, Second Ed., McGraw Hill Book Co., New York, 1975.

16. Young, L.R., Curry, R.E., Albery, W.B. "A Motion Sensing Model of The Human For Simulator Planning," Proceedings of the 9th. Intec/Industry Conference, Orlando, Florida, November, 1976, pp 149-151.