LOW-COST COCKPIT TRAINER DESIGN: CHALLENGES AND SOLUTIONS

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ABSTRACT

The challenge to today's training system design engineer is changing; adapting to this change is necessary for survival in a demanding economy. Previously, training system engineers met with success by using emerging technologies to develop ways to increase the capability of training devices: increase fidelity, increase task capacity, increase throughput. The result has been an evolution of larger, more capable, and more expensive training devices. However, in today's environment of declining budgets, another demand is being made of the training system engineer - decrease cost!

The purpose of this paper is to describe specific challenges facing the designer of a cockpit trainer attempting to blend the training requirements of high fidelity and capability with the requirement of low cost. This paper will present innovative methods to overcome these challenges in designing a high fidelity, low-cost, cockpit trainer.

The paper emphasizes the importance of front-end analysis to determine the fidelity and cost factors that would drive the design. Specific examples of training task analysis and preliminary cost determination are given. Specific problems encountered in designing a low-cost cockpit trainer and pragmatic considerations in designing solutions for these problems are addressed. The paper examines alternatives to expensive mechanical instruments and integration and fidelity of virtual displays.

The paper concludes with a discussion of practical benefits of these design solutions. Emphasis is *placed on cost savings, reliability, and efficiency through reconfigurability.*

ABOUT THE AUTHORS

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INTRODUCTION

The traditional relationship between military aircraft training device fidelity and cost has been easy to understand. Historically, as aircrew trainer fidelity and capability have increased, the cost of that trainer has also increased. The cost has been driven primarily by the high cost of computer systems required to support ever increasingly complex aircraft and environmental simulation models. The increasing cost of software development, likewise, increases the price of the models themselves. Training device cost has also historically been driven up by the complexity of the weapons systems themselves. For example, today's front-line fighter aircraft are employing multiple sensors for navigation and weapons delivery. Supporting multiple sensors in a training device can be an expensive proposition calling for multiple displays and correlated data bases. One result of the high cost was the acquisition of trainers without critical major subsystems. The old Tactical Air Command trained its fighter aircrews for years on simulators with no or inadequate Out-the-Window (OTW) visual systems. These devices became little more than avionics procedures or instrument trainers.

In spite of the historical upward trend in the cost of aircrew cockpit trainers, today's military aircraft training system customer is demanding increasing capability in his trainers at lower cost! The increasing sophistication of weapon systems brings with it increasing demands on the training systems. Today's customer wants to train his on-board sensor-based systems such as Maverick, GBU-15, and LANTIRN navigation and targeting. He wants his training devices to support training at the edge of the performance envelope for air combat maneuvering and complex tactics. He also wants his cockpit trainers to be interactive to train the synergistic effects and multi-ship tactics and related mutual support tasks. On top of all this, the customer would like his training systems to support geo-specific environments for mission rehearsal with such features as real-world terrain and cultural features and realistic weather effects.

Training in these sophisticated, edge-of-the-envelope tasks has previously been accomplished by an evolution of large, more expensive training devices. In today's environment of shrinking budgets, the military customer must continue to provide training in his sophisticated weapons in a more cost-effective manner. This need was formalized in a USAF General Officer review of Air Force flight simulator policies on 10 May 1993, which defined an emerging concept of low cost, unit level training devices. It is incumbent upon those of us in the training industry to respond to this emerging need. This paper describes specific challenges that faced the designers of a cockpit flight simulation trainer as they attempted to blend the training requirements of high fidelity and capability with the requirement of low cost. The paper presents methods used to overcome the challenges and the resulting solutions.

DESIGN OBJECTIVES

Our objectives in designing a pilot cockpit trainer for a fighter airplane were straightforward: (1) maximize fidelity and availability; and (2) minimize cost.

Maximize Fidelity and Availability

In our attempts to maximize fidelity, we found we were designing a new class of unit-level trainer. Previous types of unit-level trainers would no longer be acceptable. This design was evolving to be more than a familiarization or procedural trainer focusing on switchology and part-task training. Our design took the approach of integrating high fidelity aircraft systems functionality into a realistic environment.

To achieve accurate aircraft systems performance, we acquired engineering development models used in early design of various systems. To make the trainer fly like the airplane, we used an aero model that had been derived from engineering studies and modified by empirical data from test flights. Weapons ballistics and threat environment models from engineering evaluation facilities were used for ownship weapons flyout calculations and to provide hostile threat environment cues in the cockpit.

With all of these resources available to us, our biggest challenge to meet our high-fidelity requirement turned out to be with the trainer cockpit itself. It would have been incongruous to use these sophisticated models only to present the cues in a lesser fidelity cockpit. In addition, we were aware of user dissatisfaction with less-than-optimum cockpit geometry that compromised training in some unit-level trainer programs. Therefore, our goal for cockpit geometry was that the location, appearance, and feel of all cockpit controls and displays would be the same as in the airplane.

Trainer availability was also a design objective. High fidelity is of no value if the trainer fails frequently or requires a long time to repair. The training system user availability requirements have been increasing in recent years and meeting them has become a real challenge. We established our availability goal at 98%, using the definition that the trainer would be available for training 98% of the scheduled training days each year.

Minimize Cost

We knew the cost had to be low; but just how low? We focused on keeping recurring cost in the $500K-$800K range as our target.

IDENTIFYING COST AND FIDELITY DRIVERS

Training Task Analysis

Perhaps the single most important activity in cost-effective trainer design is the front end training task analysis. This activity is used to conduct the fidelity/cost trade-off that will ultimately end up driving the design. A thorough training task analysis should be applied to all subsystems of the trainer that are used to present cues to the pilot. One of the most significant and costly subsystems in a flight simulation trainer is the visual system. This paragraph looks at the task analysis and how it was applied to the design of our trainer's visual system.

Process - The purpose of our task analysis as applied to the visual system was to determine the visual system field-of-regard (FOR) and scene content necessary to train specific F-16 pilot tasks. From a listing of all F-16 pilot tasks associated with the F-16 and its mission, 128 different tasks were identified as potentially requiring a visual presentation during flight simulation training. A sample of experienced F-16 pilots was used to plot the desired and minimum visual FOR required to train each task at a 90%, 95%, and 100% level. Each task was also rated with an importance code. The tasks were then divided into task groups (e.g., normal procedures, emergency procedures, air-to-air weapons employment) and consensus plots were then determined for each task group. The pilots were also asked to determine visual scene content requirements for each training task group by rating a list of capabilities as critical, desirable, or not needed.

Results - Figure 1 is an Aitoff plot showing the outcome of the field-of-regard analysis. The dotted line represents the minimum FOR for all training tasks trained at the 90% level (280°H x 100°V). This FOR would require approximately ten channels of video supported by a full dome. Cost: approximately $2.5M. The dashed line represents a compromise by eliminating formation and electronic combat tasks (correlating RWR signals with visual sightings) requiring a wide FOR. Although this represented the optimum visual system FOR (200°H x 100°V) for the remaining tasks, it would require six channels of video supported

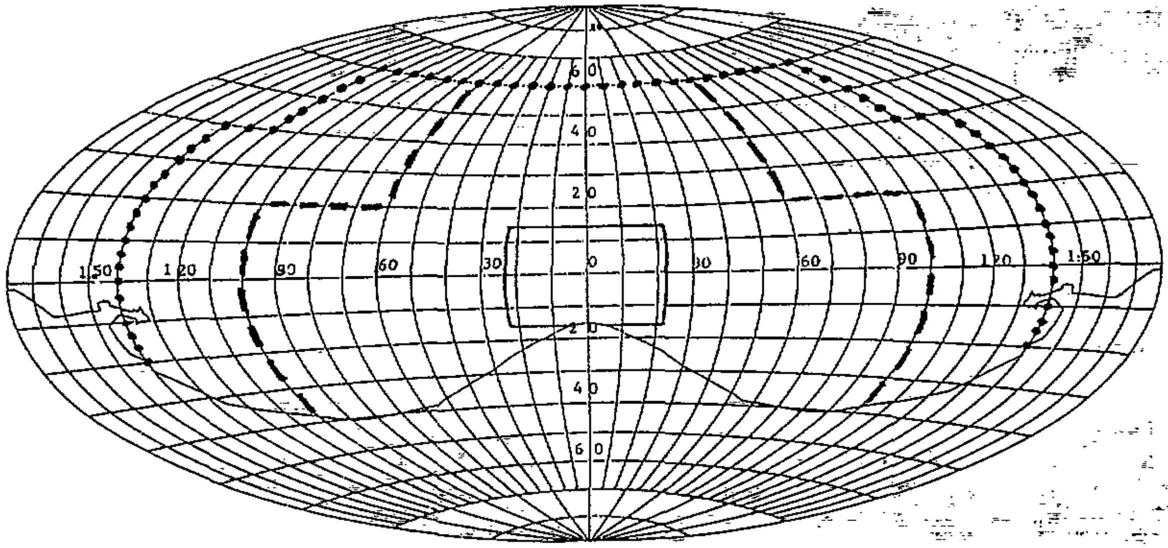

Figure 1. Aitoff Plot Showing Field of Regard Requirements

by a partial dome. Cost: approximately $1.5M. It was clear that a visual system of this size exceeded our definition of low-cost. Our final compromise is shown by the solid line representing a single channel, 45°H x 32°V system. This FOR will support the critical training tasks required of a low cost unit level trainer and represents the lower forward channel of the six channel system. Cost: approximately $250K. A key factor in our selection of this system was that any low-cost, narrow FOR solution must be able to expand gracefully to eventually accommodate the optimum FOR of 200°H x 100°V.

The outcome of the scene content capabilities assessment was somewhat surprising in that it tended to favor capabilities found in lower cost image generators as critical or desirable. Our pilot sample was of the opinion that the content and capability found only in higher end image generators were generally not needed to train the tasks in our task listing. Following is a partial summary of the scene content results:

1. Critical requirements: Horizon, Airfield, Wingman, Air Threats.

2. Desired requirements: Haze, Rain, Clouds, Generic Terrain, Vegetation, Air Threat Missiles, Smoke Trails, Tracers.

3. Not needed: Fog, Dust, Smoke, Sun Angle Effects, Geo-Specific Terrain, Bodies of Water, Roads, Buildings, Tanks, Trucks.

Cost Analysis

The training task analysis helps to identify the requirements which must be supported by each subsystem of an aircrew trainer. (This was illustrated in our previous example for the visual subsystem.) It addresses such issues as required aural, visual, and tactile cues and component level of fidelity. To accommodate the requirements dictated by the training task analysis in the most cost effective manner possible requires a detailed cost analysis. The cost analysis must determine the significant cost drivers within a given subsystem; identify relative costs (including life cycle costs) for alternate designs or the application of new technology; and addresses potential compromises in the defined requirements and level of fidelity identified for the subsystem.

The most challenging subsystem to effect significant cost reductions in our design studies was the trainer cockpit. Although the cockpit may not be the most costly subsystem of a typical low-cost trainer design, it is the core element which is required regardless of training application or options selected. The cockpit must faithfully represent the actual aircraft cockpit in form, fit, and function as will be shown later. The smallest deviation (though possibly not detrimental to training) is quickly detected by the most casual of users. Therefore, any potential design concept which could help minimize costs must be weighed against its impact on cockpit fidelity and ultimately user acceptance.

Process - In our cost analysis for the cockpit subsystem, we identified four significant cost drivers listed in order of magnitude:

1) Electro-Mechanical instruments - either actual aircraft or simulated;

2) Displays - Multifunction Displays (MFDs), Radar Warning Receiver (RWR) display, Data Entry Display (DED), and pilot fault list display (PFLD);

3) Controls or control assemblies - Pilot control stick and transducer, Throttle assembly, and rudder pedal assembly; and

4) Harnesses/Cables - especially those that support the first three cost drivers.

The following list presents examples of initial procurement costs for some of the components considered in the identified cost drivers:

Electro-Mechanical Instruments

Horizontal Situation Indicator (HSI)	$25,000
Attitude Director Indicator (ADI)	$10,500
Altimeter	$ 7,000
Mach Airspeed Indicator	$ 5,200
Vertical Velocity Indicator	$ 4,200
Angle of Attack	$ 3,000
Back-up ADI	$ 3,000
	$62,100 Per Cockpit

Displays

Multifunction Displays (MFDs)	$10,000
Radar Warning Receiver (RWR)	$ 3,000
Data Entry Display (DED)	$15,000
Pilot Fault List Display (PFL)	$15,000
	$43,000 Per Cockpit

To these costs were added initial spares cost and a yearly replenishment spares cost to estimate life cycle cost for subsequent comparisons with alternate designs.

Results - In our analysis of alternative designs and low cost technologies, we determined that the application of new "glass display" technologies would have the largest single impact on the defined cost drivers. A broad range of display types was considered as potential candidates for replacing the expensive electro-mechanical instruments and displays. The question was, "Can we make application of one or more of these display types to help reduce cost and still retain the high-fidelity requirements of the cockpit?" The answer is "Yes!"

PROBLEMS AND SOLUTIONS IN BLENDING LOW-COST WITH HIGH FIDELITY

Seeking an Alternative to Expensive Mechanical Instruments and Displays

Faced with the high initial and life cycle costs associated with mechanical instruments and actual aircraft display hardware (such as multi-function displays and data entry displays), we proceeded to explore alternatives.

Process - The purpose of this phase of our design was to determine the technical feasibility of designing an F-16 cockpit trainer using "glass" components. The following current off-the-shelf glass display devices were evaluated:

- Thin-Film-Transistor (TFT) Displays
- Plasma Displays
- Light Emitting Diode (LED) Displays
- Electroluminescent (EL) Displays
- Cathode Ray Tubes (CRT)

We supported this analysis of alternative end display technologies by using existing laboratory instrument and indicator software and an existing F-16 part task trainer design as baselines. The hardware and software baselines were then modified to support the various alternative components.

Results - Results of our analysis led to the conclusion that color Cathode Ray Tubes (CRTs) offered the optimum solution for implementation of a virtual instrument display for the F-16 cockpit configuration. We found that CRT's were available off-the-shelf in a wide variety of sizes making them easily adaptable to the instrument panel geometry. Color CRT's were readily available from a wide variety of domestic vendors reducing response time. CRT's did not have the narrow viewing angle restriction as did most other devices evaluated. This was an advantage in that the displays can be viewed by an instructor positioned at the side of the cockpit as well as the pilot in the cockpit. Finally, CRT's were the least expensive of all other display devices. Other available display components or technologies had significant shortcomings:

1. TFT displays had a poor viewing angle in both horizontal and vertical axes. Their shallow depth required the electronics to be packed into a wide frame surrounding the display glass. This compromised edge matching with contiguous displays.

2. Plasma displays represented an emerging technology. However, commercial color plasma displays were not available at the time of our study.

3 LED displays offered inadequate resolution to portray moving instruments. Only monochromatic LED displays were available.

4. EL displays were found to be monochromatic only, with wide frames. However, they were available in a wide variety of sizes.

Adapting a Virtual Instrument Display to Cockpit Geometry

Adapting a virtual (or "glass") instrument display to the F-16 cockpit proved to be a real challenge. Unlike most aircraft with rectangular instrument panels in one plane, the F-16 has a T-shaped instrument panel in multiple planes. A rather simple solution using a single, large monitor to display the instruments could be used, but we concluded the compromise to total cockpit fidelity would ultimately be unacceptable to the user. We proceeded with a design using smaller, multiple CRT's. To keep cost low, the monitors had to be commercial, off-the-shelf items.

Mockup - A proof-of-concept plywood mockup was used to evaluate various CRT types and configurations. A configuration using four small color CRT displays proved to be most compatible with the F-16 cockpit. Our mockup showed this concept would result in a trainer design with virtually no deviation from the aircraft cockpit geometry. Figure 2 shows the compatibility of the four CRT's with the F-16 instrument panel. Figure 3 shows the compatibility of the four CRT design concept with the pilot instrument line-of-sight depression angles.

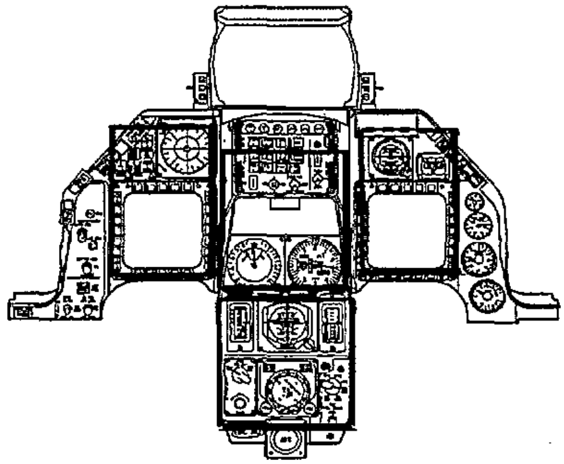

FIGURE 2
Monitor/Instrument Panel Layout

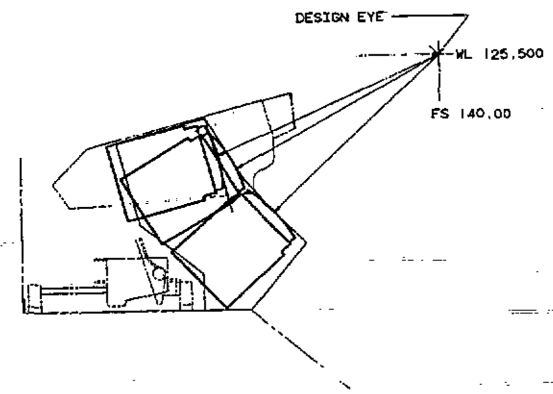

FIGURE 3
Line-of-Sight Geometry

Reducing Instrument Swimming Effect

A major criticism of glass display technology has been in the ability to adequately reconstruct the fine detail in dynamic instruments such as the *Attitude Director Indicator* (ADI) and Horizontal Situation Indicator (HSI). Problems that historically arise in this application are due to achievable pixel resolution. Limitations exist either in the selected display generator and the size of the display buffer or in the resolution achievable with the selected display device. Improving achievable pixel resolution relates directly to increased cost. The problems are manifested to the observer as an inability to resolve the fine detail (alphanumerics, vectors, etc.) and/or an apparent "swimming" (aliasing) effect. This latter problem is due to pixel quantization which produces the familiar stair-step effect in diagonal lines drawn with a raster-type display generator. The search for a solution to these problems was greatly aided by the choice of display device from our analysis of alternative "glass display" technologies. The selected color CRT display is a non-interlaced VGA design (640 pixels by 480 lines) in a 4:3 aspect ratio providing approximately 90 pixels per inch resolution. This electronic resolution is supported by a display dot pitch of .01 inches and a display generator operating at VGA resolution. With this CRT display placed at the proper distance from the pilot design eye point the resolution achieved was more than adequate to resolve the detail in the instruments evaluated. The "swimming" effect was significantly minimized by this combination of pixel resolution and relative geometry. Further reduction was achieved by adjusting the brightness level of the background fill (normally black) to a barely perceptible shade of grey, and increasing the update rate of the instrument display software.

The background fill value helped soften the edges of displayed detail by effectively reducing the contrast. The increased update rate minimized the discrete steps between each rendering of the instrument face producing smoother motion. Although low cost anti-aliasing techniques involving pixel replication or bi-linear interpolation did slightly improve the swimming (aliasing) effect, the resultant loss of resolution was unacceptable. Better anti-aliasing techniques were judged to be cost and/or performance prohibitive. In summary, the proposed solution to the simulation of trainer mechanical instruments and displays has been extensively evaluated by active aircrew members and judged to be very acceptable for training including precision instrument flight tasks.

THE IMPORTANCE OF TRAINER COCKPIT FIDELITY

The challenges and solutions addressed in this paper focus primarily on reducing cost without compromising cockpit fidelity. More specifically, they focus on the accurate replication of the trainer cockpit geometry. The practical benefit of achieving accurate trainer cockpit geometry is to gain long term user acceptance of the device. Military aircrews seem to accept *avionics familiarization trainers and procedural* trainers that violate cockpit geometry. As soon as the familiarization training is over and the procedural tasks learned, these lesser fidelity trainers are relegated to the squadron storage room. But when the training device is designed to simulate flight, that's when the typical aircrew will demand high fidelity cockpit geometry.

Design Eyepoint

Airplane cockpits are designed based on a design eyepoint - the eye location of the mythical "90% man" when sitting in the cockpit. Human factors engineers make careers out of designing ergonomically efficient cockpits. Every display and control has its position based on the airplane design eyepoint. For example, in fighter aircraft, the head-up display (HUD) plays a critical role in weapons delivery. Indeed, some pilots consider the HUD to be the primary instrument in the F-16. The HUD's display and functionality are based on the design eyepoint. The airplane boresight, traditionally used as a backup weapons delivery mode, is based on viewing from the design eyepoint through the HUD. The flight path marker, a HUD symbol displaying the airplane's path through the air, must be viewed from the design eyepoint.

The flight instruments are positioned and organized from the design eyepoint in a way that supports efficient viewing by the pilot. The pilot's "instrument scan pattern" is a behavior he develops over many hours of flying a particular airplane. This behavior becomes second nature to the point that he does it without thinking. A cockpit trainer which simulates flight must support this critical learned behavior pattern. To do so, the trainer's cockpit geometry must be based on the airplane's design eyepoint. Figure 3 shows the F-16 instrument panel line-of-sight depression from the design eyepoint. The pilot's outside visual FOR is based on the airplane's design eyepoint. A cockpit trainer's visual simulation FOR must also be based from the design eyepoint. For example, the pilot's line-of-sight (LOS) over the nose and canopy rail is critical for weapons delivery and landing training. If a trainer does not accurately replicate LOS geometry, it will violate previously learned behavior patterns. History shows that any cockpit trainer which is designed to simulate flight, but which violates the concept of design eye geometry, is doomed to controversy and, ultimately, rejection by the user.

Pilot's Seat

The pilot's seat in the cockpit trainer is inextricably linked to the design eyepoint, and is, therefore, just as critical in trainer design. Our experience indicates that a pilot's first act on sitting in a cockpit trainer is to adjust the seat. What he is subconsciously doing is positioning his eyes at the aircraft design eyepoint (or his personally established deviation relative to the design eyepoint). We concluded that an accurate replication of the aircraft seat, position, inclination, and adjustment envelope was just as critical as design eye geometry in a low-cost trainer. Why design the trainer cockpit based on design eye geometry if the pilot can't position his eyes to his customary location relative to the design eye? Accurate geometric replication of the seat functional controls was necessary to support emergency procedures. Accurate location and feel of the ejection handle and inertial reel locking lever were necessary to support virtually unconscious behaviors in emergency conditions.

Stick, Throttle, and Rudder Controls

The stick and throttle in today's high performance fighter aircraft do much more than move the flight controls and change engine thrust. They also are used to control weapons employment, avionics function, and communications. The days of a simple pickle button on the stick and radio mike button on the throttle are long gone. For example, the Block 50 F-16 stick and throttle grips have a total of 16 multiple position switches. These switches are designed to be selected by tactile identification without distracting from the pilot's visual tasks. Accurate tactile fidelity and geometric replication of the stick and throttle were critical design criteria for our trainer.

Our design analysis showed that rudder pedal form and function were also critical to our design. While the rudder is seldom used in routine F-16 flight, its use is required for takeoff, landing, and some emergency procedures training. Pilot input to the design required that we provide a rudder pedal adjust mechanism to permit full rudder pedal movement and authority.

Instrument-Mounted Switches and Controls

As our glass virtual instrument display design matured, an associated problem evolved which directly impacted cockpit fidelity and functionality. The problem was how to accommodate instrument-mounted switches and controls on a glass-faced CRT! Our research into user requirements found that it would be unacceptable for the pilot to reach outside the trainer cockpit to make control inputs that would be made on the instrument panel in the airplane. For example, a rotary control device on the face of the HSI is used to set the desired course on the instrument. Feedback from users indicated it would not be acceptable for the pilot to make the HSI course adjustment by making an input through a trainer control panel outside the cockpit.

A solution to this problem was found by designing thin form-fitting aluminum bezels that overlaid the CRTs. The bezels accurately depict and simulate the forward instrument console. The bezels incorporate very low profile controls to provide normal instrument control functions. The bezel overlays swing away from the CRTs to facilitate maintenance. Figure 4 shows two of the bezels swung down to reveal the CRTs.

PRACTICAL BENEFITS OF THESE SOLUTIONS

The use of the alternative virtual instrument display system to replace electro-mechanical instruments and cockpit display hardware is a good example application of a low-cost technology. But what are the real benefits of this exercise? Does it just produce another novel cockpit trainer design? We identified three categories that would help establish comparisons between the new cockpit design approach and a classical approach. These categories are cost (initial and life cycle), reliability, and configurability.

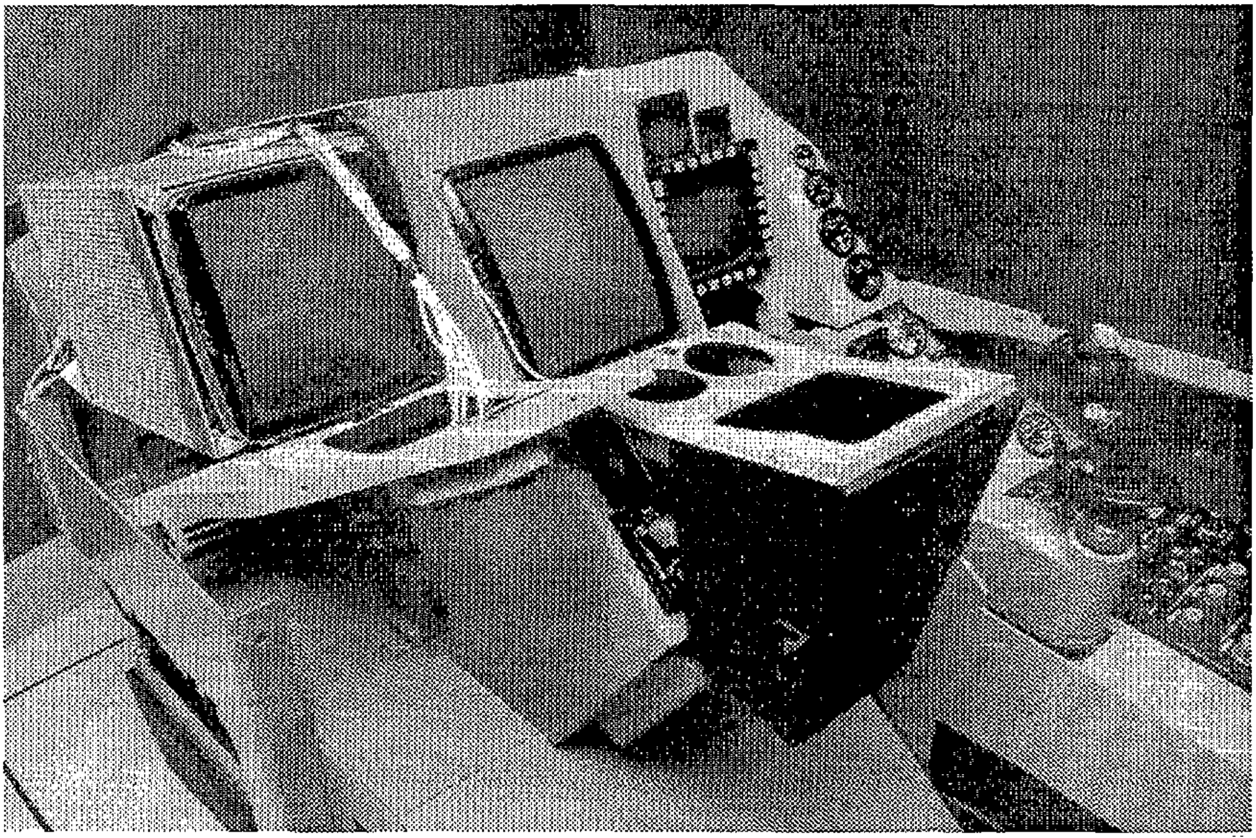

FIGURE 4 - Instrument Panel Bezels Swung Down

Cost Comparison

A cost comparison based on 10 cockpits over a 10-year life cycle was conducted between the two design approaches. All component and fabrication costs for an initial buy were well *established using actual published off-the-shelf* prices for procured components and actual fabrication costs for accommodating the new virtual display hardware. Costs for initial spares and replenishment spares were estimated based on historical data. The result of the cost comparison is summarized in Figure 5.

Reliability Comparison

The reliability comparison is based on published mean time between failure (MTBF) data for the major components and a measure of the relative complexity between the two designs. The virtual display design eliminates over 40% of the electrical and mechanical components and cables associated with a typical trainer cockpit. Both measures indicate a higher reliability for the virtual instrument display design over the classical design. The results of these comparisons are summarized on Figure 6.

Cost Comparison (10 cockpits over 10-year period)

	Virtual Display	Classical	Delta
Initial Cost (per cockpit)	$34,600	$71,407	$36,870
Initial Spares (per cockpit)	$32,500	$61,617	$29,117
Replenishment Spares/Yr (based on 15% factor)	$4,875	$9,243	$4,368
10 Cockpits over 10-years	$1,158,500	$2,254,540	$1,096,040

Net Savings:

Initial Buy - $660K
Out-Year Spares - $436K
Total Life Cycle Savings - $1.1M

FIGURE 5 - The Virtual Instrument Display System Shows a Cost Savings Benefit

	Virtual Display		Classical
Relative Complexity	4 Color CRTs	replaces	12 Instruments/Displays
	4 Video Cables/ 12 Wires	replaces	9 Harnesses (200 wires)
Major Component MTBF	- Color CRT (100,000 Hrs.)		- Simulated HSI (8,000 Hrs.)
			- Simulated ADI (10,000 Hrs.)
			- Simulated MFD (23,000 Hrs. estimated)
			- Simulated Altimeter (20,000 Hrs.)
			- Simulated Mach Airspeed (25,000 Hrs.)

FIGURE 6 - The Virtual Instrument Display System Indicates a Reliability Benefit

Configurability Comparison

The virtual instrument display system provided the additional benefit of configurability due to the flexibility in the multi-CRT design and bezel concept and the software controllability of the displays. The differences in instrument console geometry, such as exists between the F-16A model and F-16C model cockpits can be accommodated by proper placement of the four-CRT array and appropriate bezel design. Different instrumentation in the cockpit, such as a needle and dial Vertical Velocity Indicator (VVI) versus a tape VVI can be supported through a simple software change. Similar modifications to a classical cockpit would require not only extensive hardware design modification, but numerous changes to the instrument suite, display suite and computer/cockpit interface.

CONCLUSION

This paper summarizes three years of data acquisition, analysis, and design. Our overall objective of this activity was to determine the feasibility of providing the military customer low-cost, high-fidelity flight simulation training in the near future. We have successfully demonstrated our specific project objectives of maximizing fidelity and availability, and minimizing cost in a unit-level trainer. In addition, we realized another benefit of achieving system flexibility through reconfigurability. We have concluded that the future of low-cost, edge-of-the-envelope, flight simulation training for the military aircrew is available by way of this described approach.