Countermeasures for Loss of Situation Awareness: Spatial Orientation Modeling to Reduce Mishaps

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Abstract— Spatial disorientation (SD) and loss of aircraft control are the largest contributors to aviation fatalities for both military and civil aviation. A recent report indicates that air carrier mishaps attributed to somatogravic illusions (especially during “go-around”) have not decreased. Go-around is a flight path taken by an aircraft after an aborted approach to landing. Such mishaps are generally associated with a degraded visual environment (DVE) and the increased workload associated with approach to landing. The modeling of pilot spatial orientation is complex as it involves aircraft state parameters, the integration of information from several sensory systems (somatosensory, vestibular, and visual), the intention of the pilot at the controls, the increasing use of automation, and the pilot's total flight hours and types of flight experience. In addition, past models have not included the benefits to situation awareness afforded through tactile cueing and 3-dimensional (3D) audio displays. Tactile cueing and 3D audio displays have the advantage of providing continuous orientation during conditions of distraction when the pilot is not attending to the attitude indicator or outside horizon. The revised model, when accompanied by gaze information, can prevent mishaps by providing real time warning of impending SD to pilots. Alternatively, post mishap analysis can reveal the etiology of sensory failure, leading to material solutions to prevent future mishaps. When the revised spatial orientation model is used to evaluate recent air carrier mishaps involving somatogravic illusions during go-around, it becomes apparent that solutions to SD reside in novel non-visual continuous orientation devices to supplement traditional visual displays.

1. INTRODUCTION

Human error has been implicated in 70 percent to 80 percent of both civil and military aviation mishaps [1]. When investigators fail to find a materiel cause, attention is focused on possible pilot causal factors.

Although air carrier mishaps per passenger mile are very low and the industry rightfully takes pride in the safety of air travel, the percentage of air carrier fatalities attributed to spatial disorientation (SD) in particular account for 17 percent of fatalities between 1981 and 2010 [2]. Spatial disorientation has posed a problem for aircraft designers from the earliest days of flight. In the early days, pilots simply avoided deliberate flight into the clouds, as the aircraft were not equipped with instruments to provide aircraft orientation. Even after the development of the attitude indicator and other orientation instruments, SD mishaps continued to occur.

Since SD mishaps tend to be fatal, it is only on the rare occasion that there is a surviving pilot to corroborate SD as the causal factor of the mishap. As a result, SD is often considered a causal factor based on exclusion of materiel causes and presence of factors such as insufficient outside visual cues, distraction of the pilot from the orientation instruments, and unusual pilot control inputs, especially when combined with flight paths consistent with known disorientation illusions.

The primary reason to model SD mishaps has been to explain why the mishap occurred. For the non-flying public it is difficult to understand how a professional pilot, who is manually flying an aircraft, could deliberately apply control inputs that cause the airplane to impact the ground, especially when the aircraft instrument panel provides the pilots with multiple instruments having all the information required to maintain control.

When pilot perception is being modeled for the purpose of examining SD mishaps, there is a critical assumption concerning the attention (or rather inattention) of the pilot,
made by the modeler. It is assumed that the pilot, for a short duration of time, has not been directing attention to the attitude indicator or to the outside visual cues of the horizon. Most SD mishaps occur under conditions of reduced visibility such as night flight, flight in the clouds, or obscuration due to fog, rain, snow, or sand. For this reason, models of perceptual orientation for the aerospace environment have, until recently, not included visual orientation stimuli and have focused on modeling of the vestibular system as shown in Figure 1 and described by Merfeld and Zupan [3].

Figure 1. The inputs to the Merfeld model are angular velocity ($\omega$), linear acceleration ($a$), and gravity ($g$). The model outputs are the neural estimates of angular velocity ($\tilde{\omega}$), linear acceleration ($\tilde{a}$), and gravity ($\tilde{g}$). Physical effects and sensory transduction associated with these inputs are represented at the top of the block diagram ($g = \int -\omega \times g \ dt$, $f = g - a$, Canals, Graviceptors). These components represent known effects and influences. The internal model (neural representation) of these components is included within the gray box ($\tilde{g} = \int -\omega \times \tilde{g} dt$, $\tilde{f} = \tilde{g} - \tilde{a}$, Model of Canals, Model of Graviceptors). These internal model components represent hypothesized neural calculations performed by the nervous system.

In order to expand the envelope of conditions in which the model is valid, especially visual conditions, we worked with Newman to develop a new model, the Orientation Modeling System (OMS) [4]. The OMS diagram in Figure 2 includes limited visual inputs and was incorporated into a Perception Toolbox to permit comparison with several previous models' predictions of orientation.

Figure 2. Orientation Modeling System (OMS) block diagram. Blocks highlighted in red, blue and green have been added to the Merfeld model. Three dimensional vectors of linear acceleration ($\tilde{a}$) and angular velocity ($\tilde{\omega}$) are input to the model in a head-fixed coordinate frame. Angular velocity is integrated using a quaternion integrator ($\tilde{f} = \tilde{q} \tilde{\omega}$) to keep track of the orientation of gravity ($\tilde{g}$) with respect to the head. The otolith (OTO) transfer functions are modeled as unity and respond to the gravito-inertial force (GIF) ($\tilde{f} = \tilde{g} - \tilde{a}$). The semicircular canals (SCC) are modeled as 2nd order high-pass filters with a cupula-endolymph long time constant of 5.7 seconds and a neural adaptation time constant of 80 seconds. Afferent signals from the canals and OTO are compared in the central nervous system (CNS). "Observer" against expected values from a similar set of internal sensory dynamics (SCC, OTO). The resultant error signals are weighted with four free parameters ($k_{\omega}$, $k_{\text{f}}$, $k_{\text{g}}$, $k_{\text{sc}}$) highlighted in green. The model outputs are central estimates of linear acceleration ($\tilde{a}$), gravity ($\tilde{g}$), and angular velocity ($\tilde{\omega}$). Note that hatted variables (\^) represent estimated states.

When the pilot is deprived of outside visual cues that provide orientation of the aircraft, it is imperative that he/she frequently monitors the orientation of the aircraft using a combination of instruments, especially the attitude indicator. Through years of trial and error, pilots have determined the optimal arrangement of orientation instruments. The attitude direction indicator is placed in the center of the visual field and is surrounded by the supporting instruments, including airspeed, altimeter, vertical velocity, magnetic heading, and turn and bank. Pilots develop a visual scan pattern to frequently monitor the instruments since, in the dynamic environment of flight, the changing aircraft orientation can quickly place the pilot in an unusual attitude requiring an immediate response. The scan pattern varies with requirements for the phase of flight and pilots develop the system that works best for them.
With the advent of glass instruments, the attitude orientation instruments are now arranged on a single multifunction display. However, rearranging the visual instruments has not significantly reduced the pilots’ workload, as the pilot must still focus on each individual piece of information within the multifunction display and interpret the meaning just as he/she did when the instruments were separated. The limiting factor is the pilot’s ability to serially perceive, interpret, and assemble all of the information to achieve complete situation awareness of the aircraft’s orientation and the surrounding environment.

When manually flying the aircraft under conditions of degraded visual environment (DVE), it is imperative that the pilot’s scan pattern be repeated with sufficient frequency to maintain spatial orientation. When confronted with sudden additional workload that distracts the pilot’s attention away from the orientation instruments, the pilot’s brain continues to compute orientation with the remaining available sensory information (just as occurs on the ground). The remaining sources of orientation information to the pilot are the somatosensory and vestibular sensations.

![Figure 3. Primary sensory inputs for spatial orientation: vision, auditory, and somatosensory (skin-muscle-joint).](image)

In our day-to-day activities on Earth, we primarily rely on three redundant sensory systems (shown in Figure 3) to provide spatial orientation: vision, the inner ear vestibular organ of balance, and our skin-muscle-joint, or somatosensory sense. On Earth, each of these systems normally provides true or correct information as to the direction “down,” this information is usually concordant among the three senses.

Two of these systems, the inner ear and our skin-muscle-joint senses, continuously provide information concerning the direction “down” and this information rarely comes to our attention. Although we are unaware of this information, it is used by the brain automatically to adjust postural, locomotive, and vegetative reflexes associated with orientation and locomotion. These two systems are collectively referred to as proprioception and are colloquially called the “seat-of-the-pants” sensation by pilots and astronauts. In contrast, the sense of vision is discontinuous and, in isolation, generally fails to provide adequate orientation information when we are directing our attention to a specific object or when we are distracted in high workload environments.

It is normal for humans to routinely experience disorientation when entering the aerospace environment. As presented in Figure 4, this spatial disorientation is due to a combination of the following: 1. false information from our proprioceptive sensory system, and 2. the discontinuous nature of orientation information from vision.

![Figure 4. The pilot is flying in a circle at constant altitude which exposes the pilot and the banked aircraft to two forces. Gravity is always present and acts downward in the vertical direction towards the center of the earth. In addition, there is a centrifugal/centripetal inertial force of rotation shown here as acting away from the center of rotation. Together these forces combine to form the resultant force vector (RFV) which, as we see, differs in direction and magnitude from the vertical gravity force vector. The proprioceptive senses incorrectly interpret the RFV as the direction down. Without visual information, the pilot will perceive straight and level flight [5].](image)

Over many millions of years, our proprioceptive seat-of-the-pants sensations of the inner ear and skin-muscle-joint senses have learned to interpret any resultant force acting for several seconds as being the apparent vertical or the direction “down” of gravity. In the situation in Figure 4, an occupant of the helicopter who could not see the horizon would think he/she was upright. It is only by viewing the horizon or directing attention to certain aircraft instruments, that the pilot or occupant is able to determine the true attitude of himself/herself and the aircraft in which he/she is seated.

In terms of physical forces, the primary cause of SD is that the resultant force vector (RFV) differs in magnitude and
direction from gravity almost continuously, except in smooth, straight, and level flight. Without visual reference, the direction of the RFV is the only immediate sensor indicator of “which way is down” and it is wrong in any condition involving accelerated flight, including turns. Such misperceptions associated with incorrect interpretation of down based on the RFV are frequently referred to as somatogravic illusions [6].

In this paper, we employ perceptual analysis models to examine a specific, recent somatogravic mishap in light of a series of similar mishaps [7] that have been reported by the Bureau d’Enquêtes et d’Analyses pour la sécurité de l’aviation civile (BEA), which is the equivalent of the U. S. National Transportation Safety Board (NTSB). Together, these mishaps provide insight into the cause of many air carrier spatial disorientation mishaps and provide guidance for the various solutions that could prevent future mishaps.

The BEA study [7] was restricted to a specific class of public air transport mishaps and serious incidents associated with the “go-around”, the maneuver conducted by pilots when a decision has been made to terminate the approach to landing and go-around for another landing attempt or to deviate to another airport. The BEA report describes the issues of the pilots’ orientation or “aeroplane state deviate to another airport. The BEA report describes the landing and to go-around for another landing attempt or to when a decision has been made to terminate the approach to with the “go-around”, the maneuver conducted by pilots public air transport mishaps and serious incidents associated somatogravic illusions [6].

Physical Forces Producing Pitch-Up Sensation
Many in-flight forces produce an illusory sensation of pitching up. It was an unfortunate condition of this flight that the pilots of Tatarstan Flight 363 were exposed to multiple physical forces acting in concert, and some synergistically, to produce a significant false pitch-up sensation, even when the aircraft was actually pitched down by more than 45 degrees. These multiple contributors to the mishap are summarized in the next several paragraphs:

1) Mishap Contributor 1: Resultant gravito-inertial force (GIF) angle.1 The aircraft was linearly accelerating forward from the beginning of the go-around maneuver (t = 4026 s) until impact. This contributed to changing the direction of the RFV from directly in-line with the vertical torso of the pilot to a rearward direction (Figure 5, blue arrows). This force contributes strongly to the somatogravic illusion, a misperception of attitude that results in frequent mishaps [6]. There is normally a significant time lag associated with this perception [8]-[10] when the GIF direction change occurs in isolation, and is not accompanied or corroborated by an angular acceleration cue. In the Tatarstan mishap, there is minimal time lag due to the angular acceleration discussed below.

2) Mishap Contributor 2: Angular Acceleration. The aircraft pitched up from 3 degrees nose-up at 4030 s to 20 degrees nose-up at 4040 s (Figure 6), which exceeds the perceptual threshold of detection for angular motion. When this stimulus accompanies the change in GIF (Contributor 1), it provides a strong cue that confirms and adds to the perception of pitching up, making the illusion stronger than it would have been. This corroborative information reduces the usual long time constant of perceptual lag (15 s) experimentally seen in centrifuge studies [11] and [12].

3) Mishap Contributor 3: G-excess Effect. The G-excess effect refers to the increased pitch-up perception normally experienced by pilots when exposed to increased GIF [13]. The overall magnitude of the GIF vector increased for two reasons: 1) the maintained linear acceleration during the initial portion of the go-around, and 2) the increase in the vertical velocity as the aircraft began to climb. (See Gz as the aircraft Gz vector increases from 4030 to 4035 s). The increased magnitude of the GIF contributes to the G-excess effect [13][14] and results in an increased perception of pitch-up. The magnitude of the pitch-up perception is dependent upon the increase in the GIF and on the head position of the pilot. In this mishap, we assume that the pilot’s head was inclined slightly downward by about 15 degrees, which would reduce the magnitude of the pitch-up percept. The assumption of 15 degrees head down is in keeping with the normal head position while attending to aircraft instruments. As with the somatogravic illusion, 1 This refers to the resultant between the force on the pilot due to Earth’s gravity and the force caused by the aircraft’s acceleration.
there is a time lag in both the onset and offset of the G-excess illusion following application of the increased “G” force. This is factored into the dynamics of the perceptual model.

Figure 5. “Quiver” plot of resultant gravito-inertial force (GIF) during go-around. (Vectors shown relative to a side-view of the right side of aircraft.) Time on x-axis and altitude on y-axis.

Figure 6. Perceived Pitch (red and light blue) and Actual Pitch (green) vs. time predicted by Merfeld (red) and McGrath et al. model (light blue) models.

The models provide the predicted perception based on the sensory information presented to the pilot. However, there are additional factors that need to be considered when interpreting the model. These factors are included in Figure 7. The somatoreceptors provide veridical information (i.e., accurate contact orientation information of the pilot with respect to the seat), and under any condition other than smooth, straight, and level flight, the somatosensory system interprets down based on the RFV and, thus, provides false information concerning the direction “down” (which tends to be most compelling since this information is generally corroborated by the vestibular system).

Figure 7. Factors contributing to spatial orientation perception.

Several models including the McGrath et al. model [15], the Grissett model [16], the Merfeld model [17], and the recent OMS [18] all predict a perception of pitch-up to vertical and some [3] predict the inversion illusion for the Tatarstan Flight 363 mishap when the vector rotates to point towards directions above the pilot. Interpretation of the McGrath et al. model of perception was modified to accommodate a specific aspect of the somatogravic illusion based on experimental data [19] by McCarthy and Stott that largely accounted for the effects in Figure 7, represented as “preceding events” and “expectation.” In that experiment, both naive and experienced pilots were exposed to a flight path with an acceleration sequence similar to both this mishap and a 1996 U. S. Navy F-14 mishap [20]. In the McCarthy study, there was a clear difference in pitch perception between naive subjects and experienced pilots/test pilots, all of whom were blindfolded. The experienced pilots/test pilots did not experience the predicted inversion illusion; whereas, naive subjects routinely perceived inversion.

The perception of pitching up through to inversion is countered in part by a very strong pitch forward angular acceleration (+24 degrees to -60 degrees in 12 s). This partially counteracts the backward pitch sensation due to the GIF vectors and may explain why naive subjects frequently transition from upright to inverted without an intervening pitch-back sensation.

4. DISCUSSION

It is important to note that, in the Tatarstan mishap, the pilot did not have to be distracted from the orientation instruments for more than 10 seconds to find himself in a
position from which the aircraft was not recoverable. The technology is available, and has been available for many years, that could prevent such mishaps. For example, the technology of Automatic Ground Collision Avoidance System (Auto-GCAS) was demonstrated to the U. S. Air Force (USAF) in the 1980s. Nevertheless, since 2003, we have investigated three air carrier mishaps (in Bahrain, Tripoli, and Tatarstan) at the request of the NTSB and several military mishaps in which the somatogravic perception was the presumed/likely or definite (based on survivor’s testimony or comments between aircrew) cause of the mishap. It is possible that Auto-GCAS, or other technological SD countermeasures, could have prevented these mishaps. As pointed out in the excellent BEA report [7], this type of go-around mishap continues despite pilot training and awareness countermeasures.

Mishaps in the air carrier industry are rare, sporadic events not subject to accurate statistical treatment over short periods of time. However, that is not the situation in the U. S. military, where mishaps are much more frequent due to far more challenging environmental conditions (commercial aircraft are grounded under visibility conditions in which military pilots routinely depart and land), operational workload demands, and fatigue secondary to high operational temps. Traditional training and materiel solutions fall into three categories: changes in tactics or procedures, and recommended the development of materiel solutions [21]. The currently available materiel solutions fall into three categories:

1) Training – the BEA report [7] and other training specialists have pointed out that motion-based simulators are not optimally utilized in go-around and takeoff phases of flight simulation. Simulators are currently used to provide actual aircraft pitch, instead of a stimulus matching the pilot’s perceived pitch. As seen in Figure 6, actual and perceived pitch can be quite different, especially under conditions of takeoff and go-around.

2) Materiel Solutions – In the mid 1990s, the U. S. Department of Defense (DoD) realized that SD mishaps could not be significantly reduced by further training or changes in tactics or procedures, and recommended the development of materiel solutions [21]. The currently available materiel solutions fall into three categories:

a) Remove the source of error (viz., pilot) from the control loop. Automation in which the aircraft is programmed to perform maneuvers would have eliminated all of the aforementioned go-around mishaps. A pre-programmed go-around for each approach is a feasible solution to prevent go-around mishaps. Alternatively, Auto-GCAS (now being installed on USAF F-16 Block 60 upgrades) protects military pilots from controlled-flight-into-terrain mishaps. This technology could be readily adapted to air transport aircraft in civil aviation.

b) Provide the pilot with a warning of incipient SD. When coupled with eye-gaze measurement technology, spatial orientation models can predict the likelihood of SD events. Some military aircraft, such as the Apache helicopter, are capable of measuring where pilots direct their attention using the head tracker technology of the Integrated Helmet and Display Sighting System (IHADSS). This should be refined via incorporation of routine gaze tracking technology.

c) Provide pilots with continuous veridical (accurate) orientation information. There are currently available systems that are capable of providing continuous, non-visual, orientation information when the pilot or copilot is distracted from the attitude orientation instruments. The BEA study provided evidence that the copilot is carrying out more tasks and has less time than the pilot to devote visual attention to the orientation instruments. Therefore, we feel that non-visual orientation information is needed to maintain pilot and copilot orientation during inevitable distractions. Currently, the auditory and tactile sensory channels are available to provide continuous non-visual orientation information. The auditory channel technology [22] [23] is addressed in the accompanying IEEE panel paper by Brill et al. as a partial solution to loss of situation awareness in the aerospace environment. Unfortunately, the auditory channel is frequently in use as a communications channel. The unused sensory channel of touch offers the best opportunity to provide intuitive orientation information continuously in an automated fashion to maintain orientation and thereby prevent SD from occurring. National Aeronautics and Space Administration (NASA) and the U. S. military developed the tactile situation awareness system (TSAS) as an SD countermeasure [24] [25].

Figure 8. Tactile situation awareness system (TSAS).

The pilot in Figure 8 is shown wearing a garment fitted with a matrix of tactors—columns and rows of small mechanical tactile stimulators held in close proximity to the skin of the torso. As shown on the right, these tactors can be mapped to all points in the environment to provide continuous orientation cues.

The complete TSAS consists of a torso suit (Figure 8) and a seat cushion. For the U. S. Army helicopter application a
simpler, more practical system was developed which consists of a belt fitted with eight tactors, a seat cushion with two to eight tactors, and a shoulder harness fitted with two tactors.

Figure 9. TSAS-Lite belt: (A) modeled by aviator, and (B) showing electromechanical tactors on the inside of the belt.

Both the vest and the simplified “TSAS-Lite” (Figure 9) have been tested in simulators [26] and in-flight [27]-[31] to demonstrate the effectiveness of tactile cueing for hovering and glide path control under DVE conditions and the effects of fatigue [31].

Information from the platform sensor (e.g., attitude indicator) is processed through a software program to provide intuitive tactile information continuously, so that the operator can “close the loop” to control the platform without devoting visual attention to cockpit orientation instruments. This is similar to the manner whereby humans perform the far more complex task of walking.

Information can be provided from a variety of sensors and, through appropriate human engineered programs, provide an intuitive tactile stimulus that the operator will use instinctively to perform the task at hand while simultaneously attending to other tasks.

Proposed Advantages of TSAS:

1) Most importantly, TSAS maintains orientation by providing continuous intuitive orientation information.

2) By providing continuous information, the pilot does not need to constantly refer to the instruments as frequently as he/she currently does.

3) Since TSAS information can be simultaneously provided to the pilot, copilot, and flight engineer, the aircrew shares situation awareness to more efficiently achieve coordinated control of the aircraft without using the auditory channel.

4) When the autopilot is engaged, the pilot is effectively removed from the flight control loop. He becomes a monitor and often is engaged in other tasks. TSAS keeps the pilot in the information loop so the pilot can more quickly re-enter the loop in emergencies.

5) By providing intuitive information, pilot candidates will learn faster, and hence, reduce the cost of training.

6) By permitting the military pilot to spend more time looking outside the cockpit, he/she can more effectively perform his/her military mission. U. S. Air Force pilots have referred to TSAS as a “Heads Out” display.

7) By providing a portion of the critical flight information with the TSAS it is possible to remove some of the information from the HUD or HMD, thus reducing the pilot workload in using these information intensive devices.

The U. S. Army Combat Readiness/Safety Center (USACRC) conducted a study with five experienced mishap investigators who had experienced TSAS in a simulator. The five investigators independently examined all Class A and B mishaps over the past 20 years of available data (1992 to 2012) to evaluate whether TSAS could have prevented the mishap. The Army Safety Center concluded that 24 percent of U. S. Army Class A helicopter mishaps could have been prevented with TSAS [32].

5. SUMMARY

Spatial orientation models in conjunction with flight data recorders and transcripts provide a method to examine causality of aircraft mishaps in the absence of a materiel failure. Modeling of mishaps provides direction for solutions to prevent SD mishaps to include: improved simulator training, warning of mishaps, and prevention using tactile cueing.

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