The Role of Perceptual Modeling in the Understanding of Spatial Disorientation During Flight and Ground-based Simulator Training

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The Role of Perceptual Modeling in the Understanding of Spatial Disorientation During Flight and Ground-based Simulator Training

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When investigators fail to find a materiel cause for a mishap, pilot error may be implicated. Controlled flight into terrain (CFIT), aircraft upset (AU), and loss of control (LOC) are important mishap contributors. Spatial disorientation (SD) is a key causal factor of CFIT and its presence can precipitate or exacerbate LOC. SD typically is inferred based on unusual control inputs by the pilot, insufficient outside visual cues, the presence of factors which would distract the pilot from the primary flight instruments, and the qualitative similarity of the flight circumstances to those known to induce orientation illusions. We recommend that SD analysis should be more quantitative and comprehensive, involving the matching of information from on-board recorders (e.g., acceleration, pilot control inputs) to mathematical models of human orientation functioning that are designed to fit what is known about human perception. We recently combined several established scientific models into one Perception Toolbox which allows comparison of the predictions from each model. We also devised our own model, called the Orientation Modeling System (OMS), which is intended to improve the explanation of mishaps and laboratory perceptual experiments. The OMS and the Perception Toolbox are described briefly in this report. The modeling tool has been used to describe several illusions in laboratory, simulator and flight settings. Two applied examples are highlighted which entailed the successful modeling of a recent SD mishap and some published experimental results relevant to the disorienting effects of head movement during centrifuge-based simulator training. Lessons learned from the model will enhance future aeromedical capabilities by helping investigators determine if SD is a factor in a given mishap, develop educational videos of mishaps to improve mishap evaluation and pilot training, evaluate new instrumentation solutions to prevent AU, LOC, and CFIT, and improve simulation profiles in advanced centrifuge-based simulators.

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Nomenclature

$\vec{a}$ = *linear acceleration*
AU = *aircraft upset*
CFIT = *controlled flight Into terrain*
DAPS = *Disorientation Analysis and Prediction System*
DFIR = *deployable flight incident recorder*
EKF = *extended Kalman filter*
G = *gravitoinertial force*
$\vec{g}$ = *gravity (acceleration due to Earth's gravity)*
GUI = *graphical user interface*
$\int \dot{\vec{q}}$ = *integrator, quaternion*
$\vec{g}_V$ = *visual vertical/orientation*
K = *residual weighting parameters for the OMS (all nine parameters described on page 6-7)*
KF = *Kalman filter*
LOC = *loss of control*
NASTAR = *National Aerospace Training and Research Center*
$\vec{\omega}$ = *angular velocity*
OMS = *Orientation Modeling System*
OTO = *otolith organs*
SCC = *semicircular canals*
SD = *spatial disorientation*
SDAT = *Spatial Disorientation Analysis Tool*
UKF = *unscented Kalman filter*
USAARL = *United States Army Aeromedical Research Laboratory*
$\hat{\vec{v}}$ = *linear velocity, estimated*
WHD = *Warfighter Health Division of USAARL*
$\vec{\omega}_V$ = *visual angular velocity*
$\vec{g}_V$ = *position*
$\hat{\dot{\vec{x}}}$ = *visual linear velocity, estimated*
$\vec{x}_V$ = *visual position*

I. Introduction

Aircraft upset (AU) and subsequent loss of control (LOC) are key concerns of the aviation community presently, accounting for 29-46% of aviation accidents.[1] AU occurs when a condition arises that is abnormal for the aircraft and/or the phase of flight and which entails an unusual state or change in attitude, altitude, velocity, or flight trajectory.[2] Such abnormal conditions can arise due to mechanical failure, icing, turbulence, stalling, or spatial disorientation (SD).[3] Among these factors, SD is somewhat unique in that SD mishaps do not necessarily involve the pilot having to struggle against aircraft or aerodynamic limitations. A recent study of air carrier flights from 1981 to 2010 indicated that among all incidents and accidents involving LOC, SD produced the second-greatest number of fatalities, exceeded only by aerodynamic stalling.[4] (Note that SD and stalling were not mutually exclusive and that SD also occurred during or following 6.3% of aerodynamic stalling events and 36.8% of faulty recovery events.)

In addition to LOC, pilots may crash aircraft for a number of reasons in which human error is implicated. Aviation human error incidents and mishaps are described by an ever-expanding list of overlapping constructs or phrases, including LOC, loss of situation awareness, loss of position awareness, controlled flight into terrain (CFIT), and approach-and-landing accidents.[5] Spatial disorientation (SD) frequently is an important contributor in each of these situations. SD is defined as a failure by the pilot to sense correctly his/her position, motion, or attitude relative to the surface of the earth and the gravitational vertical.[6] SD is induced when the forces during flight and/or the visual cues are misleading. When SD occurs, loss of situation awareness quickly follows. Moreover, in most cases of severe accidents due to loss of situation awareness, SD is implicated.[5] This may be because loss of situation awareness is not generally due to a high-level failure of cognitive interpretation of information, but rather a lower-level failure to attend to the needed sensory information, such as attitude and altitude information from the primary flight display.[5] A recent evaluation of loss-of-control accidents[2] found SD to be a contributing factor in two of the 18 mishaps in which the LOC was initiated by inappropriate crew action and in five of the six mishaps where poor visibility led to subsequent inappropriate crew action. Clearly, the understanding of SD is important to the understanding of LOC.

Unusual accelerations and associated sensorimotor (e.g., visual-vestibular, psychomotor) discordances are common not only during aviation operations, but also during sea travel, cross-country land travel, space travel, and moving-based and centrifuge-based training. These situations contribute to SD, degraded dynamic visual acuity, motion sickness, and difficulty concentrating.[5,7-9] During aviation operations, altered perceptions of motion and acceleration contribute to fatal mishaps.[10] During centrifuge-based aviation training, head movements out of the main axis of centrifuge motion elicit a vestibular response that leads to nausea and causes a disorientation abhorrence reaction.[7] Such factors have limited the adoption of advanced simulators for high performance flight training.[11] This report describes how a new tool for modeling spatial orientation perceptions helps to explain disorientation during aviation mishaps and centrifuge-based training. A review of past models is offered, then a brief description of the new model, and finally, a description of how the model describes the disorientation associated with a disorientation-related mishap and an unpleasant centrifuge stimulus. These applications of the model should be of interest to those involved in modeling, simulation, and analysis in support of aerospace operations.

II. Limitations of Current Qualitative Evaluations of Disorientation

Mishap reports concerning probable orientation errors are usually too general. Mishap reports associated with CFIT, SD, and LOC frequently describe the human error using phrases which imply that the pilot failed to maintain a proper cross check of the instruments, that the pilot failed to respond in a timely manner, or that the pilot failed to maintain adequate ground clearance. These descriptions are technically accurate but not very helpful in terms of understanding the proximal contributors to the pilot's judgment of the situation immediately preceding the mishap and the reason for his/her recorded control decisions and inputs to the aircraft. For example, it is important to determine why the pilot failed to maintain adequate ground clearance. Similarly, in cases of LOC, it is important to determine whether key LOC contributors (such as poor flight handling near critical points of the flying envelope or poorly-executed 'go-arounds'[12]) may sometimes be explained by the pilot's incorrect perception of his attitude and altitude (SD).

Mishaps involving SD are often fatal. Therefore, mishap reports which mention that SD was a factor tend to rely upon general, qualitative justifications for this inference. For example, SD may be deemed likely based on a lack of visual cues, the presence of high workload, distraction, or fatigue, and/or a general similarity of the flight circumstances to known orientation illusions in the literature or to known SD mishaps from the past. There are numerous, well-documented SD illusions, including the leans, the somatogravic illusion, the somatogyral illusions, the giant hand illusion, the visual vection illusion, G-excess effect, etc.[6,13-17] SD can also be caused by failure to detect subthreshold drift in a helicopter.[18]

Linking a mishap flight profile qualitatively to a known SD illusion is a start, but we recommend that mishap analysis should be more quantitative, comprehensive, and well-supported. We believe that a better approach to inferring SD as a mishap contributor entails matching data streams from the on-board recorders (e.g., acceleration, pilot control inputs) against scientific, quantitative models of SD to determine if SD would occur. The flight parameter data provides the force vectors experienced by the aircrew prior to the mishap. The existing spatial disorientation models using vector analysis can exploit this information and knowledge of perceptual functioning from basic science (e.g., dynamics of vestibular and somatosensory responses) to model what the pilot would have perceived if he/she was not adequately accessing veridical orientation cues from the aircraft attitude instruments or outside visual cues. Many reasons have been identified for the adverse mental states or mental habits that create unsafe flying conditions, including: poor scan, narrowed (or "channelized") attention (e.g., upon one display), distractions (e.g., from flying), high workload (or "task saturation"), sensory illusions, complacency, fatigue, poor crew coordination, and cockpit designs that do not promote optimal human-computer interaction or mode awareness.[5,19-22] There is also some evidence from a driving study that vehicle operators sometimes look at significant objects (such as instruments) without *attending* to them.[23] If one or more of the aforementioned circumstances are present when the pilot encounters misleading visual, vestibular, and/or somatosensory cues, SD can develop rapidly and cause a mishap.

The vestibular organs have been the focus of many past efforts to understand the SD aviators experience during flight. The vestibular organs are important because they constitute the key sensory modality specifically evolved to detect acceleration of the head in inertial space, yet they are not designed to provide veridical body orientation information within the unusual sensorimotor and force environments that occur during aerospace operations. For this reason, many classic vestibular (or more accurately, vestibular/somatosensory/visual) spatial orientation illusions have been named which can contribute to LOC or CFIT.[6,14-16] The authors believe that the inability of an aviator (or a flight crew) to accurately perceive aircraft position intuitively without reliance upon visual cues is a major crux of the aviation mishap problem. Maintaining spatial orientation cannot be accomplished during instrument flight unless one is attending to the appropriate visual instruments. Unfortunately, many of an aviator's distracting secondary flight tasks are also of a visual nature. The problem concerning the allocation of limited visual attention is compounded by the fact that nonvisual attention will be drawn to the more intuitive and compelling body cues concerning orientation, which in the environment of flight are not veridical. Conflicts between focal, symbolic visual information versus intuitive vestibular/somatosensory orientation information can be difficult to resolve quickly.[14] Generally, disorientation in flight is not caused merely by the formation of an incomplete mental model due to limited attention; rather, the problem is the formation of an *incorrect, yet persuasive* mental model due to one's tendency to use vestibular and somatosensory orientation cues when intuitive visual information about the outside world is absent. Aircraft motions expose aircrew to a resultant gravitoinertial force that is frequently changing in magnitude and direction. Under such circumstances, somatosensory and vestibular information concerning the direction of “down” will be inaccurate, and complete reliance must be placed on visual information if spatial orientation is to be maintained. Furthermore, prolonged angular accelerations and misleading visual information can produce illusions of motion and position.[14] In such circumstances, it is a physiologically normal response to experience SD, which may lead to control inputs (or failed inputs) that cause a mishap.[14]

III. Quantitative Approaches to the Analysis of Disorientation

For many years, the authors of this report and their colleagues have responded to requests from civilian and military accident investigation organizations to provide perceptual analysis of mishaps. The mathematical models we used for this purpose[24-25] helped with mishap explanation but lacked some of the experimental information desired for optimal perceptual model development. Information gathered over the years has permitted expansion of the perceptual models. We recently combined and extended several of the most advanced perceptual models to enable us to simulate laboratory findings and to examine mishaps to determine whether pilot misperception may have contributed. The latest modeling tool permits the inclusion of additional visual and non-visual sensory information not present in most previous models. This section briefly discusses some of the past models and the improvements we have endeavored to make to the state of orientation modeling.

Various researchers have developed, applied, and evaluated mathematical models of human spatial orientation based on concepts from estimation theory in engineering.[26-34] Borah and colleagues[27-28] originally developed a steady-state Kalman filter (KF) to model the orientation perception of a human riding passively in a vehicle. Their model included vestibular motion cues as well as dynamic angular and linear visual velocity information. While the Borah et al. KF model was capable of predicting responses to a number of vestibular and visual-vestibular motion paradigms, the linear nature of the KF restricted its application to small head deviations from the postural upright. Pommellet[35] modified Borah’s internal model and implemented a time-varying extended Kalman filter (EKF) to account for non-linear motion dynamics. The EKF model was able to match Borah’s predictions for simple stimuli, but it exhibited numerical instabilities during more complex motion profiles involving larger estimated tilt angles. A follow-up EKF study by Bilien[36] investigating the vestibular portions of the model encountered similar difficulties when modeling Coriolis cross-coupling responses (namely, a tumbling sensation during simultaneous multi-axis rotation which is described further in section VII of this report). Kynor[37] and Selva[34] developed stable implementations of the EKF (Selva also developed a stable unscented Kalman filter or UKF version of the Borah model) and were able to model a number of nonlinear, large angle perceptual responses successfully. While the stabilized model was able to reproduce simple visual illusions, such as linear vection, its integration of visual sensory pathways did not appear to match the true architecture or behavior of the central nervous system. For example, the model relied on visual velocity information (via visual flow of the surrounding visual scene) to suppress the somatogravic illusion in the light, a response which was not found experimentally.[38] Results were also highly dependent on model parameter assumptions and sensitive to small deviations in the assumed sensor bandwidths or noise covariance matrices. Finally, the model failed to reproduce sensations arising from contradictory vestibular sensory information. This finding led Bilien[36] to conclude that the optimal implementation of the KF and EKF may actually be "too optimal" to model the central nervous system's spatial orientation process.

Merfeld and colleagues[29] developed an "Observer" model of human spatial orientation based on the state Observer framework proposed by Luenberger.[39] Merfeld's model employed non-linear quaternion mathematics and internal models of semicircular canal and otolith dynamics to solve for central estimates of angular velocity, linear acceleration and gravity. By empirical adjustment of the four internal weighting parameters ($k_{\omega}, k_{f\omega}, k_f, k_a$), this model was capable of predicting responses to a number of motion stimuli including constant velocity earth-vertical rotation, off-vertical-axis rotation, and post-rotational tilt. Refinements by Merfeld and others[31-33] provided further model validation. Newman[40] added visual sensory information to the original Observer model framework and extended model predictions to include orientation, position and linear velocity estimates. Newman's model was able to mimic a number of visual sensory paradigms including linear and circular vection, rotation in the light and acceleration in the light.

To date, the use of perception modeling for aviation-specific applications has been limited. The three main efforts in the last four years are briefly described here, in chronological order. First was the Disorientation Analysis and Prediction System (DAPS), developed by Creare Inc.® The DAPS implemented the stable Kynor[37] EKF algorithm into a MathWorks® MATLAB®-based graphical user interface (GUI). DAPS was able to successfully simulate SD during two fixed-wing jet accidents involving the A-10 Thunderbolt. Since both of the chosen A-10 accidents were the result of underestimation of roll rate or angle, the general utility of the DAPS for high-G, supra-threshold, tactical-flight analysis needs to be established. Additionally, the aforementioned limitations of the Kynor EKF model may constrain the extent to which the DAPS can (without modification) provide accurate perceptual estimation during high otolith-canal conflict or in the presence of visual flow sensory input.

A second modeling effort was led by Ronald Small (Alion Science and Technology Corp.®) and his colleagues.[41-42] They developed a Spatial Disorientation Analysis Tool (SDAT) which included a sophisticated user interface, rules for classification of classic orientation illusions, and a rudimentary model for sensory cue interaction. Attempts to incorporate a more comprehensive Observer model of human perception into the SDAT have proved difficult so far, due to the inherent differences between the two modeling approaches. The third effort was by Groen,[43] who proposed an alternative (non-Observer) model for human orientation perception and provided a toolbox of MATLAB® routines and Simulink® block diagrams. Although comprehensive and well-documented, the result was essentially accessible only to expert MATLAB® users. Our recently developed Orientation Modeling System (OMS) attempts to address some of the limitations discussed above and to add several new model features, then package them in a user-friendly tool which is comprehensive and stable under various conditions, yet not more optimal in its perceptual predictions than actual human responses. The OMS is described briefly below.

IV. Description of a Quantitative Orientation Modeling Tool

To address some of the limitations of earlier efforts, a new perception model was developed, called the Orientation Modeling System (OMS). OMS is an extension of the Merfeld Observer family of models.[29] The basic methodology for extending the Merfeld model and adding the visual sensory components is described by Newman.[40] The many expanded capabilities and additional evaluations of the model will be described in a U.S. Army Aeromedical Research Laboratory technical report in preparation.[44] The purpose of this report is to briefly introduce a few of the features and practical applications of the model.

The vestibular core of the OMS is based on Merfeld's Spatial Orientation Model.[29] The original Merfeld topology was designed to process only vestibular-based sensory information. To incorporate visual cues, several structural modifications and extensions were required. The resulting model is shown in Fig. 1.

Newman, M.C., **Lawson**, B.D., Rupert, A.H., & McGrath, B.J. (2012). The role of perceptual modeling in the understanding of spatial disorientation during flight and ground-based simulator training. Proceedings of the American Institute of Aeronautics and Astronautics, 15 Aug., Minneapolis, MN, 14 pages.

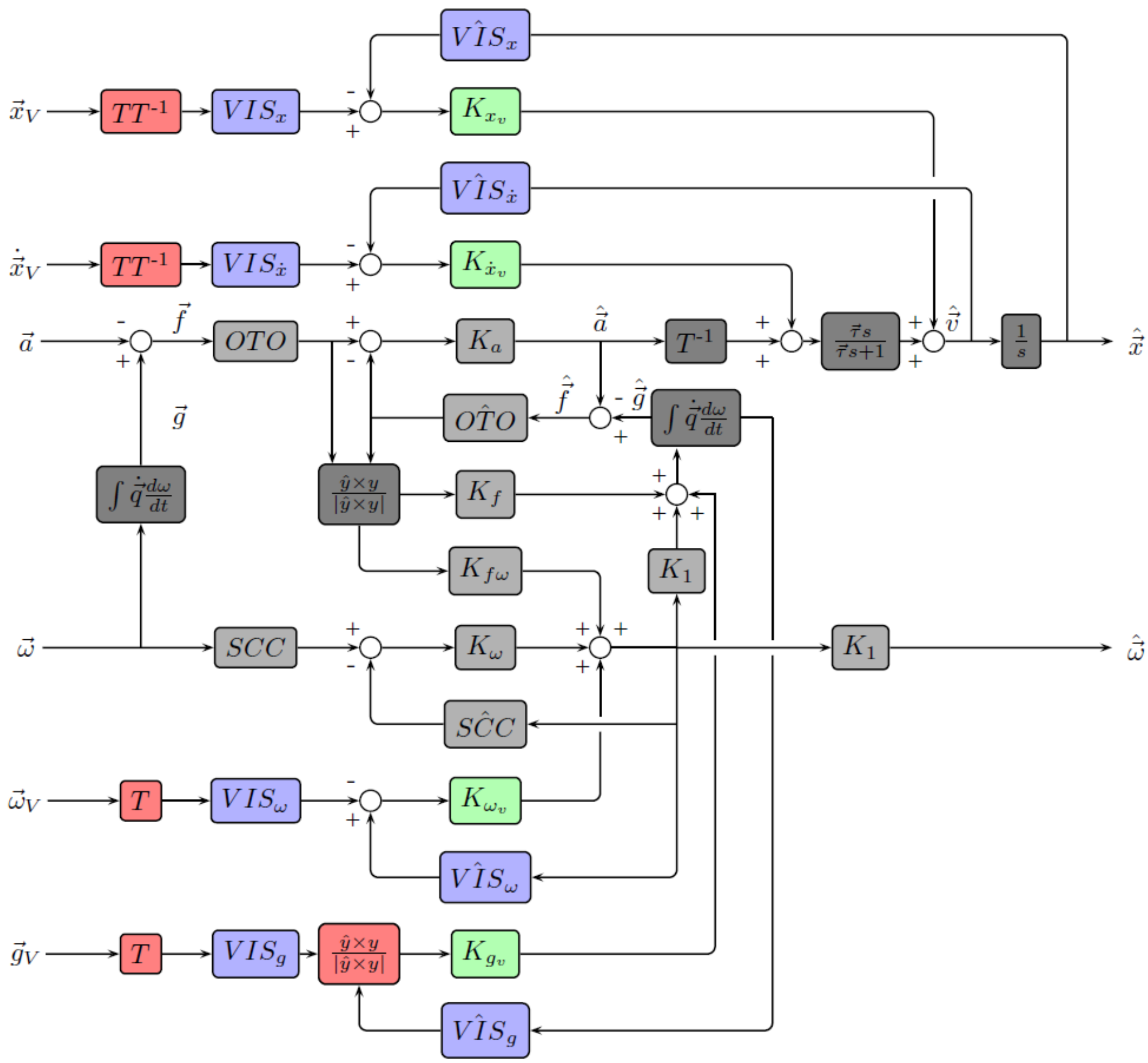

Figure 1. Orientation Modeling System (OMS) block diagram. Blocks highlighted in red, blue, and green correspond to the visual system pathways of OMS.

In the diagram in Fig. 1, three dimensional vectors of linear acceleration ($\vec{a}$) and angular velocity ($\vec{\omega}$) are provided to the vestibular system model in a head-fixed coordinate frame. Angular velocity is integrated using a quaternion integrator ($\int \dot{\vec{q}}$) to keep track of the orientation of gravity ($\vec{g}$) with respect to the head. The otolith (OTO) transfer functions are modeled as unity and respond to the gravitoinertial force ($\vec{f} = \vec{g} - \vec{a}$). 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. Vestibular information is combined with visual input from up to four visual cues: these include visual position ($\vec{x}_V$), visual velocity ($\dot{\vec{x}}_v$), visual angular velocity ($\vec{\omega}_V$), and visual gravity/orientation ($\vec{g}_V$).

The above inputs must then be integrated. Afferent signals from the semicircular canals, otoliths and visual sensors are compared in the central nervous system "Observer" against expected values from a similar set of internal sensory dynamics ($S\hat{C}C, O\hat{T}O, V\hat{I}S_x, V\hat{I}S_{\dot{x}}, V\hat{I}S_\omega, V\hat{I}S_g$). The resultant error signals are weighted with nine free parameters weighting various aspects of vestibular angular velocity and linear acceleration (K_ω, K_a, respectively), visual position, orientation, linear velocity, and angular velocity $(K_{\dot{x}v}, K_{gv}, K_{\dot{x}v}, K_{\omega v})$, the gravitoinertial force and its influence on the angular velocity estimate ($K_f, . K_{f\omega}$), and the total estimate of angular velocity (K_1). The model outputs are central estimates of linear acceleration ($\hat{\vec{a}}$), gravity ($\hat{\vec{g}}$), angular velocity ($\hat{\vec{\omega}}$), linear velocity ($\hat{\vec{v}}$), and position ($\hat{\vec{x}}$). Note that all hatted variables ($\widehat{\ }$) represent estimated states.

A program was written to serve as a user-friendly interface to the model. This program, called the Perception Toolbox, facilitates use of the model by aeromedical experts who may lack specific mathematical modeling expertise. The Perception Toolbox does not require the user to be an expert in MATLAB® or to be able to make line-by-line entries of the appropriate equations. Presently, the Perception Toolbox has the OMS and six other perception models programmed into its main GUI: the Merfeld et al. model,[29] the Haslwanter et al. model,[32] the Merfeld and Zupan model,[31] the Vingerhoets et al. model,[33] the extended Kalman filter model,[28,34-35,37] and the Selva unscented Kalman filter Model.[34]

In this report, we focus discussion on our own model, the OMS. To test the OMS, a number of established disorientation illusions were scripted and used to generate estimates of orientation and motion perception. Model predictions were compared with published experimental data and descriptions of each paradigm/illusion. The model successfully reproduced responses to angular velocity and linear acceleration steps, post rotational tilt, fixed radius centrifugation, the pitch up sensation (or somatogravic illusion) in response to forward linear acceleration, the sensation of tumbling that accompanies certain kinds of simultaneous multi-axis rotations during centrifuge training, and the SD reported during a recent mishap. These last two simulations (the multi-axis rotation and the SD mishap) are briefly described below.

V. Application of Orientation Modeling to an Aviation Mishap

On 10 August 2011, two U.S. Marine aviators (pilot and a weapons system officer) ejected from a McDonnell Douglas F/A-18D Hornet during a night intercept exercise 35 miles off the coast of Ensenada, Mexico. The mishap occurred at night, over the ocean, and with an average of 5.5Gz acting on the pilot's body during the maneuvers made during final 15 seconds of flight. The flight incident recording indicated that a series of extreme maneuvers were made prior to ejection.[*] There was no evidence of loss of consciousness, because control inputs were made throughout the end of the flight, the pilot communicated and ejected successfully, and the pilot did not report loss of consciousness. SD was thought to play a role in this accident.[*] We sought to analyze the accident further to infer when SD struck, what form it took (i.e., what type of illusion), and to estimate how it would have been expected to affect the pilot's control inputs.

A recreation of the aircraft's orientation, instrumentation and pilot control inputs was created by the Naval Air Systems Command, based on outputs from the deployable flight incident recorder (DFIR). We used this information to simulate the final 42.5 seconds of the mishap with the OMS. Information from the DFIR recording was up-sampled to 100 Hz using cubic spline interpolation, then converted to the proper coordinate frame and used to generate a series of OMS input files. For modeling purposes, we assumed that the pilot was facing forward and that he did not have a good visual reference to the outside world. These assumptions appear to agree with the conditions of the mishap. We evaluated the angular and linear acceleration cues acting on the body and compared the actual versus predicted (felt) orientation of the pilot in Fig. 2. Figure 2 shows the large misperception the pilot should have felt in his perceived self orientation in roll, pitch, and yaw. For brevity, the current report discusses the roll perception, where the error in perception was greatest. (The reader can see that pitch and yaw were in error also.)

[*]Mondeaux, Thomas, Major, Aviation Safety Officer, Marine All Weather Fighter Attack Squadron 121. Personal communication with Dr. Angus Rupert, 19 Sept 2011.

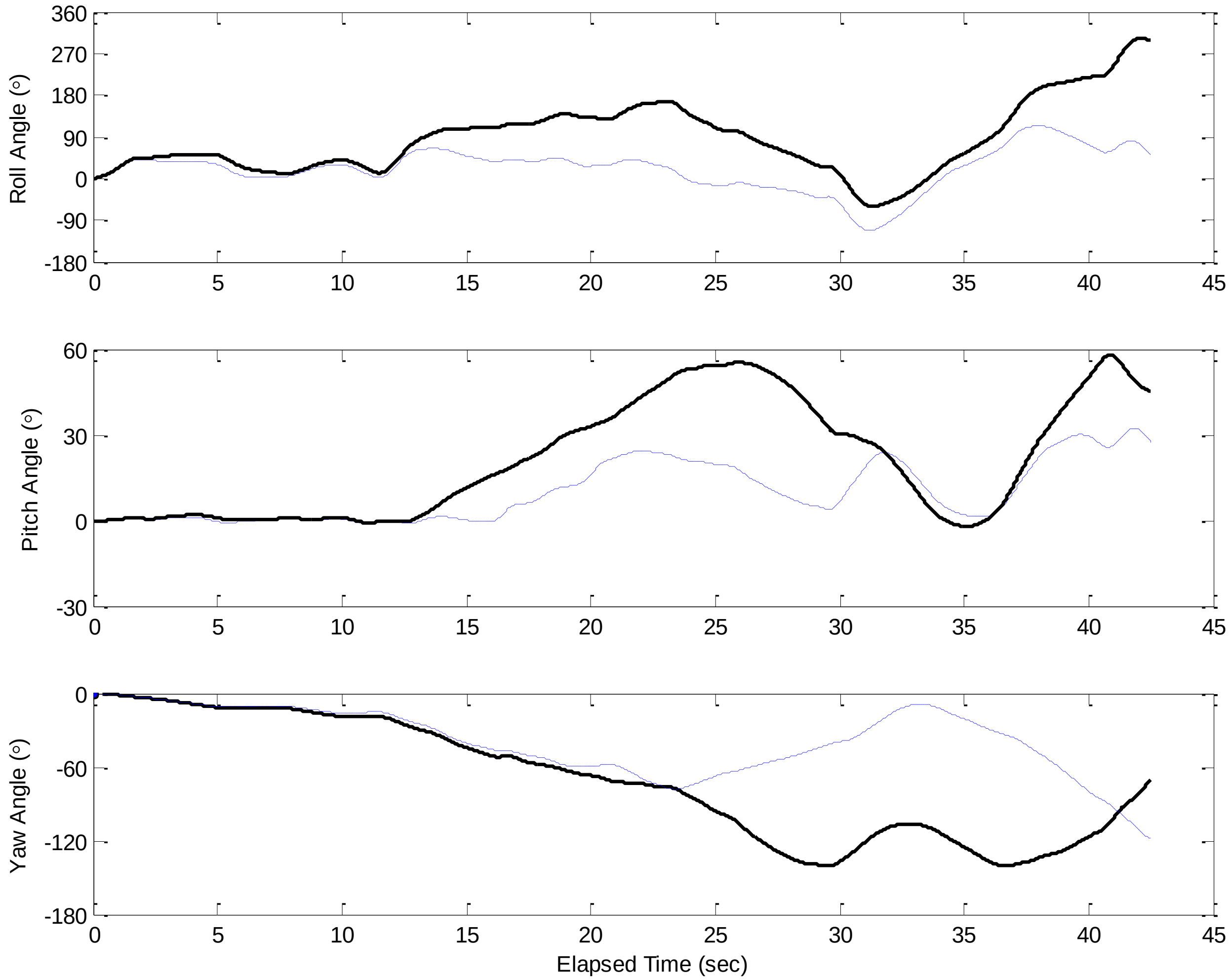

Figure 2. Perception preceding F18 mishap. Thick black line = actual orientation; dashed blue line = OMS estimate of perceived tilt. Roll angle (°) is shown on top, pitch angle in the middle, and yaw angle on the bottom.

The OMS incorporates the G-forces acting on the body during the mishap, predicting a significant misestimation of the pilot's spatial orientation. The Perception Toolbox yields a graphical recreation of the pilot's actual and estimated orientation. Two samples from that recreation are shown in Fig. 3.

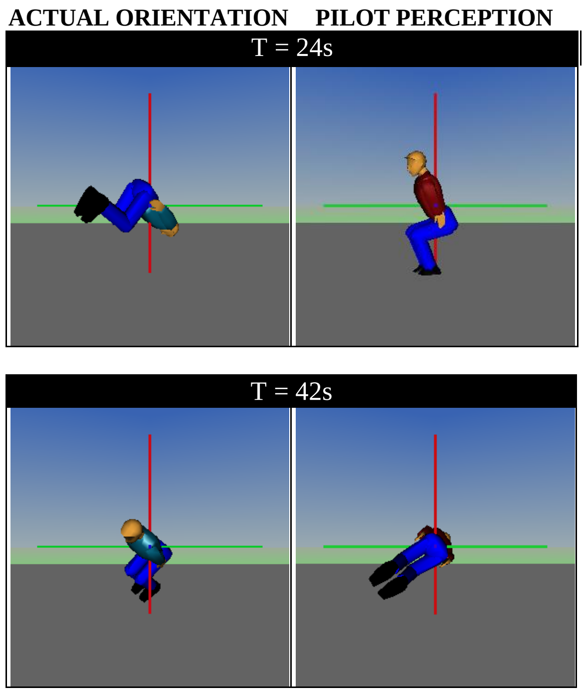

Figure 3. **Estimate of actual and felt pilot orientation** at two critical time points preceding the F18 ejection.

The model predicts that the most extreme errors in attitude perception would have occurred about the *x* (roll) axis. OMS predicts that from about 16 seconds into the simulation until 28 seconds have elapsed, the pilot would feel upright (upright = 0 degrees), *even though he was steadily rolling to a nearly inverted position* (inverted = +/- 180 degrees). The significant forces in Gz on the pilot starting at time 14 seconds would have reinforced this false perception of being upright. The OMS prediction of perceived roll orientation error (versus actual orientation) peaked at 24 seconds and, as may be expected, immediately prior to ejection (Fig. 3). In between these two extreme time points (at 32 seconds), the pilot began to pull back on the stick again in an attempt to stabilize the aircraft and regain control. Unfortunately, the pilot was not successful and the aircraft reached an average of 5.5Gz during the final 15 seconds of the flight, while roll and pitch perception degraded, leading to the aforementioned maximal roll misperception just before ejection. Based on these model estimates, we infer that a significant spatial disorientation event occurred, and furthermore, that the main initiating feature of the SD was a profound illusion wherein the pilot did not feel inverted when he actually was inverted during the aforementioned time period of the flight.

VI. Application of Modeling to Centrifuge-Based Simulation Training

In the final simulation, we discuss the application of the model to a problem which occurs during centrifuge-based flight training. In a classic vestibular experiment, Guedry and Benson[26] demonstrated that the tumbling sensations (and nausea) that result from a Coriolis cross-coupled head movement are greater when the orientation and magnitude of the resultant angular velocity impulse acting on the semicircular canals (and causing the tumbling sensation) is not aligned with the gravitational vertical. This established finding has been verified under various conditions[30,45-46] and has direct relevance for understanding the disorientation and sickness which accompanies certain head (or capsule) movements during centrifuge-based simulation training. Guedry and Benson[26] devised a simple model which we have modified and incorporated into the OMS to simulate the disorientation in this situation. In this section, we briefly highlight just the case where head movement occurs following prolonged constant velocity rotation.

In this simulation, a 30° right roll head tilt is made when angular velocity perception of the horizontal semicircular canal has effectively decayed to zero (left side of Fig. 4). As the head rolls, the resultant stimuli to the superior and horizontal semicircular canals produce a response traditionally referred to as the Coriolis cross-coupling illusion or the vestibular Coriolis Effect. This is a complicated illusion whose predominate feature in the main case studied is a sensation of forward pitch.[26] The person has an illusory sensation of angular motion forward about a third (in this case, y or pitch) axis of rotation that is orthogonal to the axes of the yaw body rotation and the roll head movement. This experience can be highly disorienting and nauseogenic when a gravity cue is simultaneously present (Figures 4 and 5).

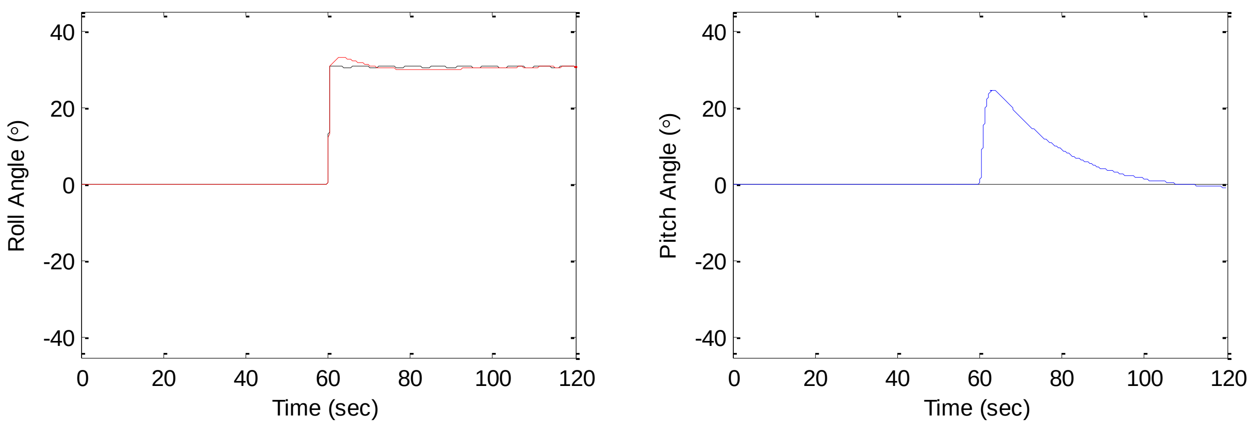

Figure 4. **Model response to a 30° head tilt during prolonged constant velocity rotation.** Perceived angles of roll (left) and pitch (right) are depicted in blue, actual angles of roll and pitch are in black.

To convey our findings more intuitively, Fig. 5 provides a simplified depiction of the model's ability to estimate the proper direction and magnitude of the resultant tumbling sensation. Part A of Fig. 5 shows the *z* (yaw) and *y* (pitch) vestibular canal axis acceleration stimuli (solid lines) and canal responses (dotted lines), which are represented as angular impulse vectors in part B. The dotted lines in part B show the predicted axis of illusory angular pitch-forward rotation, which matches the existence, direction (forward), and axis (pitch) of the illusory sensation reported by subjects[26-30] (intuitive representation in part C). Part D shows the GUI (side view), where model outputs can be observed and parameters altered intuitively.

The OMS model is a good match for the tumbling perceptions reported during Coriolis cross-coupling.[26,30] These simulation results are in good agreement with the analysis of Guedry and Benson,[26] with minor differences primarily due to the simplifying assumption they made concerning the head movement being instantaneous (we assume the head movement takes 0.5 seconds). A more significant difference is that the OMS has a feature which allows us to simulate (and animate) the paradoxical sensation of continuous tumbling velocity, but limited perception of displacement in tilt (this can only be depicted with a movie so is not shown here).

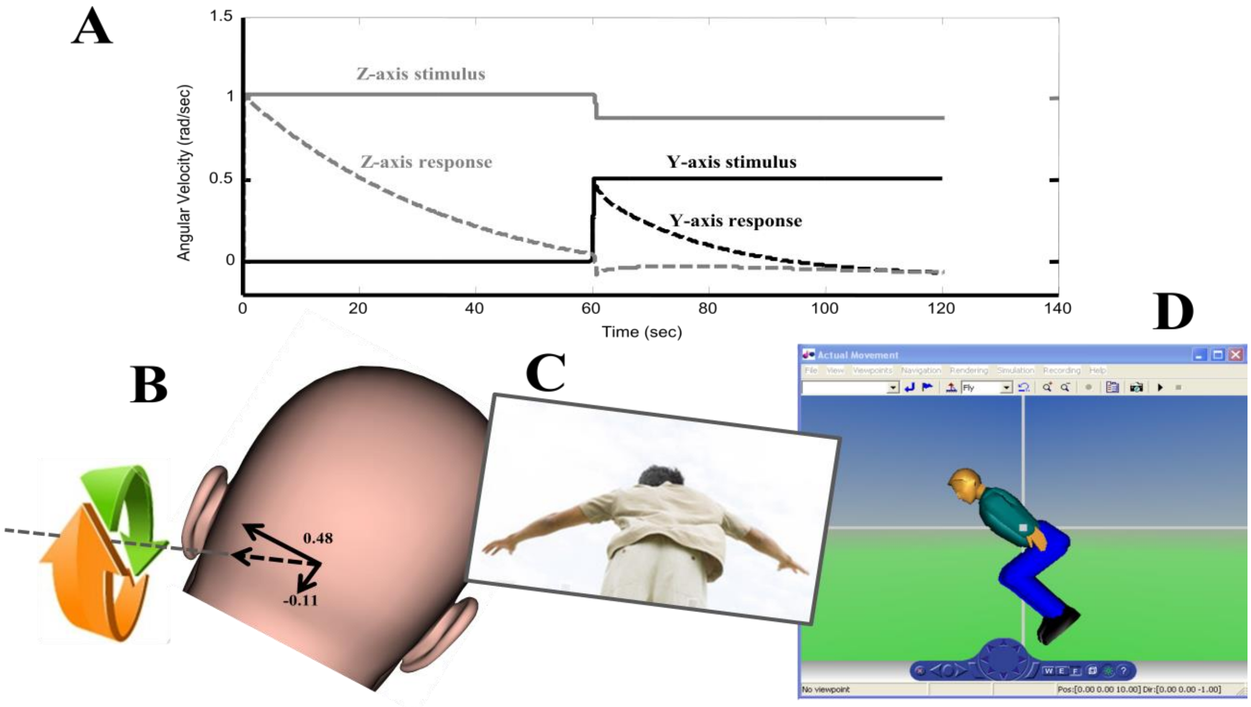

Figure 5A-D. Depiction of pitch perception during Coriolis cross-coupling.

One countermeasure for LOC or recognized SD is recovery training from aircraft upsets or unusual attitudes. While such training is most effective in flight, for safety reasons it is desirable to do much of the training in simulators.[47] Such training may be especially effective when the simulator is able to reproduce the G-forces the pilot would actually feel. This requires advanced solutions, such as a centrifuge-based flight simulator. Presenting appropriately integrated visual and motion stimuli via a centrifuge simulator expands the flight maneuvers that can be demonstrated to aviators and should aid in mishap reconstruction. Unfortunately, as we have seen in this section, the operating characteristics of the vestibular system can cause disorientation and nausea during certain combinations of centrifuge and subject motion. (Additional adverse effects can occur, including decreased ability to read visual displays and motion-induced drowsiness.)[9]

Disturbing Coriolis cross-coupling effects can be predicted with the OMS. Similarly, the OMS would predict that angular velocities experienced during real flight are usually too small to generate disorienting Coriolis cross-coupling effects and the disturbing effects in that case derive from other phenomena such as the G-excess effect.[17,11,30] Most importantly, the OMS can be used to help us identify certain vestibular or visual inputs during centrifuge-based training which can *reduce* these unwanted simulation effects. For example, the presence of an appropriate acceleration stimulus to the horizontal semicircular canals diminishes the disturbing effect of an earthward head movement during body rotation while seated upright.[26,30] Similarly, earthward head movement after prolonged rotation is less disorienting if it is preceded by viewing an earth-fixed visual reference.[48] The aforementioned visual reference tends to be helpful even under different gaze strategies and fields-of-view,[49] but it will be most helpful when the plane of stimulation of the vestibular system prior to the head movement is in yaw with the subject starting upright.[30] These various countermeasures for the disorienting effects of centrifuge training and hints about their optimal application can make advanced ground-based recovery training more feasible. They are all made possible by the development of good models of human orientation and their subsequent validation via empirical experiments.

VII. Conclusions

An Orientation Modeling System (OMS) and Perception Toolbox were developed to aid in the processing, simulation and visualization of human perception in response to three-dimensional, complex, multisensory motion stimuli. The OMS has been used to reproduce human perceptual responses to over a dozen laboratory motion perceptions and spatial disorientation illusions, among which two applied cases were discussed in this report. The OMS and six other perception models were programmed into a Perception Toolbox to facilitate comparison with previous research and modeling results. Practical applications of this new tool extend beyond the centrifuge and fixed-wing cases described. For example, the OMS is capable of modeling the inability to accurately estimate one's position during certain frequencies of vertical motion or during illusions of self motion (called vection) caused by blowing dust, sand, water, or snow. These capabilities are relevant to rotary-wing operations.

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