PROSPECTS, PROBLEMS, AND PERFORMANCE

A CASE STUDY OF THE FIRST PILOT TRAINER USING CGI VISUALS

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INTRODUCTION

The Device 2F90 was procured by the Navy in 1969 as an Operational Flight Trainer for use in conjunction with the TA4J aircraft. The typical Operational Flight Trainer at that time was designed to provide complete systems simulation in an instrument flight environment. Thus, the device found application as an instrument trainer and as an emergency procedures trainer. In actual practice, syllabus application was predominantly in the instrument training area (90 percent).

In late 1971 in response to increasing pressure to achieve some "payoff" in the use of simulators by achieving some reduction in syllabus flight hours, a series of evaluations[1,2] in the instrument training portions of the Chief of Naval Air Training Advanced Jet Syllabus was undertaken. In very general terms, these evaluations confirmed the efficacy of the 2F90 as an instrument trainer and projected incremental reductions in student flight time through use of simulation. To date student flight time in the instrument syllabus has been reduced from 44 hours to 22.5 hours with consequent substantial savings in the aircraft operating costs associated with the training of student naval aviators.

In spite of the progress made to date in the use of simulators to reduce the cost of training aviators, it should be apparent that the reduction in student flight hours through simulation in the instrument training phases is very nearly at the point of diminishing returns. Instrument flight hours today comprise less than 20 percent of the total syllabus flight hours in the advanced jet syllabus. If further significant savings are to be made through the application of simulation, we must move into the contact flight portions of our training effort. This, of course, means that some form of visual scene simulation must be achieved for use with aircraft simulators.

The need for visual displays had been formally recognized as early as 1971 when a major study of simulation and training aids conducted at the direction of the Chief of Naval Air Training[3] examined the state of the art of visual simulation. It was concluded that no existing system could meet illumination, field of view, and resolution requirements of a device suitable for undergraduate pilot training. An intensive development effort to provide acceptable wide-angle visual displays was recommended.

At about the time that the Chief of Naval Air Training simulator study was being published, the Navy became aware of the work being done by General Electric at Daytona Beach on Computer Generated Imagery. Since this approach appeared to be the most likely candidate for meeting our requirements in the near-time frame, the decision was made to procure one such device for evaluation. A significant decision, made early in the staffing process, was to procure the device for the operational 2F90 instead of the 2F101 which was then in the development stages. The decision to go with the older, less capable 2F90 was based principally on the fact that an operating device could be obtained with less lead time. It was conceded that this approach entailed somewhat higher risk but it was thought that the ability to build a device and begin evaluation approximately two years earlier on the 2F90 justified the additional risk.

In September 1972, a device was delivered to Naval Air Station, Kingsville, and the task of integrating the device with the 2F90 and evaluating the resultant training system began. What follows is a description of that process to date with particular emphasis on the technical lessons learned and the potential impact of the device on training methods.

In a CGI system, the gaming area environment exists only as stored numbers. The system accepts aircraft position and attitude data from the dynamics simulator and generates a scene with absolute perspective and spatial validity as it would be seen through the window of such an aircraft. It would seem that the task of retrofitting an existing trainer with such a system can be simply stated—"Install the display system properly with respect to the trainer cockpit, connect data cables providing position and attitude information to the visuals system, and start training."

Now, let's leave the clouds, and return to the real world. In the postulated scenario, one could expect that a host of problems, many of them unforeseen, would arise. This was the case. For the purposes of this discussion, these problems fall into three general areas:

a. Problems associated with the physical mating of two very complex systems. These problems can be considered solved when it is possible to turn the combined system on and achieve some semblance of a workable simulation.

b. Dynamic problems, arising principally due to the introduction of visual cues into the simulation problem. These problems can be considered solved when the pilot's perception of the simulation is sufficiently close to that encountered in the real aircraft as to make positive learning transfer possible.

c. Training management problems associated with determining where and how to use the new device in the existing training situation.

Some of the specific factors which had to be considered under each of these problem areas are listed below:

a. The load capabilities of the motion platform will not in general carry the added weight of a visual display system.

b. With a floor-mounted display system and a moving cockpit, how is a true feeling of the realism achieved?

c. A minor extension of Murphy's law assures that the number of scene edges desired to define the gaming area environment will exceed the capability of the system. How should edges be used most effectively to provide visual cues?

d. In the retrofit situation, the update timing of the dynamics simulator will in general differ from the frame rate of the visuals.

e. Simulated aircraft dynamics can be fully adequate for instrument training, and yet completely inadequate when the highly sensitive feedback of a visual system is added.

f. Combination effects—If subjective evaluation indicates something is wrong with response time, from control actuation to visual confirmation of desired response, what procedures will determine the cause of the problem so corrective actions may be taken?

g. What procedures are necessary to validate the training with visuals—to assign quantitative measures to the training?

h. How should the training syllabus be most effectively used in the combined system?

It will be noted that the problem areas identified above define the developmental progression of the device from concept to application in training. The remainder of this discussion will follow that general progression.

DESCRIPTION OF THE 2F90/CGI SYSTEM

The evolution of motion platform and simulated aircraft dynamics for instrument flight training has taken place over a number of years and has achieved a high degree of success. Proof of this success is evidenced by the amount of IFR simulator time which has been substituted for flight time in the syllabus for the Navy's Advanced Jet Training. Sixty-eight percent of the instrument flight training hours are conducted in motion base simulators. Because of this, it might be concluded that the same simulator dynamics would be perfectly suitable for use with visual attachments for VFR training. Unfortunately, such is not the case. Computer iteration rates, resolution, and response fidelity had been tailored to meet only the IFR flight regime. Furthermore, these only needed to meet the response and resolution that could be detected through aircraft instruments.

As an example, in the case of the 2F90 instrument trainer, there are places in the software equations where iteration rates are 20 per second for attitude, while others dealing with present position, etc., are computed only once or twice per second. While the latter are quite adequate for TACAN update, these are obviously grossly inadequate for such things as landing flare and touchdowns, formation flying, and carrier landings with all the associated flight path perturbations, etc. In addition, position calculations were in some cases quantized to only the nearest 2000 feet. This was quite satisfactory for IFR GCA approaches but would be much too coarse for GCA approaches with transition and breakout for visual landing or for taxiing along taxiways and runways. In converting the system to VFR capability, it was necessary to provide continuous motion cues with the desired "smoothness" which would be compatible with television projection systems. It was necessary to upgrade all dynamics including present position to 20 per second (the highest basic rate used in the 2F90) and the present position must be computed to the nearest 1/8 foot. These data were then converted to the 30-per-second iteration rate required by the CGI system by means of extrapolation/prediction techniques in the CGI interface equipment. Furthermore, greater fidelity is required for VFR maneuvers from the simulated aircraft dynamics, not only because its response is much more easily detected by visual cues, but also because many more portions of the flight regime will be encountered in VFR maneuvers than in typical IFR situations (i.e., acceleration and maneuvering relative to another aircraft in formation flying, arrester hook deceleration, etc.). Each of these factors need to be considered in modifying and upgrading the 2F90 system for use with the CGI system.

BASIC SYSTEM BLOCK DIAGRAM

Figure 1 shows an artist's concept of the layout of the system with General Electric's CGI visual system integrated with the Goodyear 2F90 motion base simulator. The visual system has three display channels. The images are projected by color television light valves onto the rear of three juxtaposed screens. These screens are

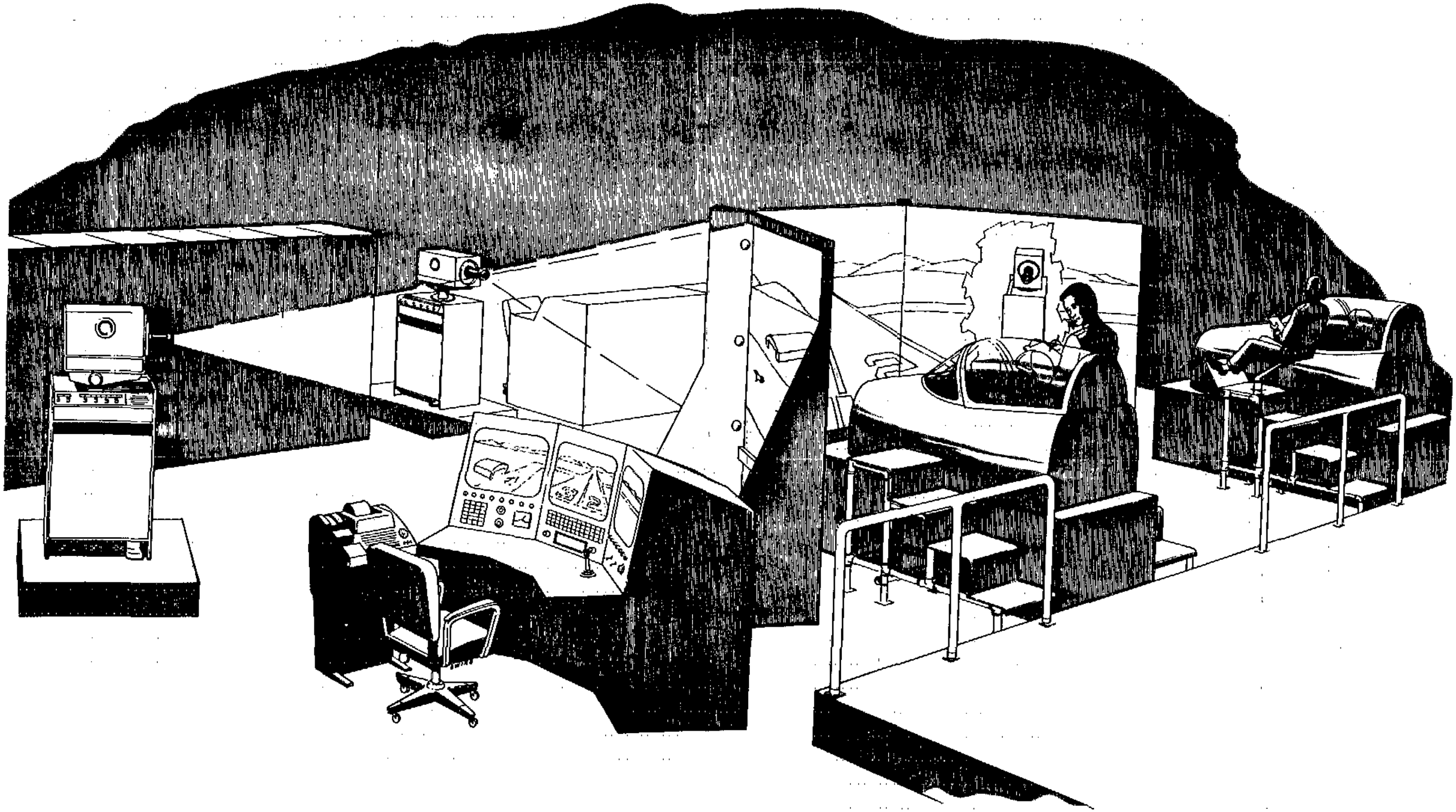


Figure 1. Advanced Development Model CGI Visual System for TA4J Operational Flight Trainer

floor mounted in front of the motion platform. The screens give a 60-degree vertical by 180-degree horizontal field of view to the pilot. Three color CRT monitors provide the instructor with the same video information at his console. Computed aircraft position and attitude signals from the 2F90 digital computer and motion platform attitude and position are fed to the CGI system so that it can generate the correct differential picture. Motion excursions are scaled down and washed out in the motion platform dynamics. Because of this it is necessary for the CGI system to "know" position and attitude both for the computed aircraft and for the platform in order to generate the correct differential parameters in the scene.

For example, the cockpit may only roll 10 degrees in response to a 60-degree computed aircraft bank. The additional 50 degrees must be supplied by opposite rotation of the CGI scene.

Figure 2 shows a simplified block diagram of the 2F90/CGI system. The blocks with heavy outline represent the hardware added by the CGI system. Pilot inputs from the cockpit are sent to the Sigma 5 computer in the standard manner.

The Sigma 5 computes aircraft attitude path and present position dynamics. It also provides computation for aircraft instruments, navigation and radio facilities, and motion platform drive signals. Factors such as aircraft carrier motion and wind are also computed. As was discussed earlier, upgrading the system to a visual retrainer required modifications and improvements in the Sigma 5 software.

A Nova 800 mini-computer was used for the interface between the 2F90 system and the CGI system. One other very important input to the Nova mini-computer is that from the cockpit position sensors. These were added so that the cockpit position could be known with precision. This was important because the cockpit drive is more or less "open loop" as great precision was not needed in roll and pitch washout for IFR application. By using the cockpit position signals and the computed ownship attitude, the CGI system can readily generate the image with the correct differential attitude for display on the floor-mounted screens.

The Nova computer also extrapolates (using rate information) the 20-iterations-per-second data from the Sigma 5 computer to the 30-per-second rate required for the CGI system.

The SEL 840 acts as the controller for both the Nova 800 and the special-purpose CGI hardware. It also does special data preparation and computation each frame for use by the image generation hardware which does the fast, highly repetitive type computations.

The special-purpose hardware consists of "Frame II" and "Frame III" functions. Frame II functions consist primarily of vector calculation and edge generation necessary to convert the three-dimensional data base into two-dimensional definitions

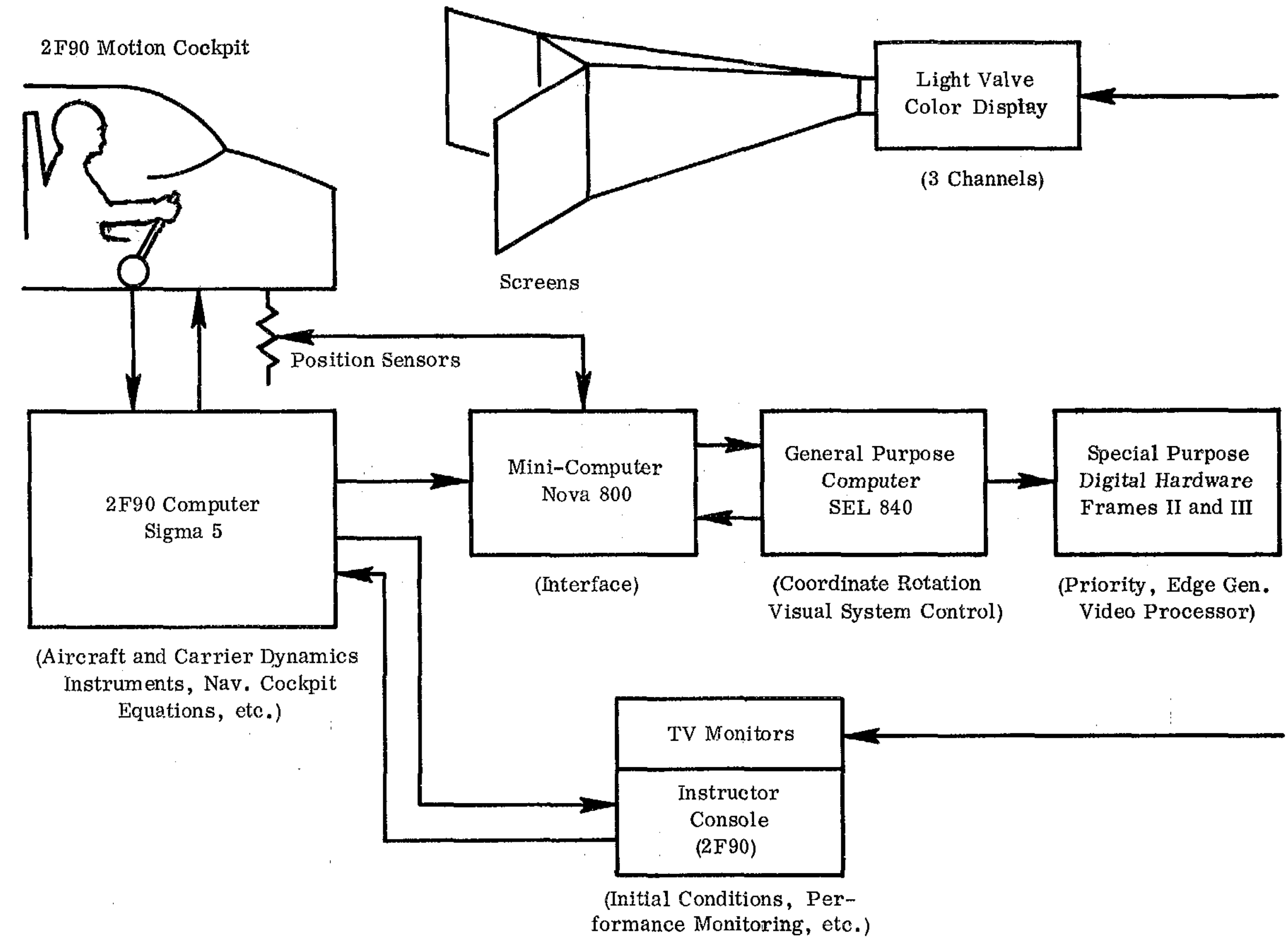


Figure 2. 2F90 Visual System

corresponding to the three computational "view windows." Frame III hardware generates the "edges" with which the image is drawn, and fog and color fading, and all the other functions that go into generating the video signals for the three display channels.

The three television light valve projectors are positioned and appropriate masks are provided so that the image will have good edge match across the juxtaposed screens.

2F90 SOFTWARE MODIFICATIONS

POSITION DATA

Because the 2F90 computations were tailored for IFR flight as seen through cockpit instruments, there were several places where equations had to be upgraded in the 2F90 software to make them compatible with the requirements of the CGI system.

The visual system requires accurate position and attitude data for each scene it generates. The fidelity of the scenes displayed to the pilot along a trajectory is dependent upon the accuracy of computations of the flight path and the data subsequently provided to the visual system. Similarly, the position and attitude computations for moving model (carrier, strobe lights, meatball, formation aircraft) determine the fidelity of its portrayed operation.

The CGI visual scene is updated each 1/30 second; therefore the position and attitude data for ownship as well as any moving model must be computed by the 2F90 and be available for transmission to the visual system as required. Present position is computed in the form of latitude and longitude in the 2F90 and is updated at a 2-per-second iteration rate.

The visual system requires the x and y (ground trace) coordinates and the altitude above ground level of the pilot's eye point and the center of gravity of all moving models—all at a 30-per-second rate. The x, y, and altitude coordinates must be accurate to 1/8 foot to provide the maximum accuracy in the visual scenes. It was necessary to modify the present-position calculation up to a 20-per-second iteration rate to achieve an adequate information rate. These were then converted to 30-per-second signals in the CGI interface equipment by extrapolation/prediction computations.

ARRESTED LANDING SIMULATION

The 2F90 software was modified to provide computations for simulating arrested landings. These involve not only the flight trajectory but also the motion cues associated with arrested landings.

The capability for arrested landing simulation required a mathematical representation of the carrier and its flight deck characteristics to be calculated. These characteristics were derived from the dynamics equations for carrier motion.

The carrier's position and orientation were computed each 1/30 second from the carrier's dynamic equations. Mathematical rotations and translations were required to locate the position and orientation of the simulated wires each 1/30 second. Logic was required to determine which, if any, has been engaged by the extended hook. Identification of a wave-off input from the instructor station was provided for, along with the generation of an output to the visual system, to activate the wave-off lights.

At the instant of detection of a captured wire, the existing flight conditions are the required inputs to the arrested dynamics equations. The instrument indications, the motion platform commands, and the outputs to the visual should be in agreement to provide a consistent set of cues.

Provisions were also made for bolter landings which include similar operations to those required to detect hook capture performed on bolter/landing zones. The bolter simulation allows for realistic flight dynamics beyond the limits of the carrier deck.

CRASH INDICATION

With the added dimension of a visual world, the conditions detected as crash conditions had to be expanded. New crash conditions included:

a. Landing short of depicted runways.
b. Carrier ramp strikes.
c. Bolters or catapult launches in which the airplane lands in the water.
d. Landings on the carrier deck which are outside predefined landing/bolter zones.

Since these additional crash equations are performed in the visual system, additional data (for example hook-down, wheels-down signals) must be transmitted to the visual system from the 2F90. A crash indication discrete, in turn, had to be transmitted back to the 2F90 if calculations by the visual system indicate a crash.

NAVIGATION AIDS SIMULATION

Since carrier operations became possible with the addition of the CGI visual it was necessary to add the navigation aids associated with carrier operations. This included the TACAN channel and its location (as a function of carrier dynamics). The operational software had to have the provisions to tune in the desired channel and to command the directional and ranging instrumentation to indicate consistently over the normal ranges of operations.

The accuracy of GCA simulation routines were limited to 2000-foot resolution and required upgrading to provide the 1/8-foot accuracy required by the introduction of the visual scene. The touchdown point for the GCA had to agree precisely and consistently with the corresponding point on the depicted runway.

WIND SIMULATION

The wind simulation in Device 2F90 was modified to make provisions for ground operating conditions. These operating conditions included taxiing, parking, and preparation for both unassisted and catapult assisted takeoffs. While the vehicle is on the ground, the crosswind effects had to be cancelled by simulated tire friction. It is necessary to include tail/head wind effects to the degree that these are present in airborne operations.

The wind simulation routines in the vicinity of the carrier allow for the crosswind effects normally encountered in carrier operations.

PROVISIONS FOR INITIAL CONDITIONS

For carrier operations, it was desirable to insert initial conditions for the carrier simulation at the beginning of an exercise (or by a reset). The initial conditions include carrier heading, speed, sea state (to determine roll and pitch), and location. Initial conditions for the aircraft position and orientation included the capability to locate the aircraft (with engines running and instruments operational) at the catapult launch position of the carrier.

Additional initial conditions for the aircraft were desired to achieve maximum effectiveness from the simulation. For example, to train students on GCA techniques, an initial condition at entry into the pattern which could be reinitialized after landing eliminates the time required to "fly" back to the re-entry point. The results of this capability allow more GCA landings to be performed within a given period.

COMMON MODE OPERATION

Formation flying exercises involving two students could be performed with the visual system by the addition of a common mode capability to Device 2F90. This capability would require provision to make available to the visual system, position and attitude data from more than one cockpit.

Additional capabilities necessary for common mode operation include voice communications between students and coordinated instructor station controls (reset, freeze, resume, replay).

PRELIMINARY WORK AND MATING OF GE CGI TO 2F90

Obviously some basic engineering had to be accomplished before the two devices could be mated. Since the 2F90 was an operating device, there was virtually no option but to require that the final device conform to the general envelope of capabilities defined by the existing 2F90 hardware. Furthermore, since it was not envisioned that all 2F90's would be equipped with visuals, it was recognized that some care would have to be exercised in making software changes to the 2F90. The first problems to present themselves under these constraints were:

a. The question of how to handle the visual display screen relative to the moving cockpit of the 2F90. The limited capability of the 2F90 motion platform dictated a moving cockpit—stationary screen approach.

b. The question of harmonizing the iteration rates of the two computer systems involved.

MOVING COCKPIT—STATIONARY SCREEN

If a pilot is flying straight and level, with the horizon directly ahead of him at 0-degree elevation, and his aircraft suddenly translates up or down (with no pitch), the horizon will remain at the same angle directly ahead of him. Now assume he is flying the simulator and the horizon on the screen is directly in front of his eyes. Assume the cockpit moves up several inches, to generate the inertial cues for the above effect. If the picture on the screen remains unchanged, the horizon will now appear at a negative elevation angle—a very unrealistic effect. Similar analyses apply to left-right and fore-aft cockpit translations.

Several approaches can be used to eliminate this problem. If the display system were mounted on the motion platform, the relationship between the viewpoint and the display would not change and the above effects would not exist. Unfortunately, size and weight restrictions ruled out the use of an on-platform display system for the 2F90 visuals.

The use of a collimated image would also overcome the cockpit translation problem. A collimated optics system provides the effect that, for relatively small ranges of motion of the viewpoint, the scene appears at infinity—the image on the retina remains unchanged. These systems, however, cannot accommodate the range of motion of the 2F90 cockpit.

Because of the characteristics of Computer Generated Image technology, this problem was easily solved for the 2F90. Cockpit position is sensed for each scene time. This information is used in the computation of the scene to be displayed, so that as the cockpit translates, the CGI scene moves to track it properly. The result as the cockpit moves is the same as though the pilot is looking through a window at a scene at a great distance. This "synthetic collimation" can accommodate far greater movements of the viewpoint than any existing optical collimation systems and makes feasible the moving cockpit-fixed screen configuration.

UPDATE RATE DIFFERENCE

The 2F90 aircraft dynamics simulation provides updated aircraft data 20 times a second—every 50 milliseconds. The visual simulation system, in order to eliminate distracting intensity flicker and scene jumpiness or jitter, operates at the television standard of 30 frames per second, 60 field per second. It thus requires aircraft position and attitude data 30 times a second, every 33-1/3 milliseconds, on which to base the computation of the next scene.

Suppose we have independent timing of the two systems, and at the beginning of each new scene, the visual system uses the latest data received from the dynamics system. One might reason that each scene would be valid for a time which is only a matter of milliseconds removed from the time of its generation.

Simulation is an approximation to reality. Its goal is to produce a subjective effect of realism. In regard to this timing, as to so many other questions in simulation, analysis can provide guidance, but the answer must come from a test of proposed approaches to evaluate the actual results. Fortunately, a real-time laboratory system with flexibility for such evaluations was available during the design phase of visuals for the 2F90, so the great majority of such questions could be answered prior to fabrication and installation.

Simulation of the above technique for handling the timing showed the results to be completely unacceptable. The display looked very jumpy. Figure 3 shows why this occurs. Yaw angle versus time is plotted. The circles indicate the sample times and values from the dynamic system—these define a constant 30-degree-per-second turning rate. The x's show the visual system times and angles, based on the approach discussed above. The dashed line connecting the x's indicates the turning rate information seen by the observer. The scene can be described as having a "jitter" of about one degree magnitude, at a 10-per-second rate. The eye is exceedingly sensitive to angular effects; further, the 10 Hz region is a highly sensitive frequency for subjective phenomena such as flicker, jitter, etc.

Let's consider a modified technique. At each time that a position and attitude data sample is required by the visual system, apply a first-order extrapolation to the previous two samples from the dynamics simulation. For the example shown in Figure 3, this would put all x's precisely on the line connecting the o's; results would be perfect. This is true for any constant velocity or turning rate. Let's examine an example with a non-constant rate.

Assume the simulated aircraft is in a 60-degree-per-second turn rate and begins to decelerate at the rate of 15 degrees per second squared. Figure 4 is a plot of yaw angle versus time, with "zero" for both being at the point where deceleration begins. As before, o's indicate samples available from the dynamics, and x's are values used by the visuals, determined by the first order extrapolation rule. These appear to fall exactly on the line indicating actual values. Consider the visual sample time identified by the vertical line at 133 milliseconds. The mathematically exact value of yaw angle applicable to this time is 7.866 degrees. The value obtained by extrapolation from the two previous values is 7.888 degrees, a difference of only 0.022 degree. These analytical results give great promise this technique will prove effective. In actual dynamic simulations, there have been no indications of invalid results or of jumpiness when this technique has been used.

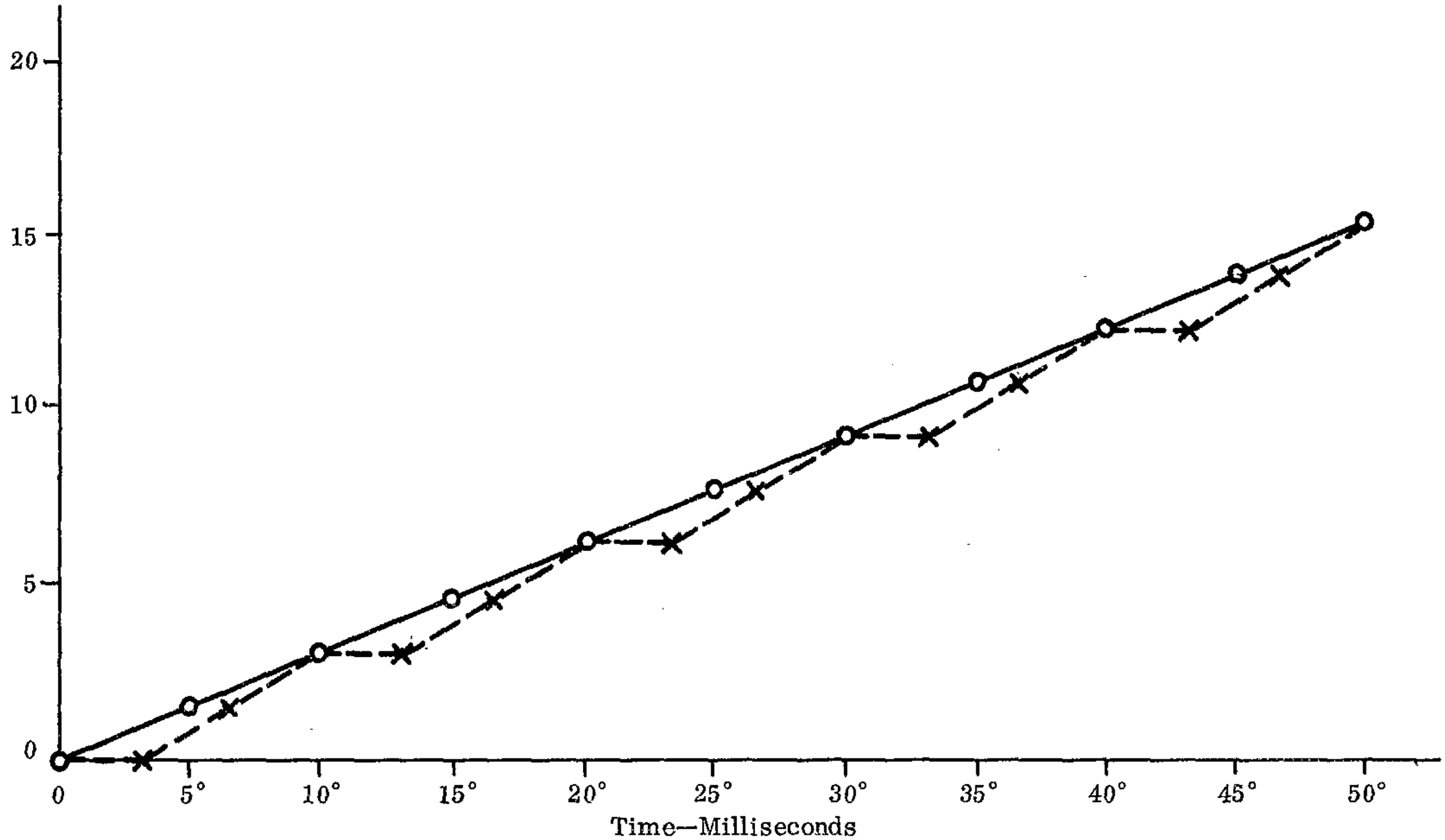


Figure 3. Dynamic System versus Visual System (Constant Turning Rate)

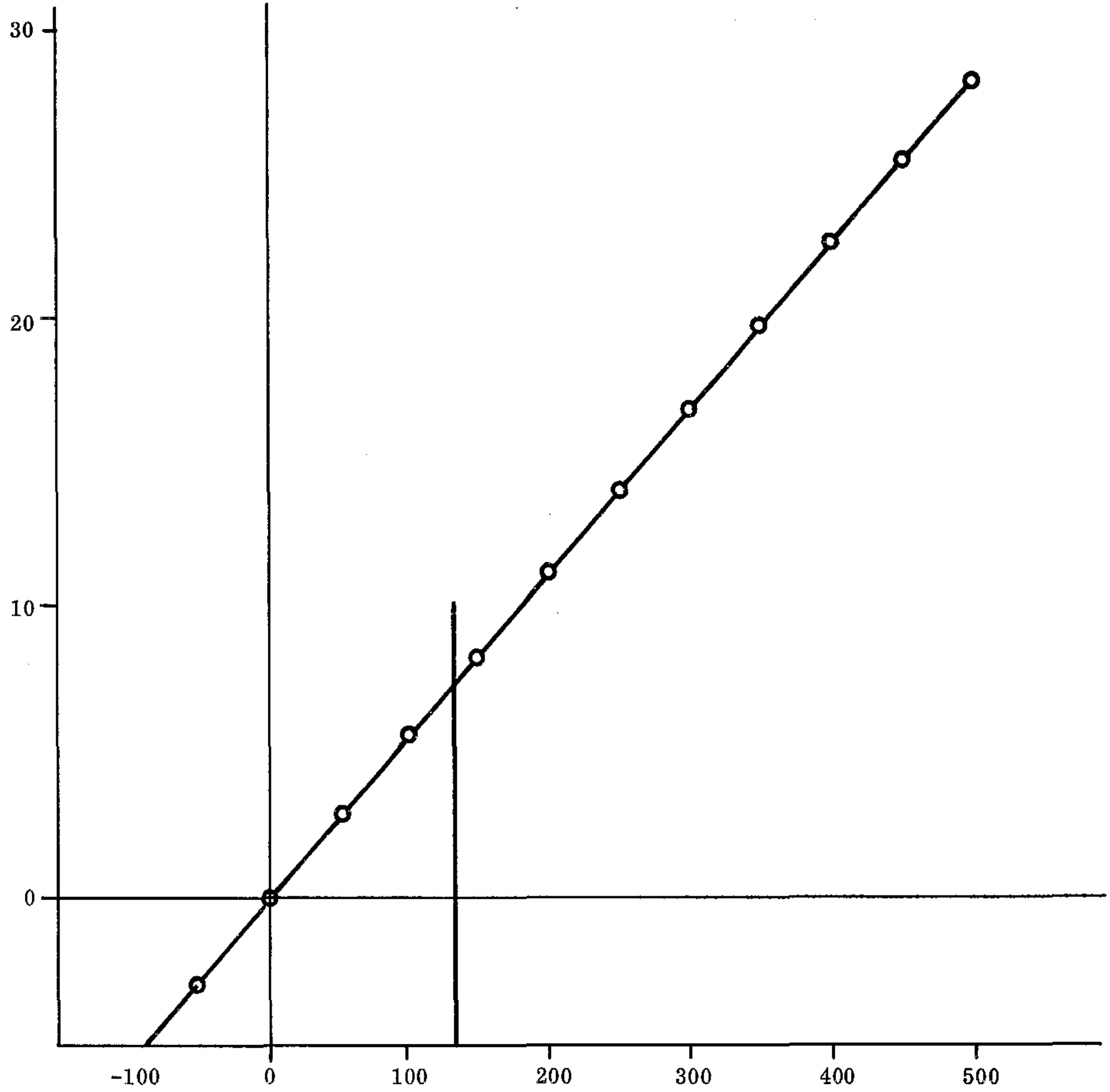


Figure 4. Dynamic System versus Visual System (Non-Constant Turning Rate)

DYNAMIC PROBLEMS

Having achieved a mating of the visual display with the basic simulator which produced something approximating an aircraft in a contact flight environment, the next step was to subject the device to critical evaluation by aviators experienced in the TA4J aircraft. As had been expected, this evaluation revealed a number of areas in which the performance of the simulator was adjudged to be so different from the aircraft as to require corrective action before using the device for training. It should be noted that these same pilots flying the 2F90 as an instrument trainer had no substantial objections to its performance. In fact the 2F90 was generally considered to be an excellent simulation of the TA4J in the instrument flight regime. It seemed quite obvious that the addition of visual cues and the consequent increase in the sensitivity of the pilot as an element in the feedback loop was the cause of the apparently poor performance. Evidently minor errors due to approximations made in implementing the equations of motion in the simulator, which had previously been masked by normal instrument error and/or instrument lag, became evident and objectionable in the contact flight regime. Problems arising in this portion of the evaluation were loosely classified as dynamic problems and the corrective procedure was viewed as a process of "fine tuning" the simulator to produce responses acceptable to the pilot. The following problems were addressed in this manner:

a. Inadequate engine response/poor aircraft drag characteristics.

b. Controllability problems in pitch and roll relating to stability and flight control feel characteristics.

c. Lag effects which led to controllability problems in certain special cases.

d. Navigational accuracy problems.

e. Human factors considerations involved in how best to use the limited edge capacity of the visual.

Each of these is briefly discussed below.

ENGINE RESPONSE/DRAG FUNCTION

Engine response difficulties were encountered first in attempting to fly the optical landing system in both the Kingsville data base and the carrier data base. Pilot complaints were that the simulator did not respond quickly enough to minor changes in power setting. Similar, though less objectionable, characteristics were noted in the clean configuration in other flight regimes. Aircraft acceleration and deceleration in response to large power changes were also noted to be substantially different in the simulator as compared to the aircraft. It was evident that aircraft drag calculations or engine system response calculations in the basic 2F90 were inaccurate. As it turned out, both computations had to be adjusted to give satisfactory performance.

ENGINE SYSTEM

Problems with the engine system were evidenced directly as inadequate response to the addition or reduction of power. These stemmed from two deficiencies:

a. Engine system calculations in the basic 2F90 were iterated too slowly (10 Hz) to accurately "track" rapid power control level (PCL) changes.

b. Aircraft dynamic calculations had too great a lag between thrust change and consequent measurable effect.

The first problem was, unfortunately, an inherent result of choosing to perform engine system calculations at less than the maximum system clock rate. A modification to increase this iteration rate, though feasible, was not within the scope of the contracted software support effort. Therefore, in order to more closely simulate aircraft response, a departure from theoretical calculations was taken and engine thrust was made a direct function of PCL position rather than a dynamic function of the difference between current and commanded thrust. Calculation of instrumented engine parameters was basically unchanged since any lag in their response was masked by instrument lag.

The necessary departure from "theoretical" considerations was not desirable, but is justified by the constraints of system design and by the resulting improved system dynamics.

DRAG FUNCTION

During an evaluation of system dynamic data, it was found that several of the lift/drag coefficients were inaccurate. The basic trend of these inaccuracies was that total aircraft drag, especially in the dirty configuration, was too small. Several changes were incorporated to reflect different drag coefficient data for aircraft with drop tanks. In addition, the speed brake drag coefficient was arbitrarily increased by 20 percent. This gave better response to power addition/reduction by requiring a higher power setting for stable flight conditions with speed brakes deployed.

The combination of engine system and drag function changes did finally result in acceptable simulator response.

CONTROLLABILITY PROBLEMS

Perhaps the most striking problem encountered by pilots as they attempted to fly the simulator were those associated with controlling the "aircraft" as they attempted to maneuver it in response to visual cues. Put quite simply, the simulator did not react the way the TA4J does in a given perceived situation and consequently there was a tendency to overcontrol and enter minor pilot induced oscillations. Complaints centered around roll response with some objections noted to pitch response and none with respect to yaw. It should be pointed out that the pilot expects rates of response about aircraft axes in about the order in which complaints were ranked. About the roll axis, where moments of inertia are low and available control forces high, the pilot expects rapid response; can be expected to command such response frequently; and is likely to be most critical of any adverse dynamic characteristics. About the pitch axis moments of inertia are relatively high and characteristic times are longer; the pilot is not as likely to command high pitch rates; and the threshold at which the pilot perceives adverse dynamic characteristics is more remote. The point is that, although dynamic deficiencies of the same kind and magnitude probably existed in the 2F90 about all axes, it was necessary to pay more attention to roll axis response than pitch axis response because the objective was to achieve acceptable subjective response on the part of the pilot rather than absolute dynamic fidelity of simulation.

ROLL AXIS RESPONSE

About the roll axis three basic requirements were identified which the simulator would have to achieve to be acceptable.

a. Adequate roll response to aileron control inputs.

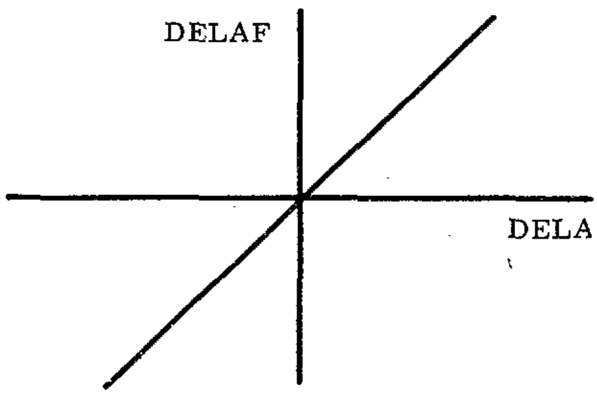
b. Stability/controllability (i.e., once a bank or wing level condition established, ability to maintain it without wing rocking).

c. Proper control feel (breakout force).

These three requirements are interrelated and their implementation is a function of the interaction of mechanical, electromechanical, and software design. However, the only feasible way of meeting the requirement in the 2F90 was through software modifications. Software design approach to the problem was as follows:

The functional relations shown relate effective aileron deflection (DELAF) as a function of lateral control stick deflection (DELA).

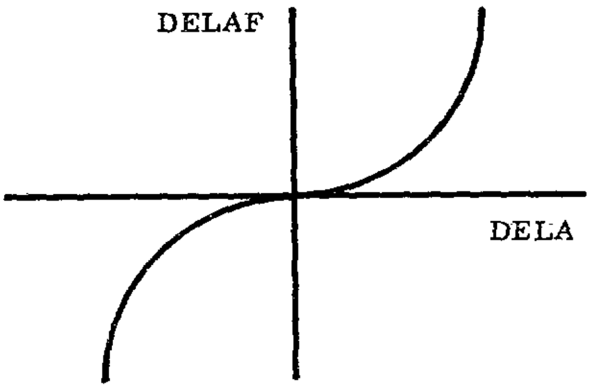
Original Dynamics (As Delivered) Theoretical (Linear Response)



This provides excellent roll response; however, lack of any "deadband" coupled with inadequate mechanical simulation of control feel made system too unstable.

The control feel system utilized a hydraulic servo system with control force a function of stick deflection. An attempt to "software" simulate a "breakout" force failed because of the hardware design.

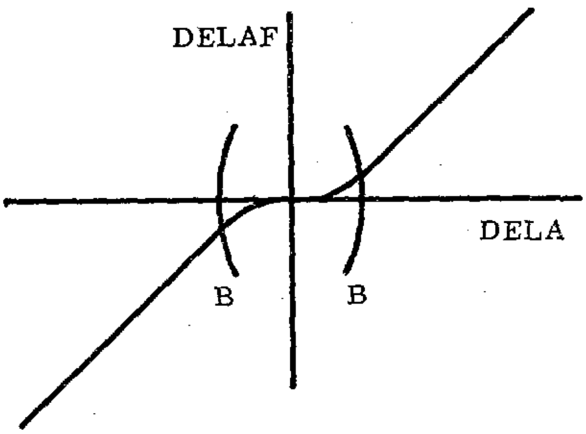
Old Dynamics (Original Modification) (Parabolic Response)



DELAF = |DELA|: DELA

This provides excellent stability and adequate feel; however, the roll response was so slow that PIO could occur when late line-up corrections were made (similar to problems with 2H87).

GAC Modification

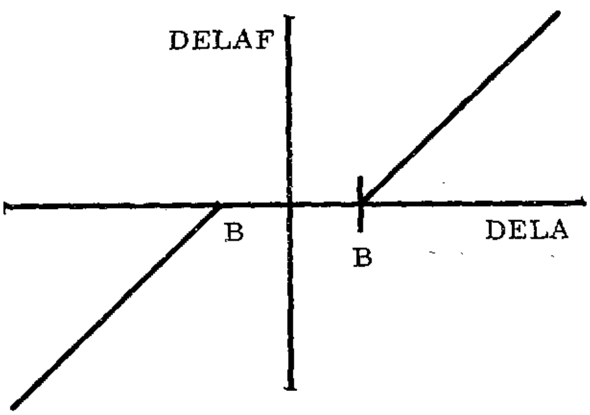


$$DELAF = 1/K(DELA)^3 \quad K = \frac{1}{B^2} \quad |DELA| \le B$$

$$= DELA \quad |DELA| > B$$

This approach was used to provide stability (using the cubic section as a deadband with the width controllable), and adequate roll response with linear function outside the deadband. This gave good results except that control feel was still not "mechanically" realistic. Also width of deadband was limited to about 2 degrees because for B > 2 degrees the discontinuity in slope at B becomes too abrupt.

Final Attempt (Linear Deadband)



This approach combines the stability and response of the GAC modification with the capability of choosing other deadband widths > 2 degrees to provide greater stability at high speeds (e.g., acrobatics).

This also seems to more closely approximate breakout force feel of the actual aircraft.

To the extent that iteration rate and other system delays allow adequate roll response and adequate stability/controllability have been achieved.

However, control feel still leaves something to be desired primarily as a result of deficiencies in the mechanical/servomechanical system by which aircraft stick forces are simulated.

PITCH AXIS RESPONSE

Early in our evaluation of simulator dynamics, it was recognized that a problem in the area of Fresnel lens landings was that of adequately simulating the aircraft pitch stability characteristics in the dirty configuration.

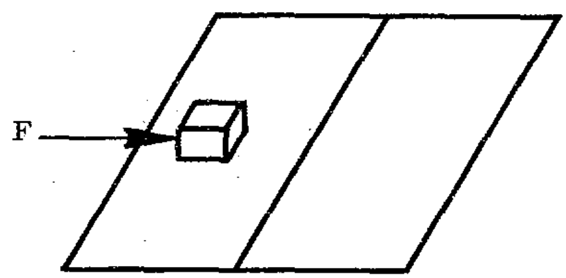
It was concluded that the system 20 Hz iteration rate coupled with the sequence of calculation of state variables could be the reason that simulator dynamic pitch stability did not approximate aircraft pitch stability. Several attempts to improve this was made by trying to adjust the "short-period" mode of the simulator: these proved unrewarding.

In an effort to duplicate the aircraft's pitch stability in the dirty configuration, the thrust moment arm was arbitrarily set to zero. By varying the moment arm with the flap setting, the desired pitch stability was obtained and simulator performance greatly increased.

TRANSPORT LAG EFFECTS

Lag effects occur in a simulation problem because of the time required to display present aircraft position and attitude to the pilot after the simulator has taken account of all inputs and computed the necessary quantities. In a simulation involving instrument flight, these lags are not ever likely to be objectionable because, in general, this can be made much smaller than the typical dynamic lags inherent in aircraft instruments. Therefore, the pilot perceives an environment very similar to that encountered in an actual aircraft when flying on instruments. However, once visual cues are provided, the simulation must then compete with a situation in the real world in which the pilot perceives changes with a lag which is dependent only on the distance to a reference object and the speed of light. The transport lag will be much larger than this lag in most practical scenarios.

To assist in visualizing the effect of transport lag, it is helpful to visualize a mass (m) sitting on a frictionless plan. An arbitrary force F can be applied to bring the mass (m) to a commanded position represented by a line in the plane. The force F can be varied within fairly broad limits in a direction perpendicular to the command line to cause the mass to move to the line. It seems clear that one could very quickly learn to move the mass smoothly to the commanded position with a minimum of damped oscillation as the commanded position was approached.



Now consider a similar experiment in which the general setting was the same except that the controller's only reference to the scene was a television picture which was presented to him after a delay of Δt_ℓ seconds. Now the controller is always looking at a picture which is Δt_ℓ seconds old and the mass has continued to move in response to his applied force in that interval. In fact, if he is unaware of the lag and if the magnitude of Δt_ℓ is significant in comparison with human response time, he is likely to be pushing on the mass after it has actually passed the commanded position. Obviously a substantial oscillation can occur as the controller "chases" the actual position by reference to his delayed picture. In this simplified situation the controller could easily learn to "lead" to compensate for display lag. This would be much more difficult to do in a three-axis simulation, and, in any event, learning to "fly the simulator" in this manner is likely to be undesirable from the learning transfer viewpoint.

The effect of transport lag appears to be most objectionable in roll axis response. The reason appears to be the same as for the general tendency to criticize dynamics on the roll axis. In the aircraft rolling moments of inertia are relatively low and roll command is generally high. The pilot expects good roll response. In particular, pilots expect rapid roll response and good controllability "in close" in the landing approach. In this position where distance to touchdown is short, the pilot is likely to command high roll rates to refine his lineup with the runway centerline. It is in this circumstance in the simulator that he is likely to end up in a very rapid rolling oscillation as he chases the display.

Experience with the visual device indicates that transport lag instability in the simulator will occur when the pilot's perception of the time available to complete a correction is of the same order of magnitude as the lag. For example, after all of the corrections to 2F90 dynamics were made, it appears that objectionable roll oscillations will still be generated during a landing approach if a rapid lineup correction is attempted within 1/8 mile of touchdown. This represents an improvement from roughly 1/2 mile when the device was first integrated.

While it would be desirable to eliminate transport lag effects entirely, the present performance of the device at Kingsville is considered to be acceptable. There is no evidence of lag instability about the pitch or yaw axes in any training maneuver attempted so far, and the impact of roll instability is only evident in the very late stages of precision landing attempts on the optical landing system.

NAVIGATIONAL SYSTEMS

Unsatisfactory results of the navigational system simulation when the combined systems were initially flown identified an additional area in which simulation fully adequate for instrument flight training must be upgraded to be compatible with the increased sensitivity and precision provided by visual feedback. The relevant criteria are outlined below:

a. Visual system calculates position 30 times per second to 1-1/8 feet (24 bits).

b. As modified for visuals, the 2F90 calculates position for visual 20 times per second to 32 bits accuracy.

After extensive investigation, it was determined that problems were not a result of discrepancies between the two position keeping systems.

The problem was found to be in the 2F90 Communication-Navigation programs where TACAN navigation and GCA calculation were performed. Fortunately, these calculations were performed to full 32 bits accuracy; however, the deficiencies arose because navigation facility location data was packed in half-words to only 16 bits accuracy. The resulting inaccuracy was the cause of problems with navigational accuracy. By changing the storage of several key facility locations to full 32 bits accuracy, this problem was solved.

We now have the capability of making full instrument approaches to visual transition at NQI or at the LEXINGTON with precision at least equal to that available in the aircraft.

HUMAN FACTORS CONSIDERATIONS

The data bases delivered with the 2F90 visuals were quite extensive. These covered an area about 60 by 80 nautical miles and included a representation of airfields at Kingsville-NAS and South Field, a target area for air-to-ground weapon delivery practice, and the shoreline/island complex including Corpus Christi. A detailed aircraft carrier with deck markings was also included.

These data bases were carefully built using maps and aerial photos to assure as much fidelity as possible. Principal roads and significant landmarks were included where practical. Major towns or settlements were included in outline form. In the quest for realism even the coloring was carefully planned. Dull, low contrast tones were used for the countryside surrounding the airport. With the 500-edge limitation of the CGI system, however, there proved to be inadequate texturing and ground patterns for proper velocity and altitude cues for good line up and landing on both the airfield and the carrier. This problem was further heightened by the extremely uniform coloring which the CGI system was able to produce. There were no blotches, highlights, or local imperfections which would give velocity cues within the large uniformly colored fields. As a result, it was difficult to adequately judge velocity and altitude at critical landing phases.

A short human factors study was initiated to try to find ways to improve the situation. It was soon determined that too much emphasis had been placed on realism (low contrast, uniformly colored fields, etc.) and not enough on using the lines (surface edges) in the picture to emphasize linear perspective to the maximum degree. The CGI system computes perfect perspective, but many of the edges in the scene were too subdued or inefficiently used for this linear perspective to be adequately observed.

As a result of data base experiments, several techniques were used to enhance the velocity and altitude cues. A brief discussion of several of the more important techniques used is given in the following paragraphs.

AERIAL PERSPECTIVE

Advantage was taken of the feature already built into the CGI system to produce haze or fog. A very light haze which varied as a function of altitude was used. In addition to producing a less prominent horizon (with some effective horizon depression), it also provided a variation of color of the "earth's" surface as a function of range. The warm foreground colors faded to lower contrast colder colors (with a slight blue grey tinge) in the distance. This provided a sensation of "depth" and expansiveness to the ground plane. Figures 5 and 6 show before and after adding aerial perspective to the computed scene.

TEXTURING

Artificial texturing was added in various forms on the ground plane around the airfield to provide the velocity cues needed for VFR approaches and airport traffic pattern work. Some of this texturing is evident in the two photographs discussed in the paragraph on aerial perspective. Both brightness and color variations were used to provide adequate contrast.

In the case of the aircraft carrier, artificial squares were added near the aircraft carrier to provide velocity cues for both ownship and carrier to the pilot. In addition, the carrier wake was modified to provide abrupt color variations along its length and width instead of the more "realistic" blended variations of the original. In this way, the edges which were used in the scene were much more effective.

COLOR CONTRAST

In addition to using color contrast to make ground texturing more apparent, it was used in slightly different manner to overcome some of the undesirable CGI quantization (stair step and scintillation) effects which made it difficult to achieve early line-up on the carrier approach. In the original "realistic" data base, the deck was dark and the landing area markings were a highly contrasting white. At longer ranges from the carrier, the computer quantized representation of the stripes

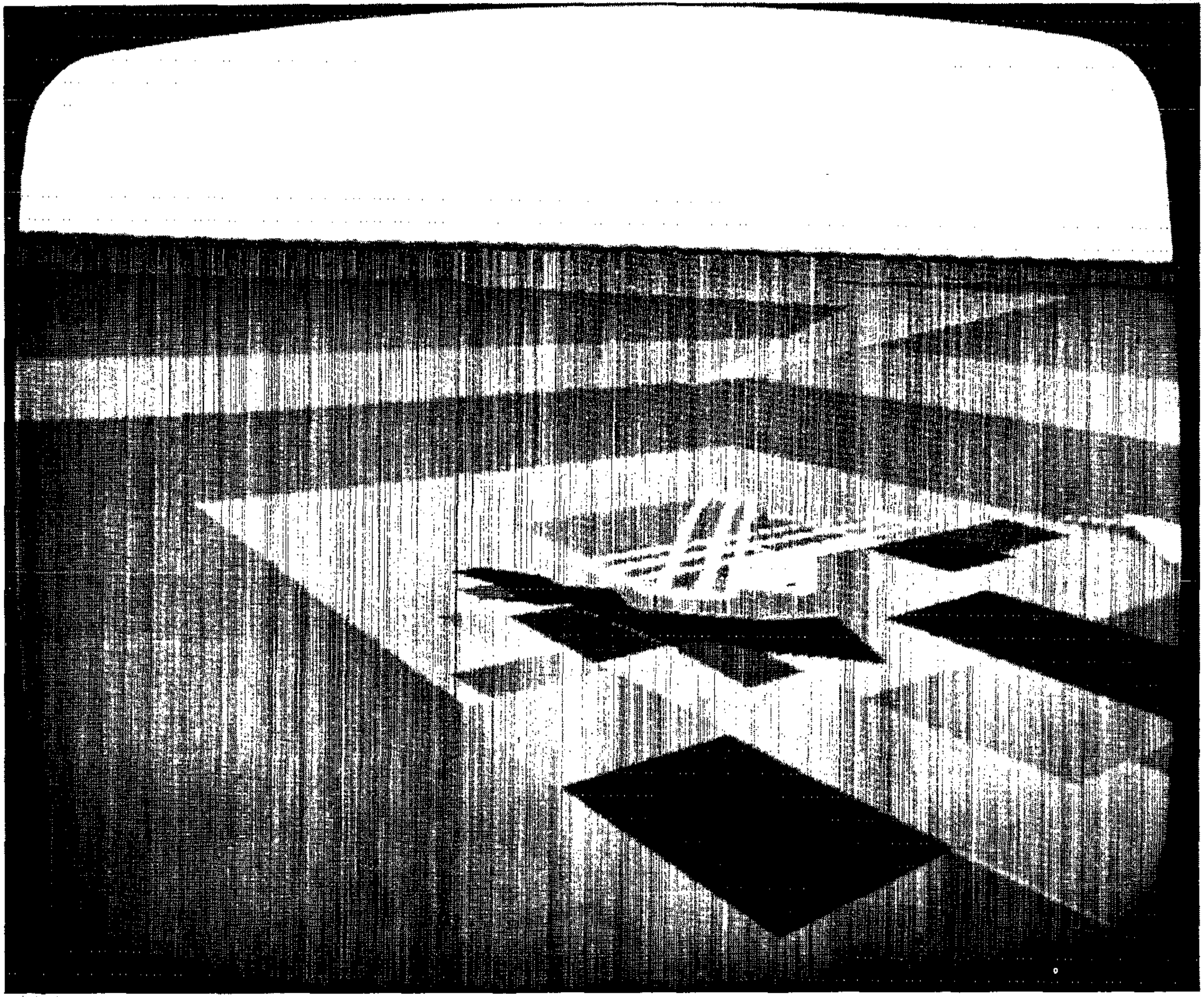


Figure 5. CGI With Haze

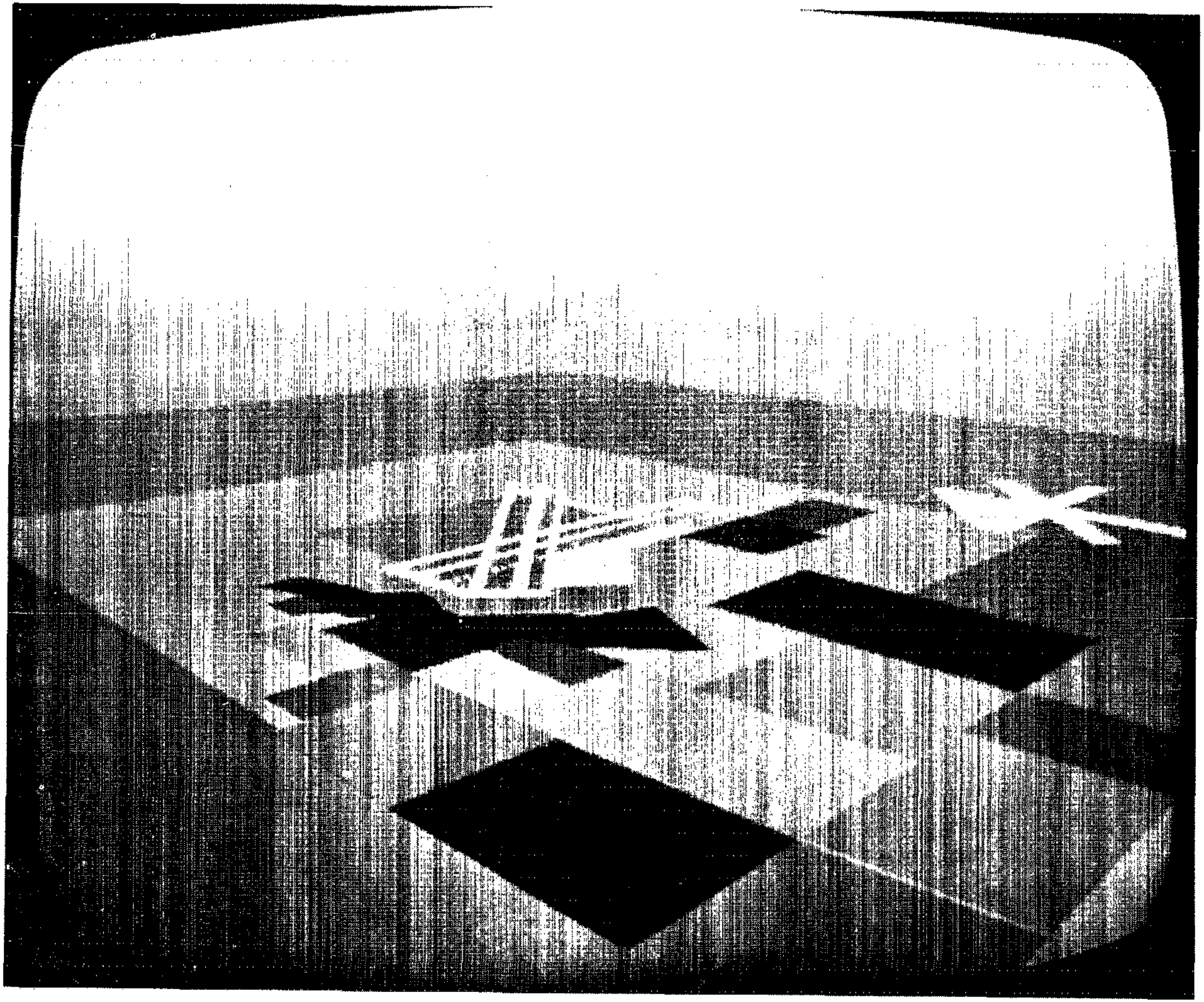


Figure 6. CGI Without Haze

caused them to scintillate and move about abruptly as these intercepted different raster lines and picture elements. This scintillation completely masked the aspect angle of the carrier at longer ranges.

This problem was largely overcome by coloring the whole landing area white and overlaying lower contrast grey deck markings. The stripes were "lost" in the white deck at greater distances and so did not scintillate. The more massive area of the deck was less affected by quantization and held together as an entity at longer ranges to show the familiar trapezoidal shape from which aviators can determine high/low and left/right alignment information.

SIZE CONSTANCY

In addition to the use of color contrast on the carrier deck, another improvement was added. Because of the reduction of detail and contrast, representations of large objects in optics and display systems often seem to be too small. It has been found that this size constancy problem can be overcome by artificially increasing the size of the object to the point that it "seems right" to the observer. Experiments on the CGI system on the 2F90 showed that an increase of about 1.5 was about optimum for the carrier. This not only made the carrier seem to be full-sized, but the larger image size subtended more television picture elements and so was capable of being resolved at 50 percent longer ranges.

PARALLAX CUES

One of the deficient ingredients in the original data base in the area around NAS-Kingsville was that of vertical objects which would provide parallax information valuable for both altitude and distance cues. Some artificial towers 200 feet high were added at critical points where they could be observed on downwind and the final approach. The relative motion of these towers against the background texture and between themselves proved to be very strong dynamic depth cues for both altitude and distance. Several pilots commented that this finally provided the sensation of height that had been missing in all previous data bases.

TRAINING APPLICATION

With an operating device which had dynamic qualities which were acceptably similar to those of the TA4J aircraft, it was possible to move to the final step in the evaluation process—the testing of the device in the actual training of students. During the nine-month period while the device was being installed, tested, and refined, experienced flight instructors had been giving considerable thought to the question of where and how the device should be applied. It was decided that applications testing should proceed in the following advanced jet syllabus stages in the order of priority listed:

a. Familiarization Stage (A Stage).
b. Carrier Qualification Stage (K Stage).

c. Formation and Basic Tactics (D, E, and J Stage).
d. Air-to-Ground Weapons (I Stage).

Application in the instrument training phases was not considered a profitable area for application for a single device since substantial progress had already been made with the basic 2F90, and the only really new dimension added by the visual device was the capability for presenting the instruments to contact transition in an instrument approach.

The Familiarization Stage was chosen as the highest priority area for testing for two reasons: First, it was thought that the student's lack of familiarity with the TA4J aircraft would tend to make him less critical of the simulation and, therefore, more likely to accept the training offered in the device. As it turned out, recent changes to syllabus sequencing in connection with work on the instrument phase resulted in the student having substantially more simulator than aircraft time as he enters A Stage. A second reason for choosing A Stage as the first to be investigated was that it included the broadest range of contact flight training requirements while simultaneously demanding the least (in a relative sense) of the student in terms of precision. The student stood to gain the most from simulator availability while at the same time much could be learned regarding training methods with the device which would apply to tests in other phases.

Carrier Qualification Stage was chosen as the second area for investigation because it provided a relatively well defined, high precision task of restricted scope in which to test simulator application. It was also a logical extension of A Stage landing work.

Both the Familiarization and Carrier Qualification Stages are attractive from the aviation safety standpoint since experience indicates that these are both high risk training areas. Obviously, any substantial amount of training accomplished in simulators will have a favorable impact on accident statistics if only by reducing exposure.

At the time of this writing, the Familiarization testing is well underway. The process of constructing a test plan for the Carrier Qualification Stage has been initiated. Testing in these two areas will occupy the time available on the device and the limited instructor population at least into the second quarter of 1974. Therefore, consideration of testing in the remaining portions of the advanced syllabus is premature at this time.

FAMILIARIZATION STAGE TEST (A STAGE TEST)

The A Stage test was designed following experience gained in two previous experimental flight time substitution tests conducted by CTAW II in the instrument stages of the syllabus.[1,2] The following were the principal characteristics of the experimental design:

a. The existing A Stage syllabus was accepted as the current training requirement. Historical data maintained by the Naval Aerospace Medical Institute is therefore a valid statistical reference.

b. All simulator training is to be complete before beginning in aircraft training. However, the train-to-proficiency concept was not applied in the simulator. Rather a fixed simulator syllabus was defined. This avoids introducing the statistical variability which would have been associated with the judgment of proficiency, assessed in a new device by a large number of flight instructors.

c. Proficiency in the aircraft was defined as satisfactorily meeting standards of the A-7 check (safe for solo).

d. Provision was made in the test for checking proficiency on the first (A-1) and fourth (A-4) flights in addition to the normal A-7 check. Regardless of outcome on the A-1 flight, the student was not allowed to solo on the A-2. The A-4 was treated as a standard A-7X with automatic continuance to A-7 if not declared safe for solo.

e. To reduce the impact of instructor variability as much as possible, eight highly experienced instructors were designated as check instructors to fly all A-1, A-4, and A-7 flights during the test. These instructors were not permitted to participate as visual simulator instructors.

f. The test plan calls for processing approximately 96 students through the test syllabus. Of these, 48 will be randomly assigned to a test group and will receive both simulator and flight training. The remaining 48 will become the control group and follow exactly the same regimen except that they will receive no simulator training.

g. In addition to measuring A Stage performance, provision was made for monitoring student performance in tactical training stages subsequent to A Stage. This precaution was dictated by experience in the instrument syllabus in which downstream performance differed significantly from what had been projected based on instrument stage performance.

The actual testing involving students began in late June 1973. Testing will continue, involving all student inputs to advanced training at Kingsville through September 1973. It is expected that the last testing in A Stage will be complete by 1 January 1974 and the last of the follow-on data will be available by March 1974. The interim report on test progress is due at the end of August 1973, and it is expected that a final report will be submitted in April 1974.

At present, only a very few students have progressed through FAM Stage under the test program. While these students are doing extremely well, it is much too early to come to any definitive conclusions regarding the training effectiveness of the device.

THE CARRIER QUALIFICATION STAGE TEST

As was mentioned earlier, planning for a test in the Carrier Qualification Stage has only just begun. It is envisioned that the methodology for this test will be essentially the same as for the FAM Stage test. It is recognized that some question regarding the validity of historical comparisons could arise in this test due to the fact that students will have already been exposed to the visual device in the Familiarization Stage test. Therefore a small group of students, trained under the present syllabus, who will not have been exposed to the device have been tagged as initial inputs to the Carrier Qualification test plan. It is expected that testing will begin in late August 1973 and that testing will be complete by the end of December 1973.

CONCLUSION

The preceding paragraphs have described the process by which the General Electric CGI was procured, mated to the 2F90, made ready for training application and tested in the training environment. It will be recognized that this was hardly a conventional development and evaluation routine for the following reasons:

a. The bulk of the effort took place at NAS Kingsville, an operational training base.

b. Practicing flight instructors were heavily involved in the evaluation process. A continuing dialogue was maintained between flight instructors and engineers to the benefit of both.

c. The approach to problems tended to be pragmatic. The object was to make the system work. All personnel involved recognized that simulation is just that. If it will "fool" the pilot, it is good regardless of the scientific or engineering niceties.

In retrospect, a major training device has been placed in the field at a training site in less than two years from initiation of procurement. Operational testing has begun with high expectation of favorable results.

In the final analysis, whatever the critical evaluation of the methodology, perhaps this is the best testimony to the effort.

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- Microcircuit and large scale integrated circuitry
- Display systems
- Data transmission and monitoring systems

This work involves both hardware and software developments which range from the design of special processors for information and data handling to the development of automated techniques for designing new LSI (large scale integration) circuits.

In the previous 14 years, he was a consulting/project engineer on numerous computerized systems. These included fire control, missile, flight control, communication, and satellite systems.

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