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VISUALLY GUIDED CONTROL OF MOVEMENT IN THE CONTEXT OF MULTIMODAL STIMULATION

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ABSTRACT

Flight simulation has been almost exclusively concerned with simulating the motions of the aircraft. Physically distinct subsystems are often combined to simulate the varieties of aircraft motion. "Visual display systems" simulate the motion of the aircraft relative to remote objects and surfaces (e.g., other aircraft and the terrain). "Motion platform" simulators recreate aircraft motion relative to the gravitoinertial vector (i.e., correlated rotation and tilt as opposed to the "coordinated turn" in flight). "Control loaders" attempt to simulate the resistance of the aerodynamic medium to aircraft motion. However, there are few operational systems that attempt to simulate the motion of the pilot relative to the aircraft and the gravitoinertial vector. The design and use of all simulators is limited by poor understanding of postural control in the aircraft and its effect on the perception and control of flight. Analysis of the perception and control of flight (real or simulated) must consider that (a) the pilot is not rigidly attached to the aircraft and (b) the pilot actively monitors and adjusts body orientation and configuration in the aircraft. It is argued that this more complete approach to flight simulation requires that multimodal perception be considered as the rule rather that the exception. Moreover, the necessity of multimodal perception is revealed by emphasizing the complementarity rather than the redundancy among perceptual systems. Finally, an outline is presented for an experiment to be conducted at the NASA Ames Research Center. The experiment explicitly considers possible consequences of coordination between postural and vehicular control.

1.0 AN EXOLOGICAL PERSPECTIVE ON FLIGHT SIMULATION

1.1 Purpose and Assumptions

One purpose of research in flight simulation is to enhance the simulation of the force and motion environment generated by an aircraft. A need for enhancements is based largely on the assumption that extant systems do not adequately simulate certain flight regimes. The criteria for adequacy are rarely stated explicitly. The implicit criteria fall into two general categories: (a) Subjective experience in the simulator and the aircraft should be similar. Ideally, the simulation should not be perceived as such, but rather as motion of the pilot in an environment with recognizable objects. (b) Flight control skills acquired in the simulator and those acquired in the aircraft should be similar. Ideally, transfer of training from the simulator to the aircraft should be cost effective.

Inadequacy is an assumption because there has not been sufficient formal experimentation to conclude that any flight simulator is inadequate. However, it is equally important that there has not been sufficient formal experimentation to conclude that any flight simulator is adequate (cf. Cardullo & Sinacori, 1988; Lintern, 1987). The dearth of formal experimentation on the adequacy of flight simulators is almost certainly due to the fact that the criteria for adequacy are considered to be too nebulous or too complex in any situation that even remotely resembles flying an aircraft. Because of this fundamental lack of information, there has been considerable speculation and controversy about the utility of various flight simulation systems. In spite of the lack of information, there have been developments in flight simulation. One of the challenges for research in flight simulation is to demonstrate that new simulation concepts can be derived within a substantial scientific framework.

1.2 Approach

Developments in flight simulation have relied primarily on "sound engineering judgment," that is, on the ability of the engineer to translate the needs of the user into the actions of some physically realizable system. While this process can be very efficient, its effectiveness is limited by the precision (detail) and accuracy (validity or relevance) of specifications provided by the user. Developments in flight simulation may not engender improvements in usefulness if they are motivated by specifications that are not relevant to explicit criteria for adequacy. This is especially problematic in the design of human-machine systems because of the limited capacity for analytic introspection (by novices or experts) about the factors that are relevant to perception and action.

A more tractable approach to flight simulation has been to focus on the "limiting factors" in flight control that are peculiar to the simulator. The focus in on the interactions between the perception and control of the aircraft's attitude and motion, that is, the way in which perception of the aircraft's attitude and motion influences control of the aircraft's attitude and motion. Other factors (e.g., orders, plans, and threats) influence the pilot's actions once the situation is perceived, but such factors are more or less arbitrary given the plethora of present and future flight scenarios. Moreover, such factors must take into account the constraints on observability and controllability imposed by the human-machine system. This has provided a "principled basis" for developments in flight simulation: developments should be motivated by theory and experiments in psychophysics and manual control that suggest the ways in which observability and controllability of attitude and motion is different in the simulator and the aircraft. This approach is exemplified by ecological and control-theoretic research in flight simulation (e.g., Kron, Cardullo, & Young, 1980; Flach, Riccio, McMillan, & Warren, 1986; Martin, McMillan, Warren, & Riccio, 1986; Cardullo & Sinacori, 1989; Warren & Riccio, 1986; Riccio & Cress, 1986; Riccio, Cress, & Johnson, 1987; Riccio 1989; Riccio & Stoffregen, 1988, 1989; Stoffregen & Riccio, 1988, 1989a; Zacharias, Warren & Riccio, 1986).

It is sometimes suggested that developments in flight simulation could be based on "cognitive theory" or "consistent pilot opinion," but no principled basis for inclusion of such factors has ever been revealed. Cognitive theory should be dismissed as a basis for developments in flight simulation because it reveals virtually nothing about limitations that are peculiar to the simulator. One could consider situation-specific anxiety (e.g., about crashing) that may not be present in extant simulators; however, anxiety inducing devices in flight simulators have never been considered seriously. Any other differences between cognition in the simulator and in the aircraft are ultimately attributable to differences in observability and controllability. Pilot opinion is also questionable as a basis for developments in flight simulation. It should not be considered seriously unless there is corroborating theory suggests an important role for a particular source of information but where experimental evidence is either unavailable or inconclusive.

1.3 Unique Areas of Emphasis

The *sine qua non* of flight simulation is generally considered to be the capacity to induce perception of self motion through an environment without moving the observer. This capacity becomes useful if the observer is allowed to control the simulated self motion; that is, the observer-actor can achieve goals. Most goal directed motion through the environment requires perception of objects and surfaces that are distant from the observer. Visual perception is thus crucial for goal directed motion. For this reason, there is no question that "visual display systems" are necessary in flight simulation. There is general agreement that further developments in visual display systems are important because recognition of familiar objects and layouts increases the range of flight tasks that can be performed in the simulator. For example, the detail on a tanker aircraft is important in the approach and docking phases of in-flight refueling; the depth of a ravine or the presence of telephone wires is important in low level flight. In addition, there is no question that visual display systems are sufficient to induce the perception of constant velocity or low acceleration. The issue in flight simulation over which there is the greatest controversy, and for which there is the greatest design consequences, is whether there are any situations where visual display systems are not sufficient (e.g., Cardullo & Sinacori, 1988; Lintern, 1987).

The design considerations in flight simulation can be organized into three categories: movement of the aircraft relative to an inertial reference frame (section 1.3.1), management of kinetic and potential energy (section 1.3.2), and coordination of postural and vehicular control (section 1.3.3). Modifications to extant flight simulators are suggested in each of these categories. The basis for the modifications is provided by a consideration of the exigencies for perception and control. The relevant interactions between perception and control are summarized in conceptual block diagrams (see Fig. 1, Fig. 2, and "Glossary").

1.3.1 Movement relative to an inertial reference frame. The focus here is on acceleration. Motion cannot be controlled without producing variations in velocity. Goal directed motion requires that these variations are observable. The question for flight simulation is whether these variations (i.e., acceleration) can be perceived visually, and if so, whether these variations (i.e., acceleration) can be perceived visually, and if so, whether they are attributed to motion of the environment or motion of the observer. It is important to note that there is very little research that is relevant to this issue. The basic research on visual perception of acceleration generally concentrates on object motion. Basic research on the visual perception of egomotion generally involves situations where acceleration if either small, nonexistent, or irrelevant to the task. Moreover, the visual perception of accelerative self motion is rarely mentioned as a theoretically important issue. It is especially surprising that the visual perception of vehicular acceleration has been largely neglected in flight simulation research.

If the visual perception of vehicular acceleration were in some way deficient, it would be important to exploit vestibular and somatosensory perception in flight simulation. The sensitivity of these systems to acceleration is well established. In this respect it is important to note that deficiencies in the visual perception of vehicular acceleration would not necessarily be due to limitations in the visual system. Such deficiencies may exist because vehicular acceleration is fundamentally a multimodal phenomenon. By was of analogy, perception of vehicular acceleration without multimodal stimulation (i.e., with only the visual system) may be like perception of color without stimulating the "cone" cells of the retina (i.e., with only the "rod" cells). The visual perception of accelerative self motion may be limited (like the function of rod cells) to low levels of stimulation, perhaps as in special cases of postural sway (Stoffregen & Riccio, 1989b).

The most obvious concern about excessive reliance on visually simulated self motion is that the phenomenon requires the presence of optical structure. Optical structure is not always available in flight (e.g., at night, under a uniform sky, over water). Use of simulators is potentially more important in these dangerous conditions than in good visual conditions. Nonvisual stimulation would not be an option, it would be a necessity, if the simulator were to be used in such optically impoverished situations. A challenge for developments in flight simulation is to design systems that provide information about vehicular acceleration without relying on the visual system.

1.3.2 Management of kinetic and potential energy. The focus here is on coordinated maneuvers. An approach that is based on coordinated maneuvers is to be contrasted with one that is based on the degrees of freedom that can potentially be controlled independently in an aircraft. For example, the so-called "degree-of-freedom" approach might consider perception of roll, pitch, yaw, and airspeed to be fundamental (lift, drag, and thrust might be considered most fundamental but they would be difficult to relate to perceptual sensitivity). Data on the sensitivity of perceptual systems to these degrees of freedom of motion could be exploited in the design and integration of visual and nonvisual "display" systems for flight simulators. The advantage of the degree-of-freedom approach is that there is a considerable body of basic research that can be used to quantify the design process and objectify design decisions. However, there are several disadvantages to this approach: (a) an additional step is needed to reduce these data to a form that directly relates to actual flight control tasks (i.e., maneuvers); (b) there may be interactions among the degrees of freedom that alter sensitivity to the individual degrees of freedom of motion; (c) new dimensions of control may emerge when motions in various degrees of freedom covary.

A "maneuver based" approach would consider the aircraft's trajectory or flight path through the environment to be more basic than the mediate control parameters. Control of the trajectory involves changes in altitude and heading that constrain the covariation among roll, pitch, yaw, and airspeed. (It follows that adjustments of the stick, rudders, and throttle are also constrained to particular patterns of covariation.) The way in which covariation is constrained depends on the "evaluation function" for control. While the function (or criteria) on which control is evaluated (or guided) can vary, a generally important criterion that guides control is energy management. With respect to this criterion, efficient flight requires that the pilot monitor (directly or indirectly) the kinetic and potential energy of the aircraft. In particular, the pilot should be sensitive to the rate of change in, and exchange between, these parameters.

Management of kinetic energy requires control of the aircraft's velocity. The issues that pertain to perception of changes in velocity were mentioned above. Management of potential energy involves control of the so-called "G" forces acting on the aircraft. The magnitude and direction of the G forces are controlled primarily in curved trajectories (e.g., a "pull up" or a "coordinated turn").

The curvature of the trajectory determines the magnitude of the G forces. The attitude with respect to the trajectory (e.g., "angles of attack") determines the direction of the G forces on the aircraft. The magnitude and direction of the G forces, in turn, influences the trajectory of the aircraft. It is not known to what extent perceiving the magnitude and direction of G forces is required to produce efficient (coordinated) trajectories. Since the G forces are lawfully related to the radius and orientation of the trajectory, perceiving the trajectory kinematics could be sufficient. In principle, kinematic information is available to the visual system whenever optical structure is available. The question for flight simulation is whether the radius and orientation of the aircraft trajectory can be perceived visually. Again, the paucity of relevant data is noteworthy. This is surprising since the relevance of trajectory radius extends beyond flight control (e.g., perception of trajectory radius for the head would be useful in understanding the coordination of body segments during stance and pedal locomotion; Riccio & Stoffregen, 1988).

If the visual perception of trajectory radius and orientation were in some way deficient it would be important to exploit vestibular and somatosensory perception in flight simulation. The relationship between canal and otolith stimulation would seem ideally suited for perception of trajectory radius (unfortunately there are few data that directly relate to this hypothesis; Riccio & Stoffregen, 1989). There would be important implications for simulator design if people were actually sensitive to this relationship. perception of G forces could substitute for perception of trajectory radius and orientation. The sensitivity of vestibular and somatosensory systems to the direction and magnitude of G forces is not controversial (although the basis for this sensitivity is in question; Howard, 1986; Stoffregen & Riccio, 1988, 1989a; Riccio 1989).

It should be noted that curved trajectories are fundamentally multimodal phenomena. Again, an analogy to color vision may be useful. Instead of the electromagnetic "spectrum," the relevant continuum would be trajectory radius. Pure linear motion would be at one end of the continuum and pure angular motion at the other. Different kinds of sensors (i.e., with ranges of sensitivity to motion that differ with respect to their dependence on trajectory radius) are an efficient way to pick up information about the distribution of activity along the continuum. Together, different sensors are sensitive to information that is not available to individual sensors. In this way, the diverse response characteristics of the visual, vestibular, and somatosensory systems may be complementary with respect to complex patterns of self motion.

Efficient control of flight also requires that the pilot has some form of knowledge about the exchange of kinetic and potential energy (although this does not assume that the pilot has an "internal model" that is easily described by classical physics). An important basis for this knowledge is information about the ways in which changes in velocity are resisted in flight. Such information is contained in the relationship of control actions (e.g., stick, rudder, and throttle adjustments) to changes in aircraft states (e.g., velocity and trajectory). To the extent that one perceives the amplitude and frequency dependence of this relationship, the moment-to-moment dynamics of the aircraft are perceived. A more thorough understanding of the "nonstationary" dynamics of flight involves a sensitivity to the dependence of the dynamics on characteristics of the trajectory (e.g., G forces), the air mass (e.g., atmospheric pressure), and the aircraft (e.g., gross weight). This requires that the pilot frequently explore the relationship between control actions and aircraft states. Sensitivity to i.e., feedback about) control actions depends on characteristics of the controls (e.g., moveability of the stick). "Control loaders" are valuable in flight simulation because they allow the moveability of the control stick to vary as a function of the simulated aerodynamic environment. however, the pick up of this information is dependent on the motion and force environment inside the cockpit (i.e., vibration and G magnitude to which the pilot is subjected). A challenge for developments in flight simulation is to design systems that provide information about the motion and force environment inside the cockpit.

1.3.3 Coordination of postural control and aircraft control. The focus here is on the fact that the pilot's body is not a single rigid structure attached rigidly to the aircraft. This has important consequences for perception and control whenever the velocity vector or attitude of the aircraft changes. Consider the effect on the pilot's body when the aircraft undergoes a linear acceleration or a change in attitude. Torques are produced in different ways in different parts of the body. These torques give rise to uncontrolled body movements unless they are resisted by muscular action (and, to some extent, by restraint devices in the cockpit). When the head moves relative to the cockpit, visual stimulation will not be specific to motion of the aircraft through the environment, and vestibular stimulation will not be specific to motion of the aircraft relative to an inertial reference frame. Stimulation of the somatosensory system (and to some extent, the visual system) will be specific to motion of the body relative to the cockpit. Note that multimodal stimulation is not redundant, it is complementary (cf., Riccio & Stoffregen, 1988, 1989; Stoffregen & Riccio, 1988, 1989a). The overall pattern of stimulation is specific to the acceleration event, and event in which motion of the aircraft and motion of the body cannot be considered independently. The event must be considered in its entirety because of the consequences for perception and control: imposed motion of the head can frustrate the pick up of optical information; imposed motion of the torso or arms can frustrate manipulation of the control stick. A challenge for developments in flight simulation is to design systems for which the nonrigidity of the pilot has consequences for perception and action.

Consider also the effects on the pilot's body when the aircraft moves along a curved trajectory. It is often desirable for the z-axis of the aircraft to be parallel to the G vector. When they are not parallel, the various segments of the pilot's body must be "tilted" with respect to the cockpit in order to maintain a state of balance. The direction of postural balance in the cockpit provides information about the attitude of the aircraft relative to the G vector. Vestibular and somatosensory systems are sensitive to this information (cf., Riccio, Martin, & Stoffregen, 1988; Riccio, 1989). Sensitivity to this information could help the pilot fine tune the maneuver (e.g., coordinating attitude and airspeed). Attention to the direction of balance is also important for postural control in the aircraft seat. The pilot must detect imbalance in various body parts and detect the relative orientation of the support surfaces used to maintain balance (cf., Stoffregen & Riccio, 1988). Postural control stabilizes the "platform" for the perception and action systems (Riccio & Stoffregen, 1988). Deficiencies in postural control could compromise perception and control of the aircraft maneuver.

Focused attention on the orientation of the body and the aircraft relative to the G vector could cause the pilot to loose orientation with respect to the terrain. The terrain generally will not be perpendicular to the G vector or the aircraft z-axis. Managing the orientation of the aircraft relative to the G vector and the terrain, and the orientation of the body relative to the G vector and the aircraft, would seem to be an important, albeit complex, component of skilled flight control. This skill cannot be acquired in a simulator that does not allow the relative orientations of aircraft, G vector, and terrain to be manipulated independently. "Motion platform" simulators allow these orientations to be manipulated independently. However, they do not allow rotation to be manipulated independently of tilt with respect to the G vector. This is required for accurate simulation of curved trajectories. For example, the perception of rotation without a change in tilt is veridical during a coordinated turn. A challenge for developments in flight simulation is to design systems that allow the independent manipulation of rotation and the relative orientations of aircraft, G vector, and terrain.

Another important aspect of curved trajectories is variation in the magnitude of the G vector. Variation in G magnitude can be large enough to have significant physiological and biomechanical consequences (see Kron, et al., 1980). Many of these effects impose "hard" limits on perception and action. For example, "gray out" precludes peripheral vision; increases in the weight of the limbs may render movement impossible. The aircraft control problems that arise because of hard limits can be viewed as errors of omission; required control actions are precluded. However, even small variations in G magnitude change the environmental constraints on perception and action. Such constraints are "soft" in the sense that they do not necessarily preclude perception and action. They change the dynamics of body movement; that is, they change the muscular actions required to achieve a particular interaction with the environment. This can lead to control problems if the pilot does not have motor skills that are appropriate for the new dynamics. The aircraft control problems that arise because of soft constraints can be viewed as errors of commission; inappropriate control actions are induced. It is important to emphasize that learning to control an aircraft also involves learning to control the interaction of the body and the aircraft. The latter is probably a nontrivial component of piloting skills in many flight scenarios. Inappropriate skills may be acquired in a simulator that does not include the soft biomechanical constraints encountered in variable G maneuvers.

The inter-dependencies between postural and aircraft dynamics also influence the response to transients. for example, there are several ways in which the pilot can minimize the deleterious effects of changes in aircraft velocity or attitude. Muscular effort can be exerted in the direction opposite to the anticipated force due to aircraft motion. Alternatively, muscular co-contraction may stiffen the body sufficiently when forces cannot be anticipated. If neither of these strategies can be used, less massive parts of the body may be used to "take up slack" in the imposed motion. For example, eyes can move in such a way that fixation on a distant object can by maintained; the arms can move in such a way that the positions of the hands are maintained with respect to the controls. These skills of coordinated motion are important when the intent is to maintain posture (or fixation) and when the intent is to change posture (or fixation). For many flight scenarios, learning the inter-dependencies between postural and aircraft dynamics should be as important as learning the dynamics of the aircraft alone. Simulations may be seriously deficient if these inter-dependencies are not included. There is no reason to believe that fidelity of postural dynamics is any less important than fidelity of the "aero model" in flight simulation.

1.3.4. Multimodal perception and constraints on control. The issues that are most important in this ecological perspective on flight simulation have to do with the consequences of variation in the attitude and/or velocity vector of the aircraft. These consequences involve the forceful interaction of the aircraft with the pilot's body. For example, the forces imposed on the pilot's body stimulate multiple perceptual systems. It is a common assumption in many areas of research, including those concerned with flight simulation, that multimodal stimulation is either redundant or conflicting. However, this assumption is inappropriate given that nonredundancies are both common and informative for a nonrigid body (Riccio & Stoffregen, 1988, 1989; Stoffregen & Riccio, 1988, 1989a). Multimodal stimulation is more accurately described as complementary. The complementarity of multimodal stimulation has nontrivial implications for simulator design. While redundant stimulation would be necessary if it provided information not available to individual perceptual systems.

The forces imposed on the pilot during flight not only change the stimulation of perceptual systems but also change the constraints on body posture and movement. Both imposed stimulation and biomechanical constraints provide information about the flight situation. The difference between these two sources of information is that sensitivity to the latter requires that the pilot is active in the cockpit. For example, head movements, arm movements, and balance reveal the dynamics of the environment in which they occur. The balance and movement of the head would seem to be particularly informative because of its multiplicity of motion sensors and because of its relative lack of support. It follows that control of the head should be an important consideration in flight simulation.

Stimulation in the aircraft and the simulator are different because the actual motion of the pilot and cockpit are different. A major design problem in flight simulation is that increasing the fidelity of some modes of stimulation often reduces the fidelity of other modes of stimulation. The designer must assess the relative importance of various modes of stimulation (e.g., particular devices and "drive algorithms") as sources of information (sometimes viewed as "cues"). Multimodal stimulation and constraints on control appear to complicate the process in the sense that more sources of information must be considered. However, they may actually simplify the process in that they provide additional criteria on which to assess the relative importance of various modes of stimulation. For example, a motion platform or a "helmet loader" (see Kron, et al., 1980) may increase fidelity of simulated acceleration with respect to the control of a nonrigid body (i.e., postural control), while a wide field-of-view visual display may reduce fidelity with respect to the same criteria.

Fidelity criteria that are based on postural control may require more justification than criteria that are based on aircraft control. This emphasizes the need for basic research on the issues mentioned above. However, there are other factors that may influence whether postural criteria will ultimately appear in flight simulation. For example, consider the problem of "simulator sickness." In spite of considerable interest in simulator sickness, there has been a notorious lack of progress in understanding this and other situations that induce "motion sickness" (Stoffregen & Riccio, 1989a). A recent theory of motion sickness argues that the malady is due to a prolonged interference with postural control (Riccio & Stoffregen, 1989). The theory accounts for a much greater range of nausogenic and non-nausogenic phenomena than do other theories. Stated simply for the case of simulator sickness: postural control will be disrupted in the simulator to the extent that it is based on simulated motion (e.g., optic flow) that is not related to the dynamics of balance in the simulator cockpit. It remains to be seen whether this theory will have any impact on the flight simulation community; however, there is increasing interest in postural control outside the simulator after adaptation to the simulator. any effect on postural control outside the simulator would have to explained in terms of the postural controls strategies acquired in the simulator. This would ultimately lead to an appreciation of the importance of postural control in the simulator.

1.4 Summary and Experimental Prologue

Flight simulation has been almost exclusively concerned with simulating the motions of the aircraft. Physically distinct subsystems are often combined to simulate the varieties of aircraft motion. "Visual display systems" simulate the motion of the aircraft relative to remote objects and surfaces (e.g., other aircraft and the terrain). "Motion platform" simulators recreate aircraft motion relative to the gravitoinertial vector (i.e., correlated rotation and tilt as opposed to the "coordinated turn" in flight). "Control loaders" attempt to simulate the resistance of the aerodynamic medium to aircraft motion. However, there are few operational systems that attempt to simulate the motion of the pilot relative to the aircraft and the gravitoinertial vector. The design and use of all simulators is limited by poor understanding of postural control in the aircraft and its effect on the perception and control of flight. analysis of the perception and control of flight (real or simulated) must consider that (a) the pilot is not rigidly attached to the aircraft and (b) the pilot actively monitors and adjusts body orientation and configuration in the aircraft.

It was argued that this more complete approach to flight simulation requires that multimodal perception be considered as the rule rather than the exception. Moreover, the necessity of multimodal perception was revealed by emphasizing the complementarity rather than the redundancy among perceptual systems. The next sections outlines an experiment motivated by a workshop held recently at the NASA Ames Research Center (July, 1989). This experiment reflects some of the concerns mentioned above in that it considers possible consequences of coordination between postural and vehicular control.

2.0 PRELIMINARY EXPERIMENTAL DESIGN

2.1 Objective

In an exploratory experiment, we will evaluate predictions made by sensory-conflict and postural-instability theories of simulator sickness (cf. Riccio & Stoffregen, 1989; Stoffregen & Riccio, 1989). Experimental manipulations will be a comprise between operational relevance and theoretical relevance. Dependent variables will include "objective" measures of simulator sickness and its hypothetical correlates. In particular, we will evaluate the effects of our manipulations on several physiological measures of discomfort, several measures of postural control, and the experience of induced self motion (vection). The effects of the independent variables and the relationships among the dependent variables will be useful in the design and evaluation of flight simulators.

2.2 Apparatus

The experiment requires the use of a flight simulator in which discomfort and sickness are commonly reported. We plan to use the LHX helicopter simulator. This is a fixed-base simulator that has a wide (110 deg) field-of-view, high-resolution graphics, and a head-slaved helmet-mounted display. The display should contain objects on a textured terrain. In some conditions, the instrument panel inside the cockpit will be visible through a "window" in the outside-the-cockpit display. We will need to perturb the aircraft states with well-defined disturbances. The disturbances will be generated by a sum of three to seven harmonically unrelated sinusoids. The disturbance power will be concentrated in the frequency range between .01 and 1.0 Hz. A trial duration on the order of three to four minutes and a sampling rate of at least 60 Hz would be desirable. In some conditions, the pilot's head and torso will be restrained with an upper torso "seat belt" and shoulder harness. Demands on control of the head will be reduced with a cervical collar.

During a trial (not necessarily all trials), we will need to collect data on (a) the aircraft states that are relevant to the pilot's control task, (b) the pilot's flight-control actions, (c) the six degrees-of-freedom of head movement, and (d) physiological measures of discomfort (e.g., gastric motility and eye muscle activity).

We will also need to construct a zig-zag "balance beam" track to assess stability of gait outside the simulator.

2.3 Procedure

The simulated aircraft will move at a constant speed and altitude over a flat terrain. The aircraft will be subjected to a roll-axis disturbance. The first factor in the experimental design will be whether or not the pilot's head and torso are restrained. The second factor in the design will be task of the pilot. The task will be either (a) visually track an object that is not along the direction of motion (no control of the aircraft), (b) simply maintain the head and upper torso in an erect posture (no control of aircraft), or (c) disturbance regulation in which the pilot attempts to maintain a wings-level attitude.. The third factor in the experiment will be the presence or absence of an inside-the-cockpit scent. These factors will be manipulated in a fractional factorial design.

After each trial, pilots will rate the magnitude of vection that they experienced during the trial. A four-point rating scale will be used.

After a set of trials, the pilot will walk on a balance beam that curves alternately to the left and the right. The time to traverse the balance beam and the number of falls will be recorded.

We will also collect data on the pilot's subjective experience of discomfort. Pilots will be queried about symptoms ranging from eye strain and fatigue to nausea and dizziness.

2.4 Analyses

Physiological measures of discomfort will analyzed for each trial. The method of analysis vary from measure to measure. For example, the dominant frequency of gastric motility will be computed form the electrogastrogram (see Hettinger, et al., 1988). Subjective ratings of vection and discomfort will also be analyzed as in Hettinger, et al., 1988).

Manual control data will be analyzed for the disturbance regulation trials. We will compute the root-mean-square (RMS) roll-axis motion. We will compare the control-stick activity at the disturbance frequencies (correlated power spectrum) with the activity that is not at the disturbance frequencies (remnant power spectrum). We will compare the shapes of the correlated and remnant power spectra. We will compute the "open-loop" gain crossover frequency and phase margin. such analyses are generally informative in the disturbance regulation paradigm (Martin, McMillan, Warren, & Riccio, 1986; Riccio, Cress, & Johnson, 1987; cf. Zacharias, et al., 1986).

Head movement data will be analyzed on all trials. we will compute RMS activity for all degrees of freedom. We will compare the roll-axis head activity at the disturbance frequencies (correlated power spectrum) with the activity that is not at the disturbance frequencies (remnant power spectrum). We will compare the shapes of the correlated and remnant power spectra for the roll axis. We also compute these frequency-domain statistics for any other axis for which there are differences in RMS head activity.

Sets of dependent variables will be analyzed by different investigators. There are five sets of dependent variables: (a) subjective measures of vection and discomfort, (b) physiological measures of discomfort, (c) manual control measures of disturbance regulation performance, (d) measures of postural stability in the simulator, and (e) measures of gait stability outside the simulator. The effects of the experimental manipulations on each set of dependent variables will be analyzed in separate analyses of variance. Individual analyses may be simplified by considering only subsets of the experimental manipulations. Collaboration among the investigators will facilitate analysis of the canonical correlations among the sets of dependent variables.

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GLOSSARY

Aerodynamics. The relationship between aircraft motion and the combined effects of commanded motion and changes in the air mass. to simplify the block diagrams, the automatic flight-control system and classical aerodynamics due to movements of the control surfaces and those due to changes in the air mass have not been differentiated.

Aero Disturbance. Changes in the air mass relative to the aircraft.

Aircraft (also a/c). An object that is capable of movement above ground through buoyancy or aerodynamics.

A/C Controls. The parts of the cockpit that can be moved or modified by the pilot in order to change or maintain the states of the aircraft.

A/C Visuals. Optical information from inside the cockpit: including the layout of surfaces in the cockpit as well as instruments.

A/C: Medium. Resistance of the medium of support (total aerodynamic environment) to particular aircraft states.

A/C: Object. States of the aircraft relative to another object.

A/C: Terrain. States of the aircraft relative to the ground.

Balance. Maintaining the orientation (or attitude) of a controlled system with respect to the vector sum of forces imposed on that system.

Biomechanics. The relationship between the motion of, and the total force acting on, various parts of an organism.

Coordination. Control of a part of an organism and/or its environment that takes into account the constraints imposed by concurrent control of another part of the organism and/or its environment.

Cost Functional. The effect of organismic and environmental parameters on the efficiency of action in a controlled system.

Disturbance. Changes in the states of aircraft relative to the terrain, other aircraft, or the air mass (including wind gusts).

Distal Layout. The parts of the substantial environment with which an organism is not in contact.

Environment. Surfaces of support (e.g., the terrain or the ground), media of support (e.g., an air mass or a non-contact force), detached objects (e.g., aircraft or projectiles), attached objects (e.g., trees or buildings).

Flight Simulator. A controlled system that recreates the motions and forces to which a pilot is subjected in an aircraft.

Flight control. A system that moves, or resists the movement of, the aircraft on the basis of information about the aircraft states (this is always the human in our block diagrams).

Gravitoinertial. The vector combination of gravity and acceleration, which can be conceptualized as an unitary force or as a potential for acceleration.

Imposed Forces. Vector combination of all forces acting on a particular part of an organism, excluding forces internal to the organism.

Manipulanda. The parts of the environment that can be moved or modified.

Medium. Parts of the environment that are nonsubstantial (i.e., afford passage through).

Object. Any substantial part of the environment that is distinct from the terrain or the ground (e.g., aircraft or projectiles).

Orientation of the Pilot. $\theta(t)$ and $\Phi(t)$.

Physiology. The systems internal to the organism that are effected by gravitoinertial magnitude.

Pilot: Balance. Orientation of various parts of the pilot's body (i.e., head, torso, arms, and legs) with respect to direction of balance.

Pilot: Controls. States of the pilot's manipulators (e.g., hands and feet) with respect to the a/c controls.

Pilot: Gravitoinertial Magnitude (also GI-mag). Physiological responses of the pilot to increases or decreases in the magnitude of the gravitoinertial vector.

Pilot: Seat. States of the pilot's body (i.e., torso and legs, including bottocks) with respect to a/c seat.

Pilot: Visuals. States of the pilot's eyes with respect to a/c visuals.

Postural Control. A system that, on the basis of information about body states, moves or resists the movement of the various parts of an organism that subserve balance.

Seat. Surface that can completely support the weight of the body through contact resistance at the buttocks, and that may resist the motion of the body through contact resistance at various parts of the torso and extremities (e.g., in an a/c seat).

Sensory Systems (also Perceptual System). Systems that can acquire information about states of an organism and its environment.

Self-Generated Forces. Forces internal to the organism that are responsible for moving, or resiting the movement of, parts of its body.

States of the Pilot/Aircraft. $\theta(t)$, $\Phi(t)$, $\psi(t)$, $x(t)$, $y(t)$, $z(t)$.

Terrain (also Ground). Surfaces that can completely support the weight f, and are large in scale relative to the action capabilities of, an object.

Vehicle. A controlled system that can transport an object form one place to another.

$\theta(t)$. Time history with respect to roll axis.

$\Phi(t)$. Time history with respect to pitch axis.

$\psi(t)$. Time history with respect to yaw axis.

$x(t)$. Time history with respect to longitudinal axis.

$y(t)$. Time history with respect to lateral axis.

$z(t)$. Time history with respect to gravity axis.

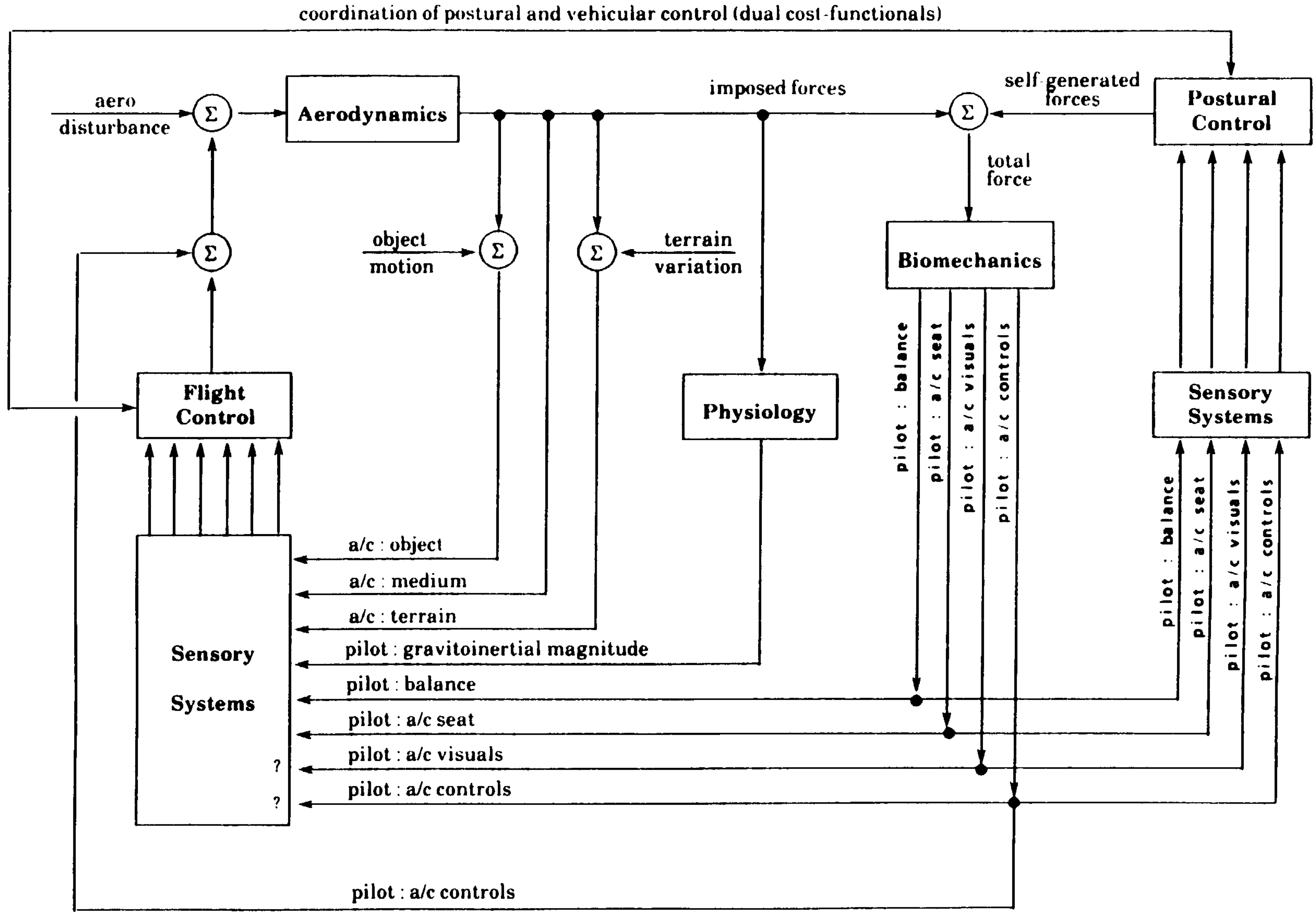

Figure 1. Coordination of postural control and vehicular control in an aircraft. The "closed loop" interactions between perception and control are indicated for the dual tasks of postural and aircraft control. Both control of posture and control of the aircraft require that the pilot monitor the "gravitoinertial" vector (i.e., the direction and magnitude of "G forces"), the parts of the environment that are in contact with the aircraft or the body, and some parts of the environment that are not in contact with the aircraft or the body. Note that control of the aircraft has consequences for control of posture and vice versa. Note also that the relationship between the aircraft and the pilot's body (e.g., relative position and orientation) provides information that is relevant to both postural control and aircraft control. See the glossary for a brief description of the labels used in the block diagram.

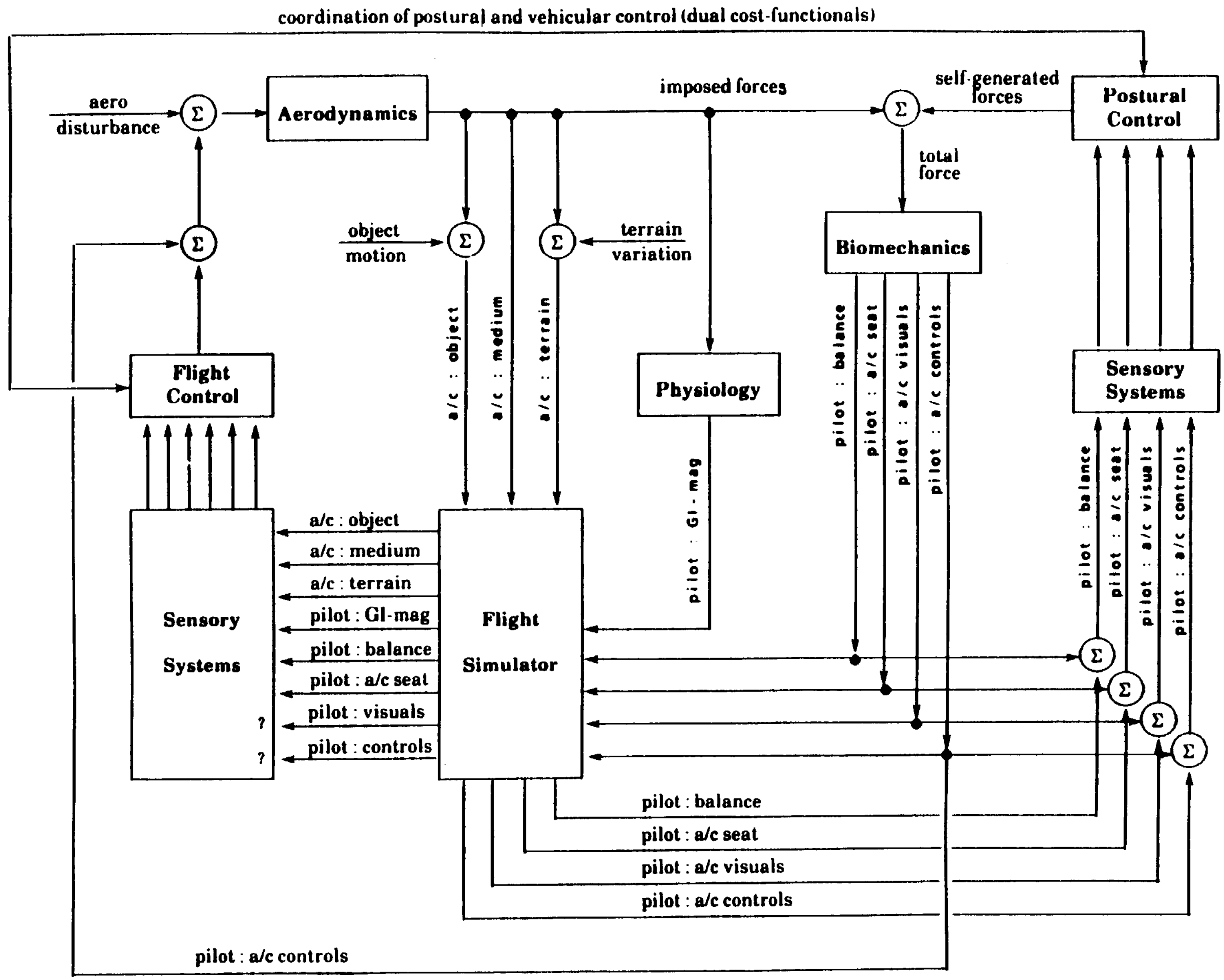

Figure 2. Coordination of postural control and vehicular control in a flight simulator. The "closed loop" interactions between perception and control are indicated for the dual tasks of postural and simulated aircraft control. Note the similarities and differences with Figure 1. The interactions between postural and aircraft control have important implications for simulator fidelity. The dynamics of postural control in the cockpit provide additional sources of information that could be exploited in flight simulation. See the glossary for a brief description of the labels used in the block diagram.