THE FEASIBILITY OF EMPLOYING AN IN-COCKPIT DEVICE TO PROVIDE MOTION CUES TO THE PILOT OF A FLIGHT SIMULATOR

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ABSTRACT

A study was undertaken to investigate the feasibility of providing motion simulation with an in-cockpit device rather than an external motion platform. The conventional wisdom has deemed that it would not be feasible to provide the necessary stimulation of the vestibular apparatus because of insufficient excursion inherent in an in-cockpit device. This paper addresses that issue in light of recent research that begins to clarify this interrelationship between the visual and vestibular systems in the perception of motion. A novel approach is suggested which relies heavily on the coordination of the visual and vestibular systems. In addition, experimental protocols are suggested by which the approach can be verified. This study was originally performed for helicopter simulators but the technique is applicable to fighters as well and perhaps even to transport aircraft.

INTRODUCTION

Since motion is perceived through stimulation of several physiological receptor systems (visual, vestibular, haptic and auditory), many designers and users of flight training simulators have felt it was necessary to utilize platform motion systems to provide the vestibular and some of the haptic stimuli. This has, by no means, been a unanimous point of view. In fact, the subject has been controversial in the flight training community for quite some time.

The reasons for the controversy are manifold, not the least of which is cost -- including purchase, facilities and maintenance. Other factors are compatibility with certain visual displays, false cues in certain maneuvers, safety and reliability.

There is then a great deal of motivation to eliminate platform motion systems. It is our opinion, however, that in order to provide the appropriate motion stimuli, the platform motion system must be replaced with an adequate surrogate. This opinion is based in the recent research which indicates some vestibular stimulation is necessary for the proper percept of self motion.(11)

PLATFORM MOTION SYSTEMS

Motion platforms are difficult to justify in terms of the more obvious factors such as initial cost, safety, facilities, maintenance and life cycle costs but also in terms of the more subtle factors relating to integration with other systems and training value obtained.

The motion platform most widely used consists of a hydraulically powered six-post synergistic, computer-driven system designed to carry and provide motion cues to a cockpit that often includes a visual system with electronics and a display system and a pilot. Such a load requires a large, powerful, responsive, and safe system capable of providing onset and sustained acceleration cues that are synchronized and compatible with all other systems.

The initial cost of a typical motion system is $400,000. If a ten year life span at 16 hours per day and 250 days per year and 10% per year inflation rate is assumed and considering costs of spares, training, facilities, maintenance and the like, a total 10 year life cycle cost of $3.7 million is predicted using a life cycle cost model. This leads to a cost of $92.50/hour to operate the motion system.

The safety aspects of motion systems must be carefully considered because they use high pressure hydraulics and powerful rams to create the motion that drives the cockpit.

Many safety features must be incorporated to preclude damage or injury. This requires hydraulic and electronic safety systems, and more and better maintenance facilities which contribute to the complexity and cost. Although over the years the systems have a proven safety record and are documented to be safe under normal utilization, the mere power, function, and form of the system is intrinsically hazardous.

The difficulty does not end there, for the platform must be integrated with all other systems. The cockpit must be mounted on the platform and requires special access for cabling and personnel. A visual system, when used, must be mounted on the platform to avoid a great many problems encountered in floor mounting such as compensating visual for motion. This can become particularly difficult when a wide-angle visual system is used due to its size, configuration, and electro-mechanical constraints resulting from mounting a dome, projectors and servo-electronics on the platform such as in the VTRS system or collimated dislays such as in the ASPT system.

Even when the visual system is mounted on the motion platform, cue synchronization is by no means guaranteed between the visual system position cuing and motion platform acceleration onset and sustained cuing.

Vision is said to be the most important of all the senses in perceiving motion. While this may, in general, be true, it must be qualified. The eye is a position sensing device, thus the perception of self motion, from its input, is generated very slowly.

In a simulator, a wide-angle visual system provides stimulation of the eyes' peripheral sensors which results in a greater visual perception of motion. However, the perception delay is still significant.

In cases of low-frequency maneuvering in slow aircraft or slow maneuvering in fast aircraft, the delay may be acceptable.

However, previous research indicates that high-frequency disturbance-type tasks, abrupt failure or turbulence effects, or flight dynamics of unstable aircraft operating in specific modes, such as helicopter hover, visual-only cuing is not fast enough to generate what is deemed good pilot performance. Motion improves performance.(9)

Abrupt motions which generate large acceleration over a small position change, are sensed better when acceleration forces are provided to stimulate the vestibular sensors.

The vestibular sensors are basically acceleration sensors and (in a perfectly synchronized simulator or the real world) respond to the second derivative of position. Therefore, their cuing information is significantly faster than the visual position information.

With the vestibular system, the pilot can get advanced warning of a position change in less time and magnitude of position change than required with visual-only cuing. A motion platform, however, has limited cuing capability due to limited travel but as long as the acceleration cue is long and large enough, and the cue is synchronized with the visual, a faster cue is provided.

This is not very easy to do considering multiprocessor configurations, throughput lags, iteration rate effects, hardware response times and all the factors contributing to mismatch between the visual and the motion; while providing adequate cuing to achieve the desired purpose.

If we consider the task of synchronizing the platform and the visual systems, there are many considerations in specifying the platform performance. The platform must provide a range of acceleration cues of acceptable time duration and magnitude with subliminal acceleration washout within the platform excursion limitations while reflecting visual position magnitude. The throughput lags and computer, hardware/software lags must be within an acceptable range of the visual lags so as not to be unacceptably out of phase; and the high response high pressure hydraulic hardware should not respond to computer iteration rate stepping.

The existence of these cue synchronization problems is known to be a variable depending on magnitude and frequency of input as well as system design and has been quantitatively documented in a few cases.(3)

PSYCHOPHYSICAL ASPECTS

It is well known that the human perceives his motion through space by the integration of information, by the brain, from the transducers of several physiological sensory systems; visual, vestibular, haptic and aural. The manner in which the apparatuses of these systems operate is described in several sources.(1, 4, 5, 7, 8, 14, 15) In addition to these there are many other sources to which the reader may refer in order to obtain complete discussions of the sensory systems. This information is processed yielding a usually coherent perception of the motion environment. The perception is not always coherent because in some cases information is ambiguous and in others specific sensory information is absent.

An example of a perceptual ambiguity is the case of the familiar "railroad station paradox." In this instance, a person sitting in a train stopped at the station perceives relative motion with respect to an adjacent train as that train begins to move. His initial reaction is that the train in which he is a passenger is moving in the opposite direction of the train that actually is moving. Subsequently, however, he resolves this ambiguity on the basis of further perceptual information. Hence, he finally concludes that it is the other train that is moving.

This visual illusion is known as vection. Vection is the perception of self motion due to stimulation of the visual system particularly in the periphery.

An example of incoherent perceptual information arising from the absence of perceptual information or incorrect perceptual information would be an airplane making a coordinated turn in a cloud bank. If the pilot does not look at his instruments, he has no indication that the airplane is changing heading. This phenomenon results from the fact that due to the cloud bank, there is no visual perception of heading change and since, in a coordinated turn, the forces are balanced, there is no stimulation of the vestibular or haptic apparatus. In this case, there is no knowledge of heading change and the situation may never be resolved without additional sensory information such as visual information from the instruments.

The modern flight simulator with its wide-angle visual system, moving platform, G-seat, anti-G-suit system and vibration systems attempts to stimulate, to some extent, all of the above mentioned sensory systems. In general, motion base systems employ an onset cue with a washout to provide an initial stimulus to the vestibular system and haptic system. Subsequently, the visual system, relying upon the vection phenomenon, sustains the motion sensation. G-suits and G-seats, both stimulating the haptic system, are employed to augment the vection phenomenon for sustained motion and to provide some high-G cuing. Vibration systems are used to provide the high frequency (up to 40 Hz) oscillatory motion cues.

The major, as yet unanswered, question in flight simulation today is: "Is platform motion necessary in the presence of wide field of view visual systems?" One point of view states that since self motion can be induced visually, there is no need for platform motion systems. Another point of view is founded in the research of Young and others, which basically states that the onset of vection is hastened by the presence of vestibular stimulation.(11, 13) Brandt and others state that without vestibular stimulation the onset of vection can be of the order of 2 to 12 seconds.(2) However, with the addition of vestibular stimulation this onset delay was imperceptible.(21) These researchers have also found that the direction of the stimulus is more important than the magnitude. Implicit in this, of course, is the fact that the stimulus must be in excess of the perceptual threshold. Young offers, "Merely a slight platform displacement or seat motion in the appropriate direction may be sufficient to bring forth well developed vection."(12)

It is safe to say, then, that there is sufficient evidence that vection takes too long to develop in the absence of vestibular stimulation to be effective in the maneuvering environment. Secondly, vection is quickened by vestibular stimulation. Thirdly, small amplitude seat motion in the correct direction will quicken the onset of vection. The foregoing is encouraging, in that it appears to offer a suitable basis for justification of a motion seat in lieu of a motion platform.

CUING APPROACHES

There are three possible cuing approaches which could be investigated here. The first is to employ an in-cockpit device in an onset cuing mode as is commonly done with platform motion systems. In this mode, the seat would be used to stimulate both vestibular and haptic systems. Onset and washout drive logic would be employed in this case. A second approach is to employ the seat to stimulate solely the haptic system in a sustained cuing modality. The third approach is to use the seat to provide a very short duration, pulse-type cue in the appropriate direction.

Onset Cuing Approach

In order to provide onset cuing with washout, a substantial amount of seat pan displacement is required. For example, to provide a vertical onset cue for 0.2 seconds with a maximum acceleration of 1.2g and employing a linear washout which is below the indifference threshold given by Hoffman and Reidel as 0.1g, the excursion required would be 30.9 inches.(6) This is obviously too great for an in-cockpit device. It should be noted that shortening the duration of the cue will serve to reduce substantially the total displacement required. For example, if the cue duration is reduced to 0.1 seconds for the onset, the system excursion requirements are reduced by a factor of four.

Therefore, reducing the onset cue duration to 0.1 would enable the presentation of a 0.3g cue and associated acceleration washout in 0.63 inches of platform excursion. This would be feasible within the context of most existing G-seats and also be acceptable within the constraints imposed by the cockpit geometry. However, the cuing dynamic range would be small, i.e., from 0.1g to 0.3g. An onset cue of 0.1 seconds would be near the upper end of the time constant range of the otoliths, which is less than 0.1 seconds.(10)

Examining the rotational axes in the same manner, and considering a rotational velocity cue required of 20°/sec., it was found that this cue would require over 40° seat pan rotation and the resulting washout velocity of 10°/sec. is above the indifference threshold of 2°/sec. These values are based on a washout acceleration of 5°/sec.^{2} and a cue duration of 0.2 seconds. The 40°/seat pan rotation results in 5.28 inches of vertical displacement, assuming a 12 inch separation of seat actuators. As was the case for the vertical excursion case, the cue duration could be reduced and this would yield lower performance requirements. However, considering time constants of 1 to 10 seconds for the semi-circular canals, then a cue duration of 0.1 sec. would be small as compared to the time constant.(15)

It should be noted that linear cuing only was considered above and if non-linear drive models were developed, the situation could improve. However, it is unlikely it would improve to the extent required for credible simulation.

Haptic System Stimulation Approach

The question here is whether using a device like a G-seat to stimulate the pressure and muscle receptors of the haptic system would be a viable approach in the context of this investigation. The traditional application of G-seats in flight simulators has been to employ them together with platform motion systems to provide the sustained acceleration cues while the platform provides the vestibular stimuli via onset cuing. The sustained cues have been provided by altering the pressure distribution, across the back and buttocks, due to pilot weight and aircraft acceleration vector. The general contribution of haptic system stimulation is quite well recognized at this point. However, what is not known is the relative importance of the two stimuli in the perception of motion. Further, no research has been performed to differentiate the relative importance of the two stimuli on the development of vection. However, it is known that some elements of the haptic system have small displacement thresholds and relatively low time constants (Table 1). This leads one to believe they might be stimulated by a small excursion system.

TABLE (1)

Sensor	Displacement Thresholds*	Time Constant
Pacinian Corpuscles	10 microns	1-10 ms
Merkel's Discs	1-5 mm	1 & 30 s
Ruffini End Organs	--	1, 5, & 20 s
Muscle Spindles	--	80 ms

*These data from Borah, et al.

These data offer some reason for optimism in that the thresholds are very low for the cutaneous and subcutaneous sensors, hence pressure stimuli, from a variable contour seat pan, would aid in the perception of motion via direct perception and perhaps through the quickening of vection.

A G-seat type device altering the pressure distribution of the back and buttocks could be used in conjunction with some small onset device as discussed in the previous section. However, this adds complication to the system.

As stated, one related area which has not been pursued is the effects of haptic stimulation, in the absence of vestibular system stimuli, on the onset of motion perception induced by vection. However, Young states that tactile cues respond most rapidly to changes in pressure and signal any rapid changes in acceleration because of the consequent change in support force "They are the ideal first simulator cue for rapid onset." (12) This is borne out by the data of Table (1).

Pulse Cuing Approach

The Pulse Cuing approach has its justification in the research of several investigators who have indicated that the vection phenomenon is hastened with vestibular stimulation, (2, 11, 13) and also that the vestibular stimulation need only be a short pulse in the appropriate direction. (12)

While this approach might involve a multi-degree-of-freedom seat platform in the cockpit, it would have very small excursions. How many degrees of freedom are required must be determined by additional research. At least four degrees of freedom are required, the three rotational and vertical. It is probable that linear vection can be quickened with rotational vestibular stimuli, but this must be verified. Another advantage of this approach is that the software drive algorithm would be very simple. Also, since the excursions would be small, eyepoint motion would be small and hence dynamic mapping of the eyepoint would not be necessary. Because of the small excursion requirements a pneumatic system may satisfy the response requirements.

The vertical degree of freedom should also be capable of providing vibration cues in the range of 3 to 40 Hz.

SUGGESTED RESEARCH

In order to evaluate the validity of the candidate approaches further research is needed. The research falls into two categories, that which will provide more psychophysical data and that which will verify simulation concepts. Some examples of the first category are: Will haptic system stimulation alone hasten the onset of vection? Will rotational vestibular stimuli quicken linear vection? What are the required pulse characteristics, i.e., pulsewidth and range of magnitudes?

A problem with much of this research is that of finding an objective measure of the results. In this case, using visual nystagmus should provide the desired results. Other techniques are also available. One technique for obtaining quantitative objective measure of psychophysical phenomena is the method of evoked response. Much has been written in the literature about visual evoked potential (VEP) but to our knowledge, this technique has not been applied to determining the onset of vection, or for that matter other simulation research.

The second category of research is more simulation specific. Some examples of the kinds of research in this category are: employ a one-dimensional tracking task both with and without the pulse cue to hasten the onset of vection, which would be stimulated by an appropriate display. The subjects' performance in both cases would be measured and compared. The experiment should also be performed using an unconstrained single-degree-of-freedom rotational motion system in place of the pulse cue. The subject's performance on this task would then be compared with the other two conditions. Other transfer of training experiments may be performed as well.

Needless to say, subjective evaluations with experienced pilots must be performed as well, in order to ensure that the technique will gain acceptance in the user community. Also, experimentation with various drive algorithms is necessary. In the case of the pulse cuing approach, the only aspects of the drive algorithm to be considered are the magnitude, duration and direction of the pulse.

CONCLUSION

Of the three approaches suggested it appears that the option with the most promise is the pulse cuing approach. The onset cuing approach has very little expectation of success because of the limited stroke available. There is some question as to whether, even in large stroke motion platforms, an optimum drive algorithm has been developed. Hence, the degree of acceptability is very low for these systems. It is, therefore, unreasonable to expect that an in-cockpit device with much less stroke would ever be acceptable.

The second approach employing haptic system stimulation does have some promise but requires a substantial amount of research for this application. In addition, the effort to develop suitable drive algorithms would be extensive.

The pulse cuing approach is attractive in its simplicity as well as the reasonably high expectation of success it engenders.

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