Integration of a Vestibular Model for the Disorientation Research Device Motion Algorithm Application

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INTRODUCTION: Spatial disorientation (SD) remains a leading cause of Class A mishaps and fatalities in aviation. Motion-based flight simulators and other research devices provide the capacity to rigorously study SD in order to develop effective countermeasures. By applying mathematical models of human orientation perception, we propose an approach to improve control algorithms for motion-based flight simulators to study SD.

METHODS: The Disorientation Research Device (DRD), or the Kraken™, is the Department of Defense's newest and most capable aerospace medicine motion-based research device. We implemented an "Observer" model for predicting aircrew spatial orientation perception within the DRD, and perceptions experienced in flight. Further, we propose a framework that uses the model output, in addition to pilot control inputs, to optimize multiaxis motion control including human-in-the-loop control capability.

RESULTS: A case study was performed to demonstrate the functionality of the framework. Additionally, the case study highlights both how limitations of human perception are crucial to consider when designing motion algorithms, and the challenges of effective flight simulation with multiple motion axes.

DISCUSSION: We implemented a mathematical model for spatial orientation perception to improve the design of control algorithms for motion-based flight simulators, using the DRD as an example application. We provide an example of predicting perceptions, producing quantitative information on the efficacy of motion control algorithms. This mathematical model based approach to validating motion control algorithms aims to improve the fidelity of ground-based SD research.

KEYWORDS: spatial disorientation, vestibular system, mathematical model, flight simulation, orientation perception.

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Spatial disorientation (SD) in the aviation domain, as defined by Benson,[1] is a pilot's "failure to correctly perceive attitude, position, and motion [of the aircraft]." Whether or not the pilot recognizes they are disoriented, SD events commonly result in inappropriate control inputs, controlled flight into terrain, and other accidents or mishaps. While a few measures have been implemented in an effort to address the problem, such as training aimed at increasing pilot awareness and ability to recognize disorientation, SD remains a leading cause of Class A mishaps in aviation across the world. The ubiquity and severity of SD has been well documented by surveys and mishap reports. They suggest SD has contributed to 12–33% of Class A mishaps across U.S. military branches[5,6,10] with some arguing an accompanying near-100% fatality rate,[6] and annually accounts for the destruction of at least 17 Department of Defense's (DoD) aircraft, deaths of more than 20 flight crew and losses exceeding $725 million.[19] Moreover, many believe there is gross underreporting of SD events from pilots who recover from SD events to avoid potential impacts on their certifications, as well as hesitancy of accident investigators to list SD as a causal factor due to lack of evidence in cases of fatalities.

To better understand SD, researchers have historically had to rely on analysis of crew reports and black box recordings of flight data. This is made even more difficult by the many causal factors that may impact SD – such as piloting experience, currency of training, physiological state, environmental conditions, etc. – which can vary widely between persons

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and scenarios. Many have proposed SD countermeasure technologies to integrate within the cockpit in addition to training, such as a tactile[13] and auditory[4] cueing, and alternative visual displays.[18] However, as SD is difficult to replicate and predict, these countermeasures have not been successfully adopted in operational settings. With the inception and continued advancement of motion-based flight simulators, investigators now have laboratory-based experimental tools for rigorously studying SD. This may help bridge the gap between ground-based countermeasure development and successful in-flight, operational implementation.

Visual, vestibular, and somatosensory information are the main sources from which spatial orientation perception is performed in aviation. Visual (fixed-base) flight simulation has been available for many decades now, and can provide rich and realistic sensory information for pilot training. Simulating the vestibular and somatosensory inertial motion cues experienced in flight, however, is a much greater challenge. The challenge is compounded by limitations of human sensory organs, physical restrictions of motion platforms, and an imperfect knowledge of how perception differs from reality. Of particular importance is the ambiguity of inertial cues sensed by the vestibular system. Due to the equivalence of gravity and linear acceleration, the otolith organs of the vestibular system cannot alone provide information to disambiguate between tilts relative to gravity and linear acceleration. Thus, the central nervous system (CNS) may use rotational cues, such as those sensed by the semicircular canals (SCC), in order to properly perceive the motions.[8] However, due to the mechanics of SCC transduction, during constant stimulation the sensory-neural response decays,[12] leading to misperception and many SD "illusions" commonly experienced by aircrew.[11]

Knowledge of these limitations of orientation perception is critical for designing motion algorithms aimed at replicating SD on the ground. Historically, researchers have attempted to heuristically design and then validate approaches based on expert pilot feedback, comparing past SD experiences with the simulator experience. The objective is to "best" replicate the aircraft motions within the limited motion capability of the simulator. To our knowledge, using mathematical models describing human motion perception to quantitatively compare differences in the perceptions of aircraft and simulator motion for improving motion cueing algorithms was first considered in a NASA technical report by Telban and Cardullo,[16] and more formally proposed by Bles and colleagues.[3] While this idea has been pursued by a few groups,[14,15] the applications were limited by at least one of the following: 1) offline 'optimization' of washout filter methods and algorithms aimed at maximizing the usable range of motion; 2) applied just to hexapod Stewart platforms; and 3) based on mathematical models of only peripheral sensory dynamics without the subsequent CNS multisensory processing which results in central perceptual estimates. Here we present a new implementation of this concept that was developed for use in an online, 'real-time' manner as input to the motion control algorithms to enable unconstrained human-in-the-loop control. We aim to apply this to a new class of research devices with 6 motion axes including planetary centrifugation to enable sustained high G acceleration stimulation and based on state-of-the-art mathematical models of multisensory integration for human orientation perception. A case study demonstrating the potential of such a system is provided, in addition to future work in using mathematical models of orientation perception for optimized control of ground-based simulators for SD research.

METHODS

The Disorientation Research Device (DRD), also known as the Kraken™, is the DoD's newest and most powerful aerospace medicine motion-based research device. The DRD is capable of simultaneous motion in six motion axes: roll, pitch, yaw rotation, vertical and radial translation, and planetary rotation. The sustained planetary rotation can produce centrifugation of up to 3 Gs. Beyond simple programmable motion, the DRD can interface with flight simulation and allow for human-in-the-loop control, enhancing the capability for authentic sensory stimulation in highly dynamic conditions. As one of only two devices like this in the world (Desdemona being the other, at the Netherlands Organization for Applied Scientific Research), researchers are still scratching the surface of the potential this device brings for investigating SD.

In an effort toward optimizing multi-axis motion control algorithms, we implemented a model of human orientation perception with visual and vestibular inputs aiming to run in real-time with the device controllers and flight simulation software. The 'Observer' model framework that was originally developed by Merfeld,[7] and has been well-validated experimentally,[7,9,17] is a continuous state estimator consisting of two main segments: 1) Physical dynamics of the world and sensory organs to the point of neural transduction; and 2) A model of the CNS processing and estimation behavior. These two key elements can be seen on our model in **Fig. 1** (red and blue dashed lines, respectively). Further, the blue circles in the model represent points of integration for visual (gray background) and vestibular (white background) information, which together produce central perceptual estimates of gravity ($\hat{\boldsymbol{g}}$), angular velocity ($\hat{\boldsymbol{\omega}}$), and linear acceleration ($\hat{\boldsymbol{a}}$), velocity ($\hat{\boldsymbol{v}}$), and position ($\hat{\boldsymbol{p}}$) (bold lettering indicates three-dimensional vectors, while 'hat' symbols are perceptual estimates of a physical variable).

As the central contribution of our approach (**Fig. 2**), we use the orientation perception model to simulate both the "real-world" aircraft state incorporating aircraft motion dynamics and the DRD commanded state (physical orientation and motion of cabin as vestibular input with visual simulation information as visual input). This framework provides predictions of the pilot's perceptions within the DRD simulator as well as those in real aircraft flight, which are then compared. An effective motion control algorithm would aim to minimize this difference (right side of Fig. 2). More generally, we propose this difference can be used as real-time input to the motion control algorithms, in addition to the pilot control inputs, to optimize control of the DRD's six motion axes for any number of specific

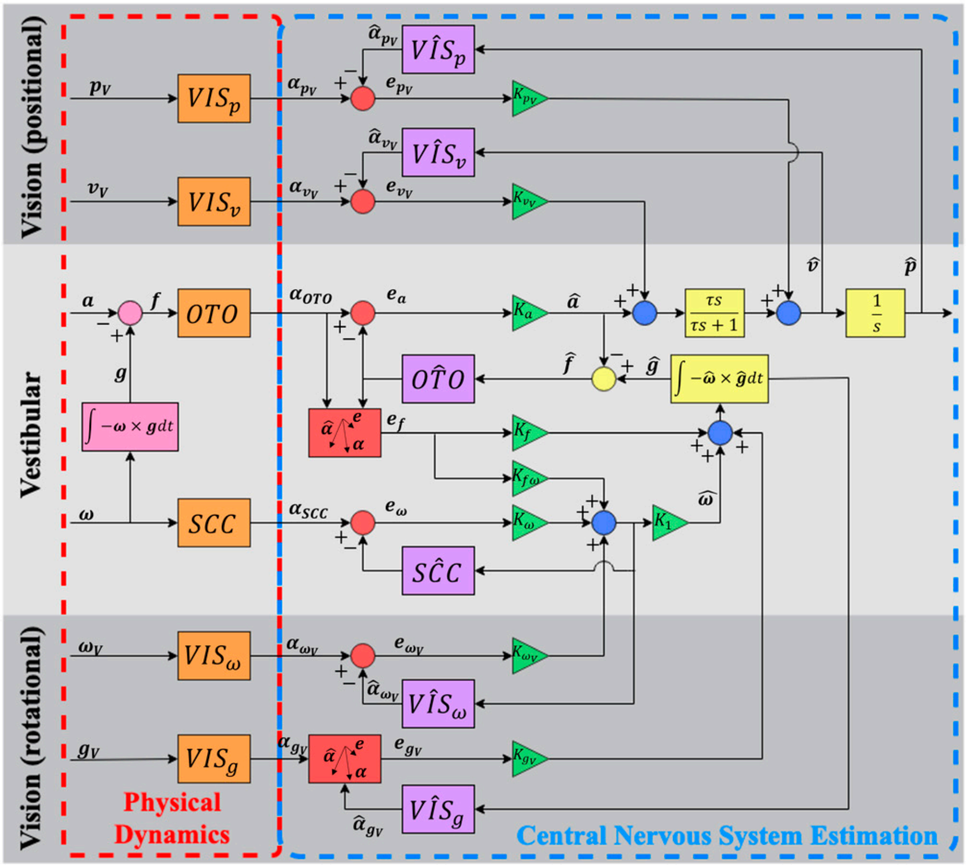

Fig. 1. A multisensory "Observer" model of human spatial orientation perception. Bold signal labels indicate three-dimensional vectors. Inertial forces – acceleration ($\boldsymbol{a}$) and angular velocity ($\boldsymbol{\omega}$) which are used to calculate gravito-inertial force ($\boldsymbol{f}$) (pink circle and block, worldly dynamics) – are input to vestibular sensory pathways (middle, light gray section). Visual pathways consist of positional inputs (top, dark gray) and rotational inputs (bottom, dark gray) – visual position ($\boldsymbol{p_V}$), linear velocity ($\boldsymbol{v_V}$), angular velocity ($\boldsymbol{\omega_V}$) and direction of gravity ($\boldsymbol{g_V}$) – that can be turned on and off based on environmental conditions. The inputs pass through models of sensory dynamics (orange blocks) including the visual system ($\boldsymbol{VIS_{p/v/\omega/g}}$), otolith organs ($\boldsymbol{OTO}$) and semicircular canals ($\boldsymbol{SCC}$). Afferent signals sent to the central nervous system are denoted by $\boldsymbol{\alpha}$, and variables with hat symbols ($\widehat{\boldsymbol{var}}$) represent CNS estimates of the corresponding parameters. Estimates of afferent signals ($\hat{\boldsymbol{\alpha}}$) are produced by CNS 'internal models' of the sensory dynamics (purple blocks), and differences between actual and expected afferents (red blocks and circles) produce error signals ($\boldsymbol{e}$) (i.e., sensory conflict) that result in estimates of orientation (e.g., $\hat{\boldsymbol{a}}, \hat{\boldsymbol{g}}, \hat{\boldsymbol{p}}$, etc.) after passing through gains (green triangles), points of sensory integration (blue circles) and internal models of worldly dynamics (yellow blocks).

goals (e.g., minimized perception differences, avoiding reaching the device's limits in any axis, enabling future expected motions, etc.). Finally, we note that the inertial motion inputs to the orientation perception model are angular velocity ($\boldsymbol{\omega}$), linear acceleration ($\boldsymbol{a}$), and gravity ($\boldsymbol{g}$), each provided in a pilot/subject head-fixed coordinate frame. Particularly for the DRD, this requires a transformation between coordinate frames accounting for the six motion axes. For initial development, aircraft flight physics data were generated using commercial off the shelf flight simulation software (Laminar X-Plane) which transformed the aircraft state into the orientation perception model inputs already in head-fixed coordinates.

RESULTS

As a demonstration of the potential of this framework for enabling dynamic, multi-axis simulations we present a case study of simulating a coordinated turn in the presence of clouds (no reliable visual information). In this case study, the motion algorithm was designed with the primary goal of accurately reproducing G-forces experienced in flight (the limitation of ground-based simulators being able to reproduce only some aspects of flight is expanded upon in the Discussion); however this is arbitrary, not our primary contribution, and our approach could be applied to other motion algorithm designs. The case study will also demonstrate both limitations of human perception that need to be considered when designing motion algorithms and the challenges of simulating authentic aircraft motion cues in a ground-based laboratory device.

G-forces during a coordinated turn in flight are a result of centripetal acceleration which is a product of the square of the planetary spin rate and the turn radius. Although these are the same means by which ground-based motion platforms like the DRD produce G-forces, the turn radius is much smaller than those experienced in flight. Thus, to produce a realistic 'seat-of-the-pants' sensation (e.g., the magnitude of the net G-force), the DRD capsule is required to spin at much higher planetary angular velocities.

For this case study the DRD is configured as shown in **Fig. 3** with the capsule (graphically depicted by an aircraft) at the end of the arm and facing in a direction (+x in Fig. 3) normal to the radial direction. The objective function of the DRD motion algorithm for this example is to accurately match the lateral gravito-inertial force (GIF)—which is coupled with the roll angle in this scenario—with low-pass filtering (smoothing) to avoid exceeding device limitations. The low-pass filter removes the high-frequency components of motion that require angular or linear accelerations beyond the capabilities of the hardware. This has a secondary effect of not reproducing some of the high-frequency "noisy" motions that a pilot might experience in flight, for example, due to light turbulence. Panel A of **Fig. 4** shows the actual (top) and perceived (bottom) angular velocity components (in a head-fixed right-hand coordinate system with +x out the nose, and +z out the top of the head—also represented in Fig. 3) for both the 'real-world' aircraft state taken

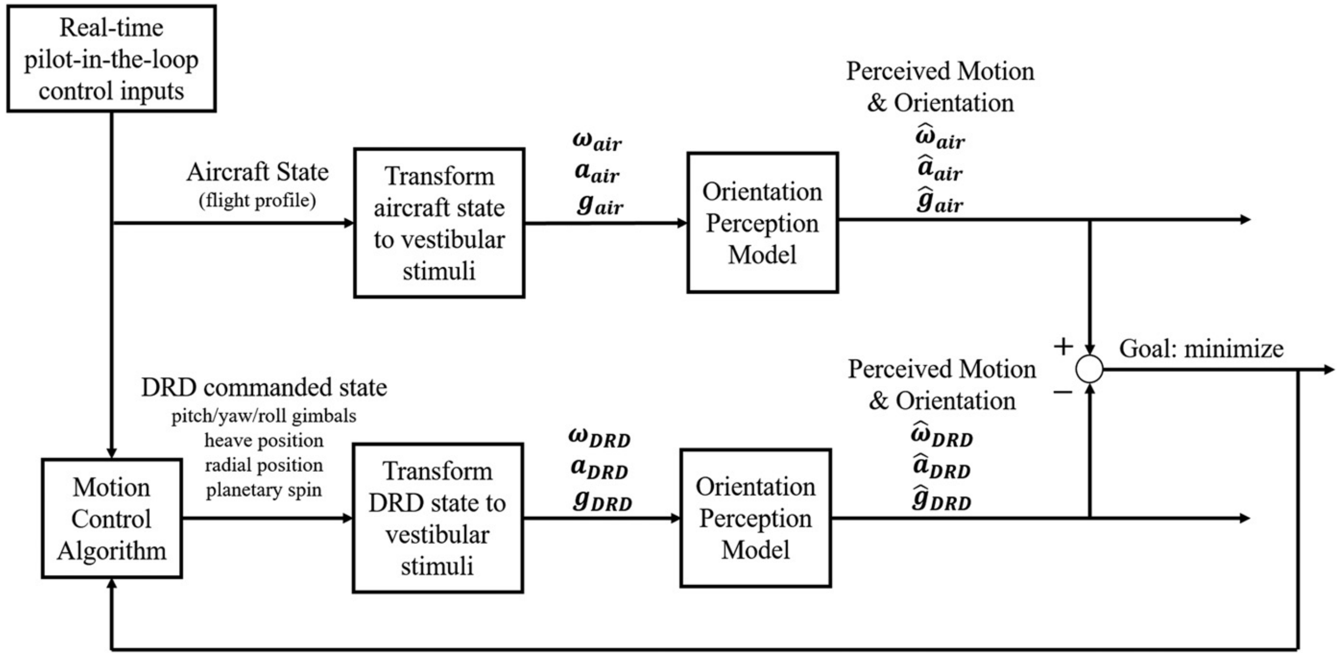

Fig. 2. Framework for optimizing motion control of flight simulators. Actual and simulated aircraft states are fed through two parallel orientation perception models to produce estimates of spatial orientation represented by angular velocity $\hat{\boldsymbol{\omega}}$, linear acceleration $\hat{\boldsymbol{a}}$ and gravity $\hat{\boldsymbol{g}}$ vectors (though more parameters of orientation may be included). The goal of the motion control algorithm is to minimize the difference between predicted perceptions expected during aircraft (air) flight and those on the motion device (DRD).

from the X-Plane simulation software (left), and the DRD capsule (right). In order to produce the two sets of perceived angular velocity (lower portions of Fig. 4A), two parallel observer models are simulated, one with the X-Plane orientation and motion inputs, and one with the DRD orientation and motion inputs. Panel B of Fig. 4 shows the differences in predicted perceptions between that experienced in flight and that to be experienced in the DRD.

In order to simulate a coordinated turn with a bank angle of approximately 40° (as pictured in Fig. 3), the DRD needs to produce 0.84 Gs (27 ft/s^2) of centripetal (lateral) acceleration, such that it sums with gravity to impose 1.31 Gs through the body-axis (rostro-caudal) of the pilot. At the DRD's maximum radius position of 4.9 m (16 ft) a planetary spin of 81 deg/s is required to produce the acceleration. This is represented in Fig. 4 (Panel A; top right) between the head y- (red) and z-axis (yellow) components as the pilot rolls (blue) into and out of the coordinated turn. Aforementioned was the SCC's limitation of having a decaying perception during constant angular velocities which can be visualized in the bottom right plot of Panel A. This may seem like an advantageous characteristic of the DRD profile when at first looking at the errors in perceptions (Panel B) where there are very large errors upon rolling into the coordinated turn. Specifically the X-Plane perceived angular velocity is very small, while the DRD angular velocity is initially larger (in y- and z-axes) before decaying, resulting in less error. However, there is a strong post-rotary illusion following the roll back out of the coordinated turn due to this misperception of actual DRD motion. We emphasize the quantified errors in perception are a function of the particular motion control algorithm used, which was not a focus of our study. Instead, Fig. 4 demonstrates the feasibility of using a model of orientation perception, simulated twice in parallel, to compare predicted perceptions on the DRD to those in a real aircraft.

Represented in Fig. 4 is the crux of ground-based motion simulation: to accurately replicate one aspect of orientation perception often requires sacrificing the accuracy of other aspects. These sacrifices largely stem from the fact that motion-based simulators are constrained to spin radii orders of magnitude smaller than those that can be experienced in flight. In this case study, the angular velocity perception in the head-centered y- (pitch) and z- (yaw) axes (sagittal and transverse planes, respectively) are sacrificed for accurately simulating the GIF magnitude (produced via centripetal acceleration) and roll angular velocity. One could think of a handful of creative strategies for taking advantage of the limitations of our biological sensors for the purpose of reducing the number of those sacrifices made. For example, because there is likely to be a post-rotary illusion following the simulated coordinated turn as highlighted in Panel B of Fig. 4, one could imagine using the yaw gimbal (not planetary rotation axis) to counter the post-rotary illusions in addition to prepositioning the cabin in a new orientation appropriate for the next maneuver. Our implementation of two parallel models of human orientation perception—one model assessing actual perceptions within the DRD, and one model assessing the perceptions to be experienced in actual flight—enables quantitative comparison and development of cost-function metrics to assess simulator efficacy. Moreover, having these models run in real-time along with the motion control algorithms is essential for enabling and

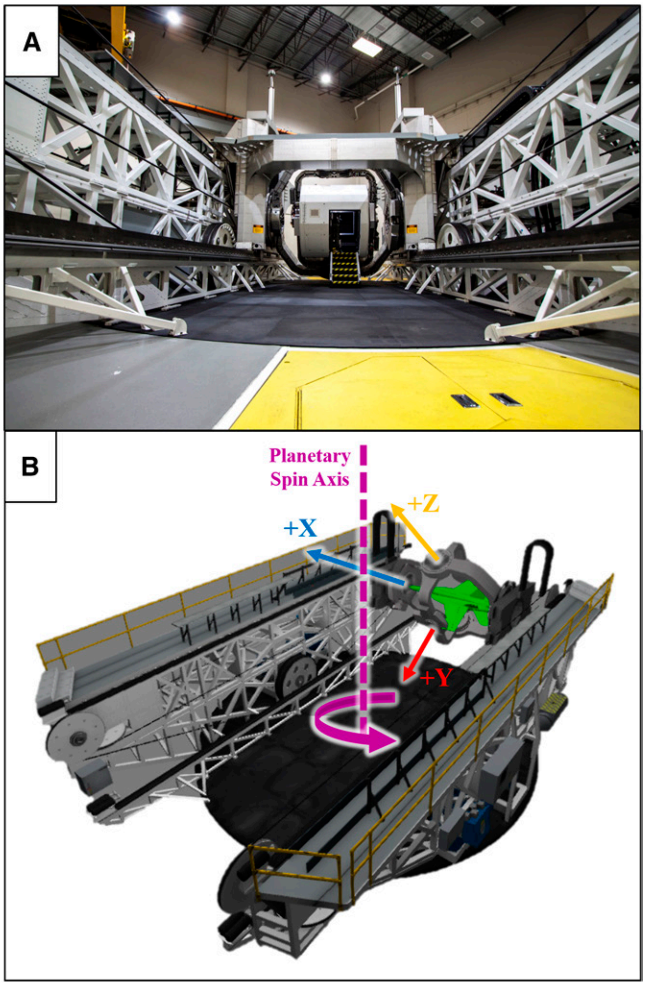

Fig. 3. Panel A: The Disorientation Research Device (DRD), aka the Kraken ™ (a six-motion axis research device). Panel B: The capsule represented by a green aircraft positioned at maximal radius performing a 40° left bank. Positive axes labels represent the head-fixed coordinate system used in the "Observer" model, and the planetary rotation axis of the DRD (purple) represents the degree-of-freedom used to produce 'G-forces'.

optimizing the end goal of human-in-the-loop manual control. Here the pilot is minimally constrained with respect to the maneuvers and series of motions they could make.

DISCUSSION

To summarize, we have implemented an "Observer" model for human spatial orientation perception with the goal of developing and optimizing motion control algorithms for ground-based flight simulators. Specifically, we have applied our approach to the state-of-the-art six-axis DRD. As a critical benefit, the mathematical model for orientation perception properly captures sensory limitations (e.g., SCC high pass filter dynamics—the inability to sense lower-frequency or constant angular rotations), multisensory integration, and central processing. Due to these dynamics it is possible to design a motion control algorithm that yields similar perceptions expected from flight by producing potentially very complex inertial motion stimulation that may not be immediately intuitive without the use of the model. We hope that this approach can be used to develop and validate more advanced motion control algorithms for ground-based recreation of SD.

While promising, there are limitations and important areas of future work. As shown in Fig. 2, the simulation of DRD and "real-flight" motion perception through parallel models enables a comparison of expected perceptions with the goal of minimizing the difference. However, as Fig. 4 demonstrates, these "differences" are multidimensional, including three-dimensional time history vectors in angular velocity, gravity, etc. In order to develop a unidimensional "cost function" of differences, we will need to better understand the following: 1) whether errors in different axes are more critical (e.g., do higher thresholds to linear acceleration in the rostro-caudal/z-axis as compared to the interaural/y-axis[2] make minimizing errors in this axis less critical?); 2) how to combine errors across angular velocity, linear acceleration, etc. (e.g., is 10 deg/s or a $1\ \mathrm{m} \cdot \mathrm{s}^{-2}$ error more critical?); and 3) how to properly capture the temporal criticality of errors (i.e., is a small difference that continues over an extended period of time more critical than a large, but brief error?). Once developed and validated, this cost function could be mathematically minimized to identify motion control algorithms which quantitatively "best" reproduce the perceptions expected in flight.

Unfortunately, simply minimizing this cost function may not yield the most appropriate motion control algorithm. Often other factors beyond minimizing the error between perceptions in the DRD, and those in flight may be highly important. For example, if the control algorithm simply aims to minimize this cost function at the current instant in time, it may command the DRD such that it is too near to device limitations to produce appropriate pilot perceptions in the future. This challenge is further complicated when simulating human-in-the-loop scenarios with flight inceptor (e.g., joystick) inputs. In this scenario, an effective algorithm must not only consider potential future motions which may need to be replicated, but should account for likely future pilot control inputs. This could be addressed within our framework using a "feed-forward" model of pilot behavior. Likely upcoming pilot actions and the resulting motions could be simulated through the model of orientation perception to inform the motion control algorithm of desirable actions aimed to minimize the cost function, not just as the current instant in time, but also in the future.

A common approach in motion control algorithm design aimed at "pre-positioning" the simulator such that it can maximize capability for effectively producing desired motions in the future is called a "washout filter." Here, the device is slowly moved back to a desirable neutral position using subthreshold motions. Washout filters have been developed and some have been well-validated for Stewart platforms, however, they become more complex for planetary motion devices with multiple, interrelated motion axes like the DRD. The desirable neutral position is not necessarily the central location of each motion axis, but instead depends upon interactions between

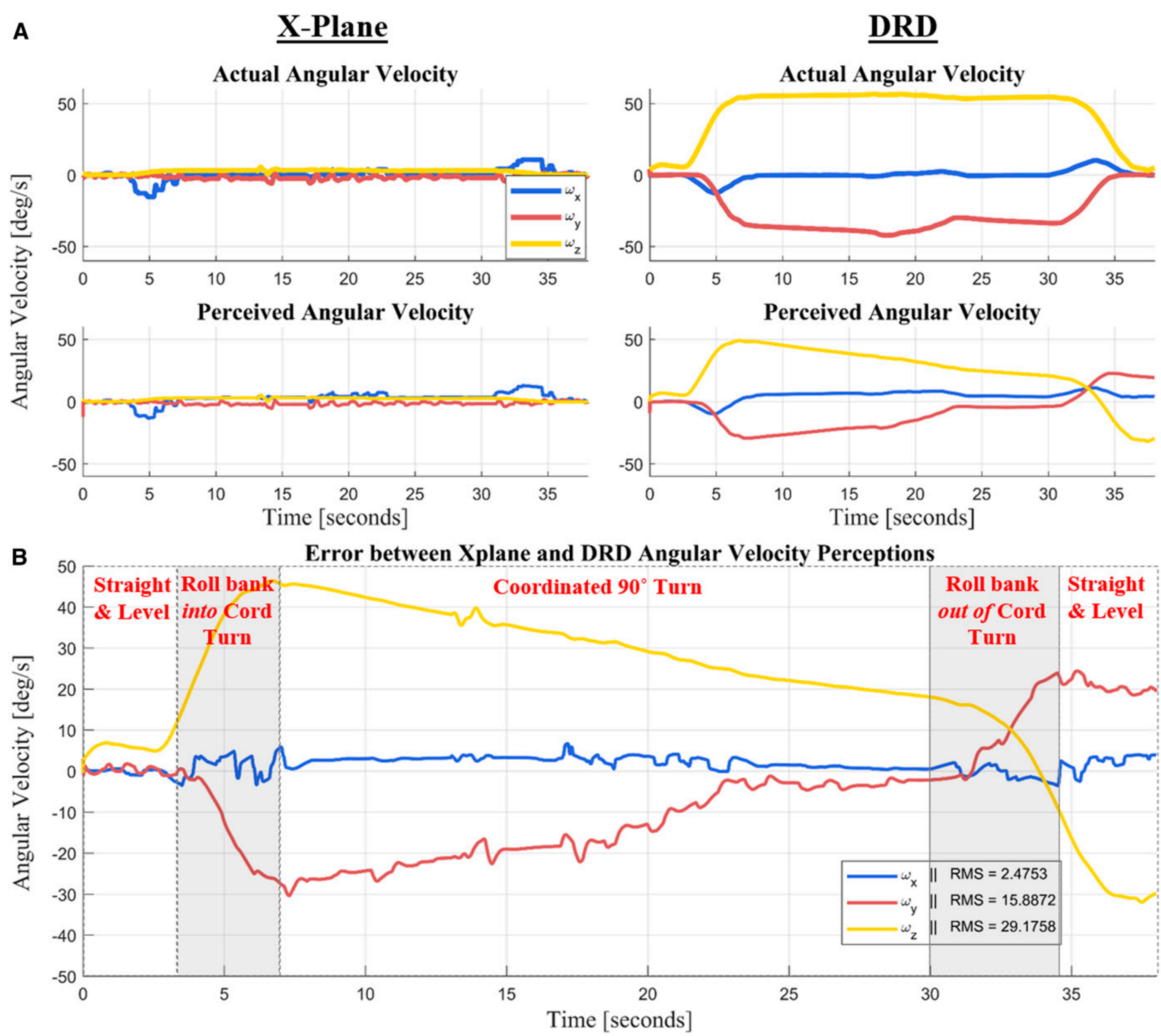

Fig. 4. An example scenario using the modeling framework to assess a motion algorithm for simulating a coordinated turn. Panel A: The left side shows flight angular velocity and the model's prediction for a pilot's perception of angular velocity. The right side depicts an example DRD motion algorithm and the corresponding predicted perception. Panel B: The difference between predicted perceptions in flight vs. those on the DRD, which is considered error in simulating the motion profile. The magnitude of the error can be quantified in each axis (x, y, z) by calculating the root mean square error (RMS), for example. Phases of the flight maneuver are denoted in red text and alternating shading.

axes (e.g., arm translation position interacts with planetary spin to produce tangential and centripetal accelerations). Further, "pre-positioning" approaches in a more general sense will depend upon future expected pilot inputs and associated motions and perceptions.

Another area of future work relates to the subject's head movements within the capsule/aircraft. Motion control algorithms primarily focus on the capsule motions applied to the whole body of the subject. Yet, the subject is capable, even likely, to perform head tilts and movements within the capsule. As the visual and vestibular system are located within the head, this will inevitably alter those cues and thus the subject's orientation perception. An important first step to account for this in control algorithm design is to reliably measure the subject's head and eye positions and orientations within the capsule in real-time. This information adjusts the inputs to the orientation perception model, providing the stimuli that are actually experienced in head coordinates. However, in a planetary motion device, such the DRD, head movements within the capsule create an additional complexity. Particularly, when producing G-forces by constant planetary motion, head movements within the capsule are likely to elicit the Coriolis "cross-coupled" illusion, which is typically not experienced during slower rotations of coordinated turns during real flight. By measuring subject head movements, potentially combined with a model of which head movements are likely, the cost function could suggest motion control approaches which are less likely to elicit these "artifact" illusions (i.e., perceptions that occur from head movements on the DRD that would not occur when making head movements in real flight).

In conclusion, we have proposed and implemented the use of a mathematical model for spatial orientation perception to improve the design of motion control algorithms of ground-based flight simulators. In particular, our approach was applied to the DRD, a state-of-the-art, six-axis, planetary motion platform. Through a case study, we provide an example of how the framework can predict motion perceptions on the DRD and compare them to those likely to be experienced in real flight. This approach is beneficial because it provides quantitative information regarding the efficacy of a motion control algorithm. Future work will be performed to feedback this information, and combine it with likely pilot inputs to produce an optimized motion control algorithm design.

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