Time-Delay Problems Encountered in Integrating the Advanced Simulator for Undergraduate Pilot Training

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An advanced Computer Image Generation (CIG) visual system has been integrated with an advanced Flight Training Research Simulator. The integration design was the first developed for integrating a CIG visual system with a sophisticated flight simulator. There was much concern for the unique CIG system transport delay, and techniques were developed which proved to be quite successful in compensating for the majority of this delay. However, not enough concern was given to previously unrecognized and unreported excessive motion system delays which were encountered during final integrated system tests. The integration scheme and the impact of iteration rates, visual and motion system delays, and delay compensation on visual and motion cue coordination as perceived by pilots are presented.

Introduction

At the time of the early planning for the integration of the Advanced Simulator for Undergraduate Pilot Training (ASUPT) Computer Image Generation (CIG) System with the flight simulator, little was known about some of the unique characteristics of CIG visual systems and their effect on overall simulator performance. One such characteristic is transport delay; the time from positional data input to a CIG system until a complete TV picture based on that positional input data is produced. In addition, excessive delays in state-of-the-art motion systems were identified as a result of the integration with a sophisticated, responsive visual system. This paper will discuss some of the problems encountered and techniques employed to accomplish the overall system integration. First, however, the overall simulator system and its major components will be described briefly.

The ASUPT System

The Advanced Simulator for Undergraduate Pilot Training (ASUPT), was designed as a research tool to be used to investigate the limits of the latest simulation technology and to define methods and techniques for maximum utilization of this technology in an ongoing undergraduate pilot training (UPT) program. Shown in Fig. 1 is an artist's conception of the ASUPT System. It is a two-simulator complex simulating the T-37B aircraft, the primary UPT jet trainer. Capability is provided for the majority of UPT flying tasks including: taxiing and takeoff, approach and landing, airwork and aerobatics, formation flying, instrument flying, and limited cross-country and night flying, and limited cross-country and night flying. The total system is comprised of three major components: 1) two basic T-37B simulators, 2) two wide-angle visual displays, and 3) a shared visual computer image generator. For more details of the ASUPT System see Ref. 1. Of particular interest for this paper are the motion and force simulation systems and the visual system.

Motion and Force Systems

The motion and force simulation is accomplished through a combination of a six degree-of-freedom synergistic motion system and a sustained G-seat (see Figs. 2 and 3). The motion system hardware is a 60-in. stroke synergistic system designed for a 23,000 lb load. The motion drive model employs the conventional transfer function approach for rotational cueing and a new approach for translational cueing. The translational drive scheme involves the tracking of simulated aircraft acceleration until the velocity and/or position limits of the motion hardware are reached with capability remaining for washout at subliminal levels. The dependent variable is the time of application of the acceleration cue; for large acceleration the time is small and for small accelerations the time is relatively long. The motivation behind this scheme was to obtain maximum performance from the motion platform at all times, from the gentle maneuvers to the radical maneuvers. Both onset and relaxation acceleration cues are tracked. The model is flexible with certain variables such as thresholds, washout rates, etc. easily varied.

A technique called gravity align also is employed to provide limited sustained cueing. The more extensive sustained accelerations are simulated through a combination of an activated lap belt and compartmentized air inflatable seatpan, back, and thigh cushions in the seat. The sustained accelerations are imparted to the pilot through the cushions by varying the orientation and contour of the seatpan and back planes. The variation of the orientation of the seatpan and back planes alters the direction of the force vector and the variation of the contour alters the contact area thereby altering the pressure applied to certain parts of the body creating the illusion of a change in the magnitude of the force vector.

Visual System

A 14-channel computer image generation CIG system generates the visual scene which is displayed on the two seven-channel visual display systems. This provides a visual scene with a field of view of approximately 300° horizontal by 150° vertical and a resolution of approximately 7 arcmin throughout. The system is capable of providing the extra cockpit environment for all UPT contact flight maneuvers.

The visual display is formed from seven pentagon-shaped display channels mosaicked together to form a partial dodecahedron shell surrounding the cockpit. Each display channel is comprised of an in-line infinity optical system (Farrand Pancake Window), a large high brightness CRT, and associated CRT drive electronics. The display optics are approximately 1% efficient with necessitates the use of high-brightness CRT's to achieve the 6-ft-L display highlight brightness.

The CIG system is a raster-scan image generation system which generates a new visual scene 30 times a second. Each

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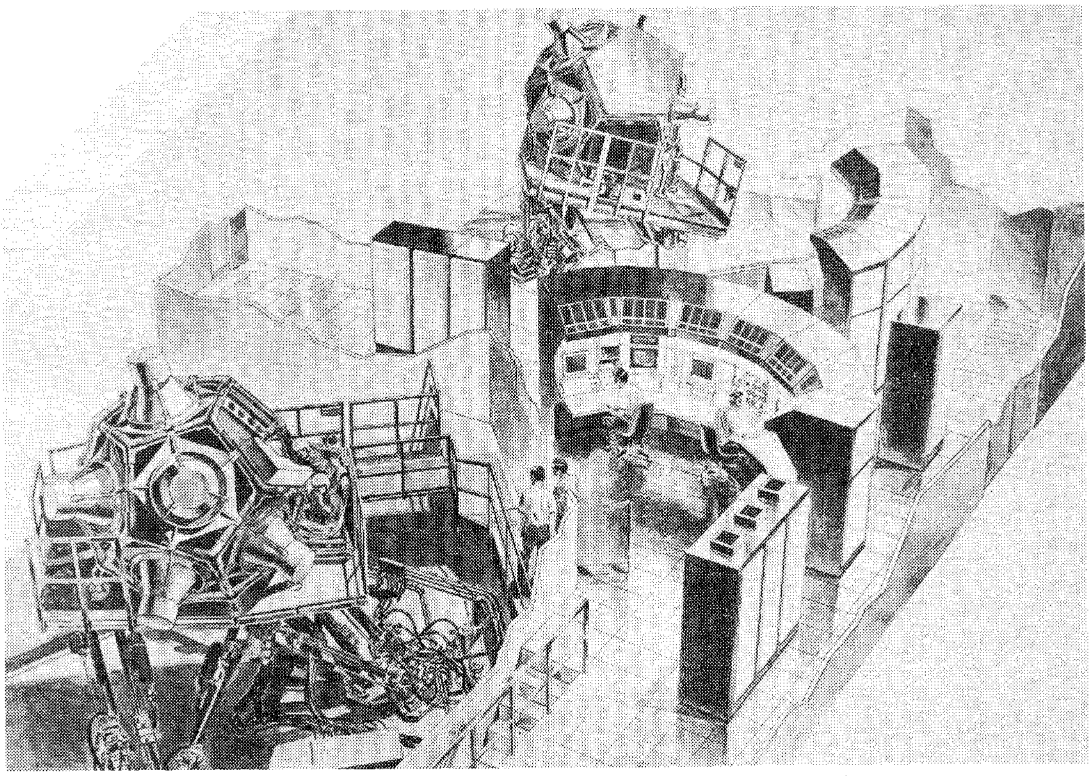

Fig. 1 Artists conception of the advanced simulator for undergraduate pilot training.

channel raster is composed of 985 active TV lines with 1000 display elements for each scan line. The system is capable of generating imagery composed of 2500 edges. Part of this edge capacity, approximately 500 edges, is used as a buffer to prevent system overload by reducing the level of detail when the edge capacity exceeds 2000 edges, and to close the left-hand boundary on surfaces crossing channel joints. The total edge capacity can be distributed between the two cockpits in any of several ratios. The edge capacity can be used for both two-dimensional surface planes or three-dimensional objects, also in any ratio.

System Interfaces

The system interfaces between the CIG system, simulator, and the display are shown in Fig. 4. The placement of the particular dividing line was chosen for two major reasons: first, to provide a proven and flexible link between the simulator and CIG system, namely the common memory interface between the SEL 86 computers; a second , to keep integrally related developmental items on the same side of the interface, namely the CRT and display optics.

Hardware Interface

Since both the simulator of system and the CIG system utilized the same type of computer (SEL 86), the hardware interface was straight-forward, employing an 8K common memory module. This is not meant to imply that the full 8K of memory was required for the data transfer, it just happens to be the minimum word boundary for shared core on the SEL 86 system. In fact, less than 50 words of memory are used across the interface.

In order to insure that the CIG system received the freshest information each frame and to insure a predictable minimal delay from simulator control input to the resulting change on the visual display, a synchronous clocking scheme was used. Both systems contain their own independent clocking source; 15 per sec maximum frame rate for the simulator and 30 per sec for the CIG system. When operating together, the CIG clock is used as the master clock. It was chosen since it had subtiming intervals necessary for logic clocking within the CIG system special purpose computer with which it had to be

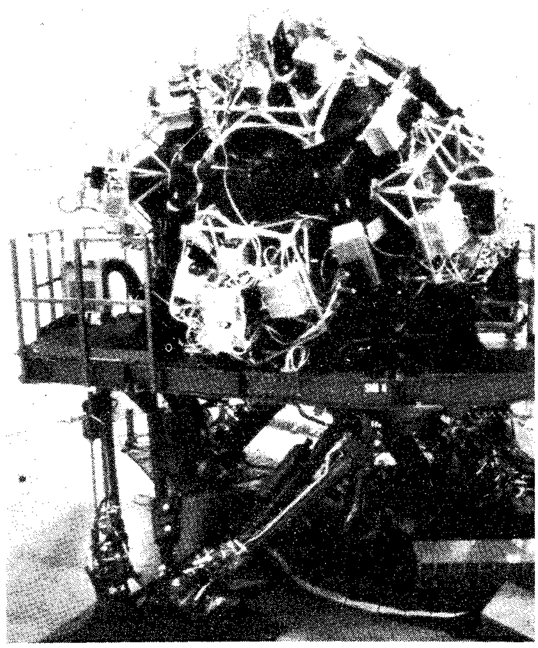

Fig. 2 ASUPT six-post motion platform with visual display/cockpit payload.

synchronized. The simulator interval timer had no such subtime interval requirements. The CIG system clocking signal was input to the highest level of external interrupt in the simulator computer. This synchronization setup allows the simulator to revert easily back to its own clock should operation without the visual system be desired.

Software Interface

The integration software consists of three subroutines: visual slow subroutine, visual logic subroutine, and visual fast subroutine. The visual slow subroutine is called once per second by the simulator executive. It computes the sines and cosines of the angular corrections necessary to correct the

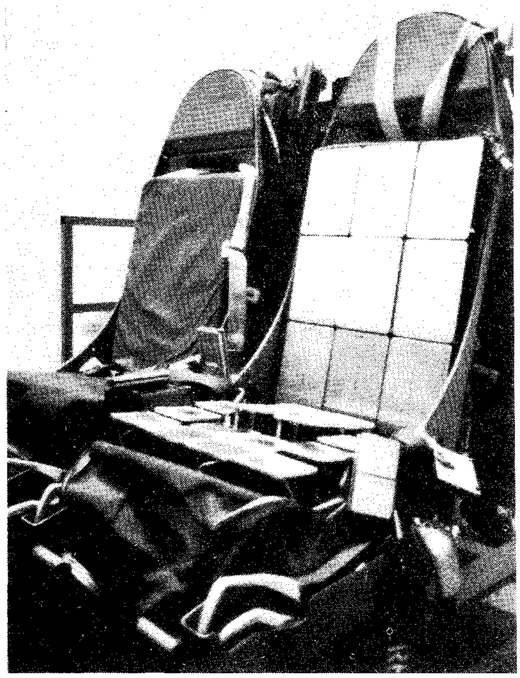

Fig. 3 ASUPT G-seat with seat and backrest air bellows exposed.

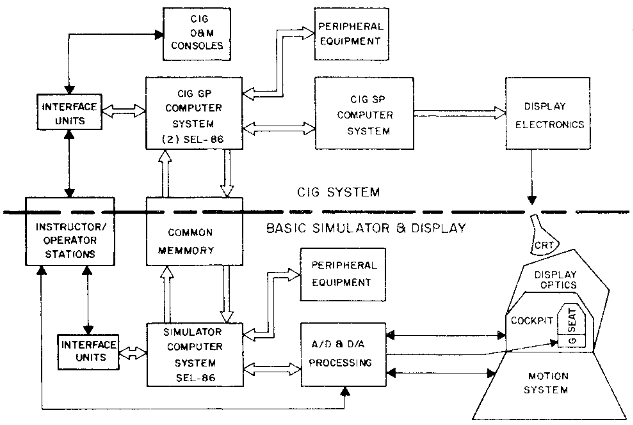

Fig. 4 CIG/simulator system interface diagram.

flight system's flat-Earth heading to map heading. This correction contains both the transport angle and the meridian convergence. The transport angle is employed by the simulator navigation programs as well as the visual slow subroutine to transform flight heading to spherical-Earth (true) heading. The meridian convergence correction is necessary to compensate for the transverse Mercator mapping scheme to which the CIG environment data base is modeled.

The visual logic subroutine is called 3.75 times per second by the simulator executive. It performs logical computations such as visual reset, on, off, crash, etc.

The visual fast subroutine is executed 30 times per second. It computes (and interfaces with the CIG system) the simulator positon and attitude data for cockpits A and B and the lead aircraft when in a formation flying mode. Unlike the logic and slow subroutines, the fast subroutine is not executed by the executive but directly by a 30/sec interrupt handler. The handler in turn is invoked at a 30/sec rate by a clock originator in the CIG special-purpose computer that leads the video frame by 10 msec. This lead allows the fast subroutine to make the position and attitude updates before the CIG starts its frame. The direct connection to the interrupt handler was necessary because the executive could not support a 30/sec rate (15/sec is maximum) with a fixed 33.33 msec interval as required. Extensive modification to the executive and module jump list would have been necessary. The fixed interval was necessary in order to compute an accurate transport delay compensation and lead prediction for the interfaced position and attitude data in the visual fast subroutine.

Visual System and Transport Delay

The typical steps involved in producing a CIG TV picture are as follows: 1) angular and translational positional data describing the viewpoint are input; 2) the appropriate three-dimensional numerical data describing what can be seen from that viewpoint are extracted from the data base mass storage; 3) the system then develops a two-dimensional display plane model from these data; and finally, 4) a TV raster produces a scan-line element at a time in sequence. This process for the ASUPT CIG system takes 100 msec from the time positional data are input until the TV raster is completed. Recognizing early in the planning stages for integration of the visual system that this transport delay could pose cue coordination problems, various delay compensating schemes were investigated.

Transport Delay Compensation

One such technique considered was a straight Taylor series extrapolation. However, it was realized that in the digital simulation of a second-order system, which an aircraft simulation can be likened to, two open integrations are performed: one on acceleration and one on velocity. In ASUPT the second-order Adams numerical integration method is used. This means that there is enough information in a given frame to determine the exact position of the simulator one full frame ahead. Figure 5 shows a typical numerical simulation of a second-order system and how positional information for the next interval can be made available during the present interval. This rather simple technique was called single-interval lead.

In determining how much delay should be compensated for, the delay inherent in digital simulations from control input to display output was not considered. This delay can be im-

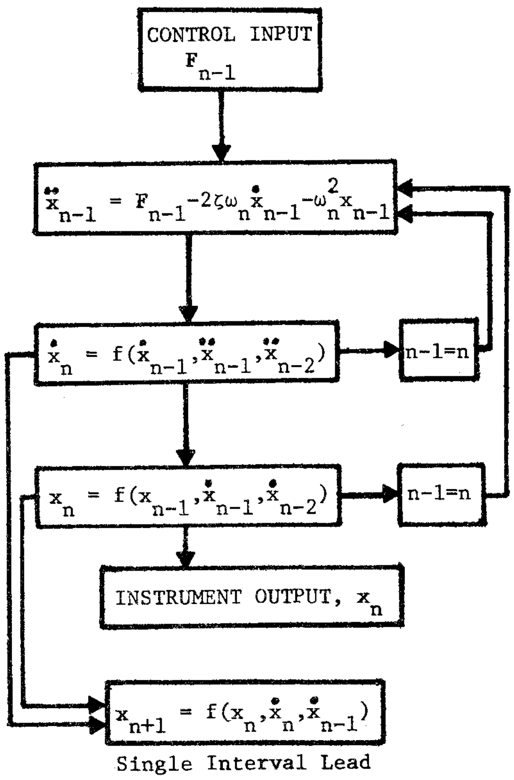

Fig. 5 Numerical simulation of a second-order system.

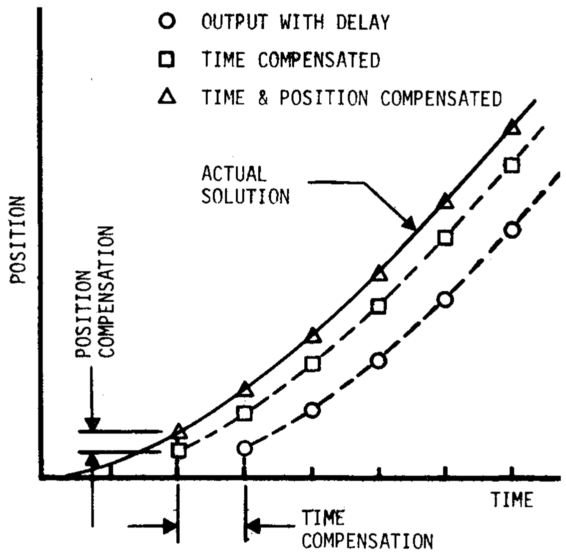

Fig. 6 Illustration of time and position compensation.

proved only through higher iteration rates. The positional output to the instruments was used as the reference point and the visual compensation value was chosen to lead the instruments by a value equal to the CIG system transport delay. Two factors went into the selection of the final compensation value. First, since the CIG system produces two interlaced fields per frame, the new positional data were assumed to be displayed after the first field was completed or 83.3 msec after receipt of the positional data by the CIG system. However, positional data could not be made available to the CIG system until 10 msec after the start of the simulator interval. This was because of the time required for execution of the CIG interface subroutine. This resulted in a total transport delay of 93.3 msec. Since the simulator iteration rate was 15 per sec, 66.7 msec of this delay could be compensated for by the single interval lead technique; the remainder of the delay, 26.6 msec was compensated for by a two-term Taylor Series. Since the CIG system produces two frames of video every simulator interval, position information was required twice during every simulator interval. The first set of positional information had to be forward compensated 60 msec and the second, 93.3 msec. These were provided by a 6.6 msec backward and a 26.6 msec forward Taylor series extrapolation about the single-interval lead. The amount of Taylor series extrapolation could be changed by varying the Taylor series interval. It is important to note that the single-interval lead and the Taylor series extrapolation are two distinctively different types of compensation. The single-interval lead is a true time compensating technique whereas the Taylor series extrapolation is a position compensating technique. The Taylor series simply puts the output signal in the proper position (magnitude) for the corresponding output time. The two types of compensation are illustrated in Fig. 6.

Motion, Visual, and G-Seat Delays

Cues of motion from the simulated T-37B aircraft are provided through the visual system, motion platform, G-seat, and flight instruments. The coordination of these cues so that they are produced in proper time relationship to each other was found to be very important. Measures had been taken to compensate for the majority of the CIG system transport delay; however it was not possible to use an equivalent scheme to compensate for motion system delays. The motion drive software uses the latest available flight model accelerations to produce a motion platform positional command which prevents a single-interval lead technique from being used to advantage.

For measurement of motion system delays, six accelerometers were mounted on the ASUPT motion platform. These signals then were combined in a motion text box, which is a custom-designed mixing circuit that transforms the six accelerometer outputs into rotational and translational accelerations. The motion system was tested for two types of software drive. The first test was conducted with the motion software set as determined to be most acceptable through subjective pilot testing. Subjectively determined settings were used for both rotational and translational cueing. These same software settings have been used consistently for the training research studies conducted to date on ASUPT. The simulator was initialized at 15,000 ft straight and level, configuration clean, 160-kt airspeed, 1600-lbs fuel weight. The test inputs were generated by a pilot pulling aft on the stick as quickly and as hard as he could each trial. The average total stick deflection time was 100 msec. The average total time delay for the ASUPT motion platform to respond to a full aft elevator deflection was 350 ± 33 msec. This delay is from the initial onset of the stick deflection until an accelerometer output was observed. The second test was conducted with translational cueing deactivated. The simulator was reinitialized to the conditions of the first test. Rotational cueing alone, with gains doubled and frequency response increased (software poles moved out) in order to see just how quickly acceleration could be built up, resulted in an average lag of 129 ± 33 msec. This delay represents perhaps the best response possible from the ASUPT motion system. However, the platform is not driven with this scheme since 1) both rotational and translational cueing software are utilized, and 2) increasing frequency response and gain causes the performance of the motion system to become subjectively unacceptable to the pilots. Such platform motion problems as acceleration cue reversals and hydraulic turn-around bump become accentuated in the ASUPT under these conditions.

The components of the motion system delay include both software drive algorithm and motion system hardware contributions. The motion system hardware response from a DAC (Digital-to-Analog Converter) update to an acceleration of 3 deg/sec^2 is approximately 60 msec. The minimum delay due to the software, including sampling the stick input, processing, and outputting to the hardware through the DAC's is from 33 to 167 msec in the ASUPT. The reason why a recorded platform motion is not observable until 350 ± 33 msec after a stick deflection is because 1) commanded aircraft velocity for rotational cueing and aircraft acceleration for translational cueing drive platform position, and it takes up to 200 msec in some instances to build up these rates to an observable level, and 2) the gains for the different cueing philosophies (rotational and translational) subjectively are set low which tends to degrade the motion output accelerations observed. These gains were set low through subjective pilot comments from two T-37B instructor pilots (see Ref. 2).

The question needs to be asked: "If the ASUPT motion system can respond within 100 msec, why is it set up to respond 250 msec later, or 350 ± 33 msec?" The most apparent explanation is that when the motion system is set up with fast poles and increased gains, all of the hardware and software problems become more accentuated and undesirable. Hardware problems include roughness and hydraulic servo-valve turn-around bump. The software problems include linear washout cue reversal, which is a false cue delivered by the software to the platform when the slope of the aircraft angular acceleration changes. By reducing these unwanted cues through selective reduction of the motion software gains and lowering the software poles, the wanted cues are inadvertently reduced as well. The tradeoff here is wanted for unwanted motion cues. Data taken from an instrumented T-37B aircraft[3] indicate a 55-125-msec delay (depending on airspeed) for a similar test; such data would indicate that the ASUPT motion system lags the actual aircraft motion in some instances by as much as 300 msec.

Table 1 ASUPT visual, motion, G-seat, and aircraft instrument delays (approximate)

System	Iteration rate delay	System delay	Total
Visual	43–110 ms[a]	83 ms	126–193 ms[a]
Motion	33–167 ms	216 ms	249–383 ms
G-seat	33–167 ms	225 ms	258–392 ms
Aircraft instruments	133–200 ms	[b]	133–200 ms

[a]Time compensated by 67 ms. [b]Assumed small.

The approximate delays of the visual, motion and G-seat systems are shown in Table 1. Also shown for comparison is the iteration rate delay from control input to simulator instrument (i.e., attitude indicator) drive output. The variation in delay from one system to another is due to the different rates for the various software modules such as flight, motion, and visual. The variation within a software module is due to the time variation from control input to the time it is processed. If the control input is made just before the analog inputs are processed, minimum delay will occur; if it is input just after the analog inputs are processed, maximum delay will occur. Figure 7 shows the approximate timing relationship between the various software modules. Also shown are the two delay time extremes for the visual system.

Since the analog outputs are started at the beginning of the second half of the 15-per-sec frame, the time for motion, G-seat, and instruments are 20–33msec less than those shown in Table 1 depending on where they are actually output. For comparison purposes in Table 1, outputs arbitrarily were assumed to occur at the end of the frame.

Effect of Delays and Iteration Rates on Simulator Performance

As evident from Table 1, the motion platform cues lag the visual cues on an average of approximately 150 msec. This amount of delay was quite apparent to the test pilots flying the ASUPT simulator.[2] At about the time these noticeable motion system delays were found in ASUPT, the simulator for Air-to-Air Combat (SAAC) was being tested in-plant at the Singer Co. Similar motion system lags were not reported by the pilots testing SAAC. In order to determine if the motion lag problem was unique to ASUPT, the chief ASUPT test pilot and the integration engineer went to Singer and ran similar tests on SAAC. The motion system lags were found to be about the same as in ASUPT. The reasons concluded for similar motion lags being detectable in ASUPT by its test crew and not in SAAC by its test crew are as follows: 1) both the motion and visual system lags in SAAC were about the same and nearly the same as the ASUPT motion lag; and 2) the ASUPT test pilots had lived with the system for over a year and had become supersensitive to its performance. The ASUPT visual system was tried without compensation, making the disparity of motion and visual system cues less; however, the preferred arrangement was with the visual lag reduced as much as possible regardless of the disparity between the motion and visual cues.

The outcome of experimenting with the amount of Taylor series extrapolation about the single interval lead was quite interesting. Attempts to extend the extrapolation resulted in an objectionable lack of smoothness in the visual scene. In fact, the preferred amount of compensation was not a value set to give proper position compensation, but a value set to make the amount of forward compensation equal to the amount of backward compensation. Equal settings seemed to produce the smoothest movement of the visual system under rapid control-reversal conditions. This lead to the final recommendation that the Taylor series extrapolation be abandoned in favor of using only the single-interval lead with a variable integration interval incorporated to provide some delay compensation variation capability.

The excessive motion system lag is disturbing during certain flight modes, but apparently tolerable. The software delay

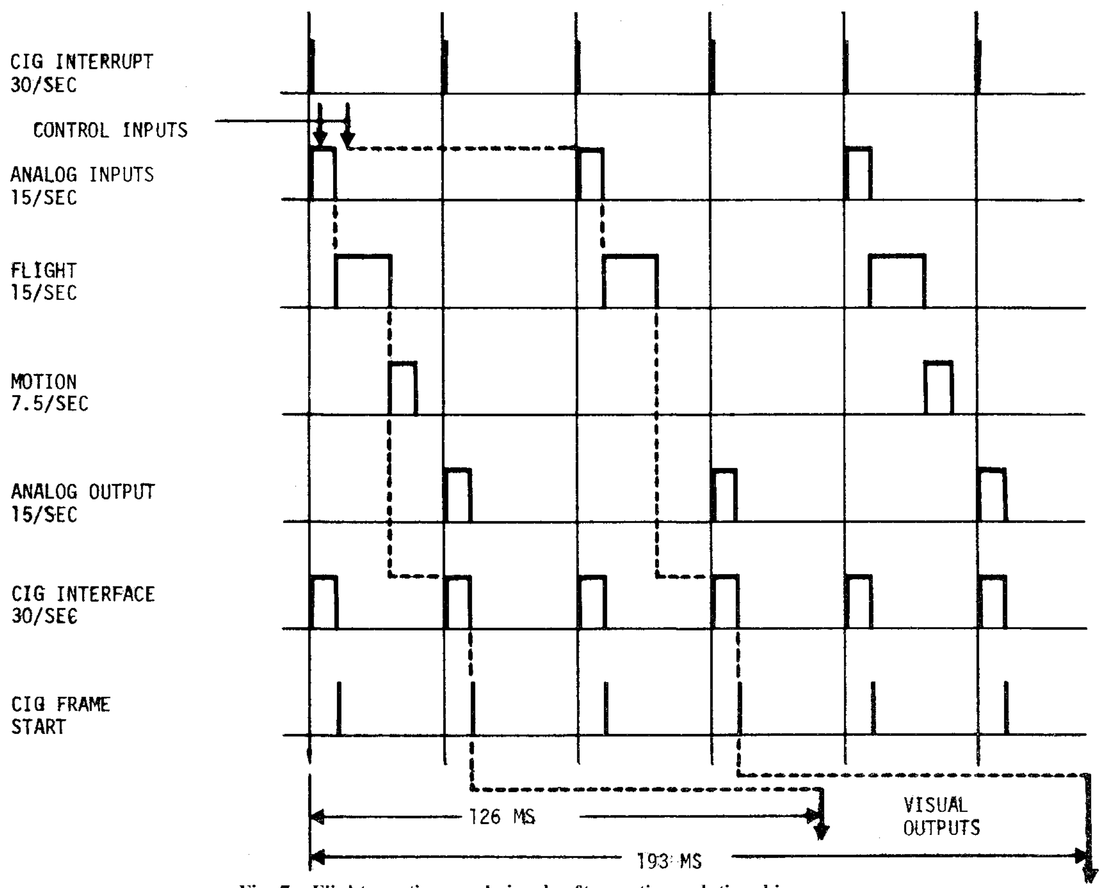

Fig. 7 Flight, motion, and visual software time relationships.

can be improved by 67 msec by increasing the motion module iteration rate to 15 per sec rather than 7.5 per sec. However to reduce the lag significantly, the motion system hardware delays must be reduced. The G-seat delays which are on the same order as the motion system delays were not disturbing. This was to be expected since the G-seat was not intended to provide rapid onset cues, but rather sustained acceleration cues.

The effect and criticality of iteration rates on certain flight tasks was demonstrated vividly during the testing of the formation flight capability. Early in the integration of the visual system with the basic simulator, latitude/longitude inertial position computations were processed at only 7.5 iterations per sec. The ASUPT system, with its large task load, cycles at a maximum rate of 15 iterations per sec. All computer input/output and flight dynamics programs operate at this rate, whereas other rates (7.5/sec, 3.75/sec, and 1/sec) are employed by less time-critical program modules. During initial formation flying pilot evaluation, none of the pilots was able to fly proficiently in formation with the CIG lead aircraft. The first formation flying evaluations were performed with visual, only, which eliminated the effect of any latent motion cues. The pilots would close in on the lead aircraft but not maintain precise control of their position with respect to the lead, once acquired. The end result was usually an induced oscillation mode of control. Upon investigation, it was determined that the latitude/longitude update rate was 7.5 iterations per sec. These computations were doubled, as a possible fix, and the pilots re-evaluated formation flying. The effect was dramatic; the pilot's ability to fly in formation flying improved significantly. This improvement was attributed to two effects of increasing the iteration rate: 1) very accurate judgment of translational rates is essential in formation flying, and by increasing the frequency of computation, feedback translational information was twice as fresh as in the previous evaluation; and 2) the control frequencies involved in formation flying, where stick inputs can be as high as 3Hz, were computed more frequently by the latitude/longitude position module, allowing the pilot to perform more precisely. The increase in inertial position computation from 7.5 to 15 iterations per sec had no noticeable impact on other tasks such as approach and landing maneuvers, but these do not require precise judgments of linear distances and are not as high a frequency control task as is formation flying.

The greatest impact of iteration rates and transport delays seemed to be in the control of aircraft roll position. The T-37 aircraft has low roll inertia coupled with powerful ailerons and light control forces, resulting in roll response which is rapid and positive. Pilots expect immediate and positive response of the aircraft to control position inputs, with accelerations into and out of steady roll rates being both rapid and smooth. With a wide-angle visual system, if the presentation of the visual simulation is close to the threshold of objectionable delay the overall delayed effect is more noticeable since the visual display provides a far more precise indication of roll response and dynamics than is available from attitude instrumentation.

Summary and Conclusions

Various advanced and state-of-the-art subsystems have been brought together to form an advanced flight training simulator which now is being used for pilot training research. The advanced subsystems, namely the CIG system and the G-seat, turned out not to be the devices preventing the achievement of the desired visual, motion, and G-seat cue relationship. The state-of-the-art six-post motion system was the device delivering noticeably lagging cues. The cues could be brought more nearly into alignment by removing the CIG system transport delay compensation. However, pilots preferred to have the visual system delay minimized as much as possible, especially for formation flying. It was found for formation flight that an iteration rate change resulting in a 67-msec reduction in visual delay and finer translational motion, significantly improved the pilot's ability to perform the formation flying task in the simulator. Compensating for the majority of the CIG system transport delay turned out to be essential for proper simulation of formation flight. It is this compensation that makes ASUPT, if not the best, certainly one of the best responding visual simulators in existence.

Motion system software in training simulators usually has been relegated to a back seat with respect to computer time. It happened in ASUPT primarily because of the excessive computer loading and the emphasis placed on the advanced training features. Time delays and cue correlation problems caused by limited computer capacity and relatively low iteration rates should not be a problem in the future as we enter an era of computer-plenty. To minimize such delays, motion software shoud not be run at an iteration rate less than that of the fastest flight module. Simulator iteration rates in the future should not be based solely on the criteria of flight model stability but also on minimizing computational delays so that better simulator cue coordination can be achieved. The iteration rate manifested delays are only a part of the total motion system delay problem. For platform motion systems to be used as effective motion cueing devices for the very responsive fighter-trainer-type aircraft simulators, their hardware and drive algorithm response time will have to be improved significantly.

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