5-2000

Implementing operator-centric cockpit design in the EA-6B ICAP III aircraft

Thomas W. Hofer

Recommended Citation

Hofer, Thomas W., "Implementing operator-centric cockpit design in the EA-6B ICAP III aircraft. " Master's Thesis, University of Tennessee, 2000.
https://trace.tennessee.edu/utk_gradthes/9338

To the Graduate Council:

I am submitting herewith a thesis written by Thomas W. Hofer entitled "Implementing operator-centric cockpit design in the EA-6B ICAP III aircraft." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

W. D. Lewis, Major Professor

We have read this thesis and recommend its acceptance:

Franks S. Collins, Ralph D. Kimberlin

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Dr F. Collins

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Accepted for the Council

Associate Vice Chancellor
and Dean of The Graduate School

IMPLEMENTING OPERATOR-CENTRIC COCKPIT DESIGN IN THE EA-6B ICAP III AIRCRAFT

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Thomas W. Hofer

May 2000

DISCLAIMER

A portion of the information contained within this thesis was obtained during a Naval Air Systems Command sponsored program in conjunction with the Northrop Grumman Corporation The research, results and discussion, and conclusions presented are the opinion of the author and should not be construed as an official position of the United States Department of Defense, the United States Navy, the Naval Air Systems Command, or the Northrop Grumman Corporation.

DEDICATION

This thesis is dedicated to my wife,

Laura Marie Henderson,

whose support has been instrumental over the last ten years .

ACKNOWLEDGMENTS

My sincere appreciation goes out to all of the professional Navy and Marine Corps Naval Flight Officers and Naval Aviators whose inputs and feedback made this thesis possible Their ideas, opinions, and knowledge assisted greatly in keeping the scope of this project within the bounds of reality.

I would also like to thank the instructors at the University of Tennessee Space Institute and the United States Naval Test Pilot School for their assistance in earning this degree

Lastly, I would like to extend my gratitude to my children, Robert and Jack, and my wife Laura for their love and support throughout the entire experience. Their support and encouragement has meant the world to me

ABSTRACT

The EA-6B Prowler aircraft was designed and built in the late 1960s by the Grumman Aerospace Corporation for the United States Navy and Marine Corps as a tactical electronic warfare (EW) platform. High losses of U.S attack aircraft to surface-to-air missiles (SAMs) in the Southeast Asia theater led to the requirement for a carrier-based tactical aircraft capable of providing EW support in the form of electronic jamming in support of strike aircraft. The EA-6B became the aircraft that fulfilled the EW requirement. The thirty years that have passed since the introduction of the EA-6B has seen many additional weapons system capabilities added to the aircraft. However, the hardware used by the aircrew to employ these additional capabilities has changed little, resulting in operator information overload during combat operations.

This thesis investigated the information overload problem associated with operating a complex integrated weapons system using legacy and non-integrated controls and displays. A review of pertinent literature and military standards, coupled with the author's extensive personal experience as an EA-6B Electronic Countermeasures Officer were used as the basis of research An operator-centric cockpit design methodology utilizing human factors engineering and the systems engineering approach to problem-solving was used to identify problems associated with the contractor's proposed cockpit design for the Improved Capability III (ICAP III) EA-6B Prowler aircraft. The problems identified were. (1) critical weapons system failure alerts can go unnoticed by the ECMOs, (2) a limited display area is available for the presentation of weapons system

information, (3) a high operator workload is required to monitor the status of the AN/ALQ-99 jammer pods, (4) navigational situational awareness in the rear cockpit is extremely poor, (5) the current rear cockpit pointing devices increase logistical support requirements and enforce negative habit transfer, and (6) alphanumeric character entry into the integrated weapons system is inefficient

Once identified, the methodology was employed by the author to develop a proposed cockpit design that will eliminate the problems and improve operator and system performance. If adopted and implemented by the manufacturers of the ICAP III program, the cockpit hardware and layout changes proposed by the author will result in minimal friction at the system interfaces, thus improving overall system performance

Specific recommendations that should be included to the ICAP III cockpit design are:

1. Install a synthesized weapons system voice warning system to provide aural alerts to the ECMO 2/3 crew stations in the event of jammer pod degradations during active Electronic Attack operations.
2. Install 8 5 inches wide by 11 inches tall (93 5 in^2) color-capable AMLCD Multifunction Displays at each of the ECMO 2/3 crew stations to provide for operator visual interaction with the weapons system.
3. Install 7 5 inches wide by 6 5 inches tall (48.75 square inches) color-capable AMLCD Pod Status Displays at each of the ECMO 2/3 crew stations to provide an automated real-time simultaneous status display of the ALQ-99 jammer pods

4. Install 3.9 inches wide by 3.3 inches tall (12.87 square inches) Electronic Horizontal Situation Indicators repeaters at each of the ECMO 2/3 crew stations to assist in navigational situational awareness.
5. Install pointing devices on the ECMO 2/3 consoles that are identical to the pointing devices installed in the forward cockpit to provide for operator tactile interaction with the weapons system
6. Install 4.75 inches wide by 5.75 inches tall (27.3 square inches) touch-sensitive data entry keyboards on the ECMO 2/3 pedestals to serve as a primary alphanumeric entry device and secondary tactile interface with the weapons system.

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LIST OF ABBREVIATIONS

ADVCAP	Advanced Capability
AGL	Above Ground Level
AMLCD	Active Matrix Liquid Crystal Display
BASCAP	Basic Capability
CMC	Central Mission Computer
CRT	Cathode Ray Tube
DDI	Digital Display Indicator
DEP	Design Eye Point
DSK	Dvorak Simplified Keyboard
DVI	Direct Voice Input
EA	Electronic Attack
ECMO	Electronic Countermeasures Officer
EFIS	Electronic Flight Instrumentation System
EGI	Embedded GPS/INS
EHSI	Electronic Horizontal Situation Indicator
EP	Electronic Protection
ES	Electronic Surveillance
EW	Electronic Warfare
EXCAP	Expanded Capability
FAR	Federal Aviation Regulation
fL	Footlamberts
GPS	Global Positioning System
HARM	High-speed Anti-radiation Missile
HDTV	High Definition Television
ICAP	Improved Capability
ICS	Inter-cockpit Communication System
IDM	Improved Data Modem
INS	Inertial Navigation System

MATT	Multi-mission Advanced Tactical Terminal
MBE	Multi-band Exciter
MFD	Multi-function Display
MSL	Mean Sea Level
NATOPS	Naval Air Training and Operating Procedures
NVG	Night Vision Goggle
RAT	Ram-air Turbine
SA	Situational Awareness
SAE	Society of Automotive Engineers
SAM	Surface-to-air Missile
SEAD	Suppression of Enemy Air Defense
SIGINT	Signals Intelligence
TACAN	Tactical Aircraft Navigation
UE	Universal Exciter
UEU	Universal Exciter Upgrade
UFC	Up-front Control
USAF	United States Air Force

CHAPTER 1: INTRODUCTION

BACKGROUND

The EA-6B Prowler is the only airborne tactical electronic warfare (EW) platform flying today in support of the United States Armed Forces Until 1998 the United States Air Force (USAF) operated a fleet of EF-111A Raven aircraft who were also capable of providing tactical EW support. With the retirement of the EF-111A, the capabilities of the aging Prowler have become more important than ever before. However, the last major upgrade to the weapons system of the Prowler was the Improved Capability (ICAP) II program that was fielded in 1984. The ICAP II program brought an increased jammer capability to the aircraft and a new display system to the Electronic Countermeasures Officers (ECMOs) that operate the weapons system in the rear cockpit. Since the time of the ICAP II program, all further upgrades have been added in a piecemeal manner leading to a non-integrated weapons system that interfaces with the ECMOs using either the legacy controls and displays or using separate control interfaces placed in available areas around the rear cockpit. A non-integrated laptop computer has even been recently added to the rear cockpit to control the communications jamming system and tactical data-link, a first for any ejection-seat equipped tactical aircraft.

Currently in its final design stage, the ICAP III upgrade seeks to return to a truly integrated weapons system interfaced with upgraded controls and displays. However, the rear cockpit design currently being proposed by the prime contractor falls short in many areas relating to human factors and systems integration. Correcting this shortfall is critical since even the best integrated weapons system will fail to live up to its full potential in combat operations unless the human operator can process the vast amounts of information presented. Ultimately, the operator must have the capability to usefully employ the information presented or the system as a whole will fail to operate at its optimal capability.

This thesis will recommend some specific hardware additions and modifications to the contractor's current design. These additions and modifications will help to eliminate the information overload problem associated with operating a complex modern weapons system using legacy and non-integrated controls and displays. It will briefly describe the basic ICAP III EA-6B aircraft and the integrated weapons system, trace the evolution of the aircraft from its beginnings, and describe the mission of the aircraft. A review of pertinent literature and military standards discussing modern controls and displays technologies will be presented. The operator-centric cockpit design methodology used by the author will be outlined and explained with an example Finally, design specifications of the cockpit controls and displays hardware recommended by the author for use in the ICAP III cockpit design will be shown and described in detail.

PROBLEM STATEMENT

The rear cockpit of the ICAP III EA-6B aircraft requires new controls and displays hardware to serve as the interfaces between the ECMOs and the integrated weapons system. The hardware must assist the ECMO in operating the integrated weapons system at its maximum capability during all specified flight regimes and specified missions

DESCRIPTION OF THE ICAP-III EA-6B AIRCRAFT

The EA-6B is a subsonic, all-weather, twin turbojet powered EW airplane designed for carrier and advanced shore-based operations. Based upon the basic two-place A-6 Intruder airframe, the EA-6B is a four-place aircraft that combines long range with a large external payload capability The flight crew is composed of a pilot and three ECMOs. ECMO 1, seated in the right seat of the forward cockpit, is responsible for operation of the AN/APS-130 ground-mapping radar, communication systems, navigation systems, and serves in the co-pilot capacity. ECMO 2 and ECMO 3, seated in the rear cockpit, are responsible for the operation of the integrated weapons system. Six principal subsystems make up the ICAP III integrated weapons system: (1) the AN/ALQ-99 tactical jamming pods, (2) the LR-700 receiver system, (3) the USQ-113 communications jamming system, (4) the AGM-88 high-speed anti-radiation missile (HARM), (5) the multi-mission advanced tactical terminal (MATT) satellite communications receiver, and (6) the improved data modem (IDM) tactical data-link. The tactical jamming pods consist of two high power transmitters and a universal exciter upgrade (UEU) capable of generating a variety of jamming modulations The transmitters and universal exciter are mounted in a common hardback and powered from a self-contained ram-air turbine (RAT) generator. The LR-700 channelized receiver system detects and identifies threat radars and presents the received emitter parameters to the ECMOs via the cockpit displays as well as provides the jamming pods with the selected parametric response. Through the use of a series of long and short baseline interferometer antennas placed around the aircraft, a geo-location capability for detected emitters is provided for by the LR-700. With the geo-location and accurate parameter measurement supplied by the LR-700, the capability to perform narrowband reactive jamming is available. The USQ-113 communications jamming system receives, analyzes, and jams communications systems. A HARM capability is also integrated into the EA-6B using LR-700 identified threat parameters for missile target designation and tracking. A hard-kill response against pre-mission designated targets and threats where jamming countermeasures are ineffective is afforded by the HARM. The MATT is a satellite communications receiver that receives signals intelligence (SIGINT) data broadcast over tactical satellite communications channels, allowing the ECMOs to monitor data collected by off-board systems. Passing and receiving of HARM targeting data and free-text messages from other EW platforms is accomplished using the integrated IDM tactical data-link. Figure A-1 shows the ICAP III integrated weapons system architecture with the additional and modified cockpit equipment proposed by the author.[1] The EA-6B Prowler is shown in figure 1.

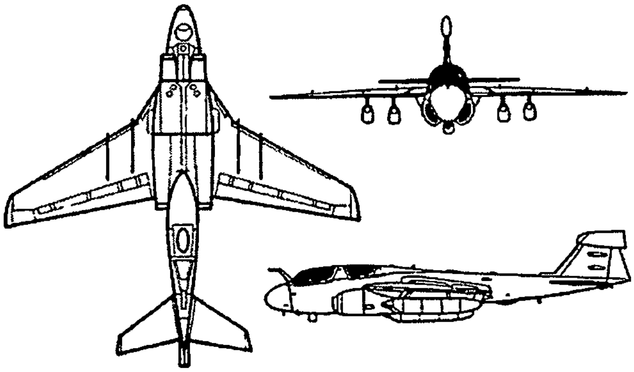

Figure 1: EA-6B PROWLER

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[1] All figures identified with a prefix of A are contained in the appendix

EVOLUTION OF THE EA-6B AIRCRAFT

The ICAP III Prowler will be the culmination of an evolutionary process that will have stretched over 45 years by the time the aircraft is retired from service in 2015 In May of 1968, the Grumman Aerospace Corporation flew the first EA-6B prototype aircraft in response to a request from the Department of the Navy for a carrier-based aircraft capable of providing offensive jamming in support of attack aircraft. The attack aircraft had been suffering high losses to radar-guided surface-to-air missiles (SAMs) in the Southeast Asia theater of operations. Five prototypes were built for flight test with no or only partial EW suites installed. The initial model with an installed EW suite that later became known as the Basic Capability (BASCAP) Prowler was delivered to the Navy for operational service in July of 1971 The late 1970s saw the introduction of the Expanded Capability (EXCAP) Prowler. The EXCAP aircraft contained a receiver and jamming system that was operated by both ECMO 1 and ECMO 2, while ECMO 3 ran the ALQ-92 communications jamming system. In 1980 the Improved Capability (ICAP) aircraft entered service, bringing with it a multi-band exciter (MBE) capable of generating jamming signals in several different frequency bands. ICAP also moved all of the receiver and jammer controls to the rear cockpit, freeing ECMO 1 to perform the navigator and co-pilot duties full time. In 1984 the current Improved Capability II (ICAP II) Prowler was delivered for service ICAP II introduced a universal exciter (UE) capable of generating jamming signals throughout the entire jamming system frequency range. ICAP II also introduced the AN/AYK-14 standard Navy airborne computer that was capable of controlling the MIL-STD-1553 data bus architecture of the weapons system In conjunction with the addition of the AN/ASN-130 inertial navigation system (INS) and the AN/ASN-123 digital display group, the Prowler ALQ-99F tactical jamming system became truly integrated and semi-automated All EA-6Bs currently operating are based on the ICAP II configuration The only major change to the ICAP II integrated weapons system was the addition of a HARM capability in January of 1986 Non-integrated additions have been the USQ-113 communications jamming system, the MATT satellite communications receiver, and the IDM data-link. Due to the memory constraints of the AN/AYK-14 computer, a non-integrated laptop computer is carried in the rear cockpit to control the USQ-113, MATT, and IDM Additional changes to the radios, navigation system, safety systems, and flight instrumentation system under the upgrades known as Block 82, Block 86, Block 89, and Block 89A have not effectively altered the ICAP II weapons system configuration. A program named Advanced Capability (ADVCAP) that would have brought receiver improvements, two additional wing-mounted weapon stations, communications jamming improvements, and vehicle enhancements was proposed and tested before being canceled in 1994 due to cost. The ICAP III upgrade will take advantage of many of the receiver upgrade technologies that were developed for the ADVCAP program

MISSION OF THE ICAP III EA-6B AIRCRAFT

The mission of the EA-6B aircraft is to provide airborne tactical EW in support of air or ground operations with the purpose of denying, degrading, or destroying enemy radar and communications systems. Specifically, the EA-6B provides electronic attack (EA), electronic support (ES), electronic protection (EP), and lethal suppression of enemy air defense (SEAD) capability to the air forces commander. The EA-6B may also be used in interdiction, strategic attack, fleet defense, defensive and offensive counter-air, and close air support missions Missions include low altitude (below 5000 feet AGL) to high altitude (above 15,000 feet MSL) flight profiles in either a standoff or escort role

CHAPTER 2: REVIEW OF THE LITERATURE

GENERAL

The invention of digital data transmission across data busses and the incorporation of sophisticated high speed computers into avionics architecture has provided the opportunity for new methods of presenting data and controlling aircraft systems The civil and military aircraft cockpits being designed today bear little resemblance to the first generation cockpits of the World War II P-51 and B-17 aircraft or the second generation cockpits of the F-14 Tomcat or British Aerospace Concorde of the 1970s In future cockpits the aircrew will deal with large amounts of information being fed to them via data busses from both on-board and off-board systems. Rapid leaps forward in controls and display technologies, coupled with an increased emphasis on human factors engineering, has resulted in cockpit designers attempting to design cockpits that can present these large amounts of information to the operator in a usable format. Extensive studies and writings have been completed in the area of human factors engineering as it applies to the implementation of new controls and display technology in cockpit design. Some of the studies and writings, plus the applicable military standards, are reviewed herein.

DISPLAY DESIGN FACTORS

A display is defined as a device that presents information to one or more aircrew members via one or more of the senses (MIL-STD-203G, 1991). Displays can be visual, auditory, tactile, and even olfactory. The vast amounts of information that can be presented to the aircrew through these varied display channels can lead to the aircrew's senses becoming overloaded (Statler, 1984). Four basic problems in future displays that can lead to information overload have been defined as: (1) the rapid increase in capability to collect and process large amounts of data, (2) the requirement for increasingly precise information, (3) the cockpit space restrictions, and (4) the diminishing gap between workload requirements and crew task-load capabilities (Grossman, 1983). Design of any display must address these four problems if the display is to truly assist the aircrew in accomplishing their mission. Multi-function displays (MFDs) are an excellent example. While an MFD can display large amounts of information pertaining to various systems while occupying a small amount of cockpit space, it must present the information in a hierarchical fashion. The operator must remember where the information can be accessed, resulting in higher error rates and slower response times than for single-function displays (Grossman, 1983). Display design must seek to capitalize on the human operator's ability to simultaneously process large amounts of information from various sources but must also avoid information overload of the operator.

AUDITORY DISPLAYS

The use of auditory displays has been commonplace in the cockpit for decades. Bells, whistles, and sirens have all been used over the years to alert the aircrew to a system status or malfunction. Audio displays should be used when the information to be processed is short, simple, and transitory, requiring an immediate time-based response (MIL-STD-1472F, 1999). Recently, the use of auditory displays has increased due to the increase in the visual workload that has accompanied the rise in the number and complexity of systems to be monitored (Stokes, et al, 1990). The idea is that if the visual channel is overloaded, there are advantages to allocating some tasks to the auditory channel. Studies have shown that a pilot's response to taped voice warnings is faster than a similar response to warnings presented only visually (Lilliboe, 1963). Additionally, a visual display combined with a voice warning provided shorter response times than did the same display combined with a non-speech (tonal) warning (Mellen, 1983). The justification for auditory displays is not limited to division of workload between sensory modalities. Auditory systems possess a number of characteristics which can, under certain conditions, make them preferable to the visual mode even when the latter is not overburdened (Stokes, et al, 1990). Disadvantages of auditory displays are that the message can easily be interrupted by other cockpit systems, can interfere with other communications, and a system of priorities must be established since only one message is presented at a time (Hawkins, 1987).

Auditory displays have traditionally been used to convey warnings and alerts to the aircrew. There are many reasons for this. Warnings and alerts must be received quickly, irrespective of eye fixation or workload (Hillborn, 1975). Auditory displays do not require the crewmember to visually scan a warning light panel or interpret a bank of engine gauges to ascertain the problem. Many individuals consider auditory displays to be unpleasantly noisy and strident, and dislike their intrusive nature (Butler, et al, 1981). The intrusive nature almost guarantees that the auditory display will not be ignored Auditory perception is less affected than visual perception by high load factors, anoxia, vibration, sunlight, glare, or darkness (Deatherage, 1972). Each of these conditions is encountered routinely by tactical military aviators. Use of the auditory channel to alert the aircrew to potentially dangerous situations has met with success over the years and continues to be a part of most cockpit designs.

One of the newest technologies in auditory displays is the use of voice messaging For critical signals, voice messaging should be used whenever feasible (MIL-STD-1472F, 1999). Historically, auditory displays have been non-speech, but recent advances in speech technology have improved the recording and storage of speech messages The initial speech methods used in cockpits were analog recordings of humans reading the messages. This type of messaging severely limited the number of messages available and the speed at which they could be used due to the constraints of the storage medium. Digitized speech is the most commonly used form of speech messaging today, presently used in the early F-16 and F/A-18 aircraft. Digitized speech is produced by a human, recorded digitally, and transformed into a time-compressed format. This allows a larger number of messages to be stored utilizing less storage space. The newest form of speech messaging used is synthesized speech. A computer generates synthesized speech, with the speech characteristics determined by software. Synthesized speech offers the advantage of being stored efficiently and retrieved quickly (Hart, 1988). Synthesized speech messaging is being used in the later F/A-18C/D aircraft and the developmental F/A-18E/F aircraft.

Speech messaging in the cockpit has historically used a female voice. The female voice was thought to be more easily detected against the background of a generally male crew and male radio voices. However, some studies have concluded that female speech may actually be harder to understand than male speech in a cockpit environment (Fairbanks, 1958; Smith, 1983). Another study that used modern voice synthesis methods found that the sex of the speaker did not contribute significantly either to intelligibility or to user confidence ratings (Simpson and Navarro, 1984). The question of which sex should be used has been overcome by modern speech synthesis using non-human voices with no discernible sex characteristics. Synthesized speech has been found to be highly distinguishable from background human speech of any variety (Deatherage, 1972). Intelligibility and the capability to distinguish the speech message from the background noise are the two most important traits of any message.

Voice messages should consist of an initial non-speech alerting signal followed by a brief standardized verbal message. The verbal message should consist of not less than four syllables with all of the essential information being presented within the first 2.0 seconds. An auditory level of not less than 20 dB above the normal speech interference level but never greater than 115 dB will capture the operator's attention without causing a startle reaction A presentation frequency of 500 to 3,000 Hz should be used (MIL-STD-1472F, 1999).

The use of auditory displays in a modern cockpit environment is tempting to a designer. With the aircrew's visual channel being overloaded by large amounts of information, it is easy to use the auditory channel to accomplish additional tasks However, aircrew members have expressed a preference for a visual presentation of advisory information and for using speech messages only to transmit more urgent information (Williams and Simpson, 1976). Cockpit design engineers must respect the preferences of the liveware component.

VISUAL DISPLAY TYPES

The most common type of display used in cockpits today is the visual display. This is not surprising due to the human operator being a visual animal accustomed to collecting information through the visual channel New and better ways of presenting information to the operator through the visual channel has been the driving force during the evolution of aircraft displays. Common practice among the civil and military aircraft built in the 1980s and early 1990s was the use of multiple cathode ray tube (CRT) MFDs, the "glass cockpit", to present the information needed to fly the aircraft and monitor onboard systems. The CRT has been the display of choice for the last 30 years due to being the most economical and most mature (Ratliff, 1992). Continuous evolutionary improvements in brightness, resolution, and the addition of color coupled with outstanding demonstrated reliability has led designers to make widespread use of the

CRT CRTs have their limitations also CRTs are heavy, bulky, and have a high power consumption for their relatively small display area (Hawkins, 1987). Military and civilian aerospace shares the problem of too much information being presented on too small of a display. Increasing the size of the CRT display to overcome this problem means a corresponding increase in the depth of the display, an increase in aircraft weight, and an increase in the electrical power required to power the display. These limitations prohibit the use of larger CRT displays in tactical military cockpits. In addition, the high sunlight conditions present in military cockpits dooms the use of CRTs for use as larger displays (Adam, 1992).

An alternative to the venerable CRT must be found for use in large displays integrated into tactical military aircraft. The aviation industry is not alone in its search for larger visual displays that weigh less, occupy less space, and use less power. The high definition television (HDTV) and laptop computer industries have similar requirements (Adam, 1992) Flat panel technology is the latest innovation in display design Flat panels are expected to require less volume, weight, power, and cooling, and are expected to be more tolerant of physical shock and electromagnetic interference (Chaum, 1992). One type of flat panel display in use today is the plasma display. Plasma displays are currently being used in several submarine and shipboard applications (Miller, 1992) Plasma displays are gas discharge displays which can be matrix addressed for high resolution and color applications (Collinson, 1996). An additional attribute of the plasma display is that due to being hermetically sealed they can operate under extreme temperature and humidity variances (Weber, 1983). The downside to the use of plasma displays in tactical military cockpits is that they do not possess the brightness capability required by high sunlight conditions (Ratliff, 1992) and have high power and cooling requirements (Spitzer, 1993).

The most promising flat panel display technology commercially available today is active matrix liquid crystal display (AMLCD) technology. AMLCD technology uses pixels that each contain a filter of one of the three primary colors. red, green, or blue, in conjunction with a liquid crystal that acts as a shutter If the pixel should be lighted, the shutter is transparent If the pixel is to be dark, the shutter remains opaque Voltages applied by a display-drive-circuit addressed to that pixel controls the condition of the liquid crystal that acts as the shutter (Spitzer, 1993) An external backlight, usually a fluorescent lamp, is used to provide the required brightness for the display. Contrast, brightness, and resolution are the greatest attributes of AMLCD technology, rivaling that of CRTs while offering lower weights, less power consumption, and reduced display depth (Spitzer, 1993). However, it must be pointed out that AMLCD displays are not truly flat, requiring two to three inches over the backlight (Collinson, 1996) The color capability of the AMLCD display and its ability to attain brightness levels that allow the colors to be visible even in conditions of high sunlight make the AMLCD display a preferred choice for tactical aircraft.

AMLCD displays also have some drawbacks. Reliability of AMLCD displays in the aviation environment has yet to be proven due to limited use The backlight required by the display to achieve satisfactory brightness levels is the weakest failure point (Ratliff, 1992). Additionally, temperatures on both the hot and cold end of the requirements scale cause performance problems in the liquid crystal and fluorescent backlights used in the display (Collinson, 1996). Auxiliary heating is recommended for aircraft applications (Spitzer, 1993). High load factor performance problems were also seen during flight testing of an AMLCD horizontal situation indicator in a USAF F-15 (Ratliff, 1992). Extensive reliability testing in the laboratory using simulated temperature conditions and flight conditions will be required when using AMLCD technology.

COLOR DISPLAYS

Humans depend heavily on their vision for attaining information about their environment. Color plays a large part in determining the speed and accuracy of the information gathered using the visual channel. Color coding may be the single most effective type of coding available, being superior to size, shape, or brightness in identification tasks and significantly reduces search times (Christ, 1975). The aesthetic appeal of color in cockpit displays is strong (Greenstein and Fleming, 1984) and can contribute to realism, enhance presentation, and lead to easier user acceptance (Stokes and Wickens, 1988).

Human beings have been found to recognize about nine distinct colors (Jones, 1962) and can discriminate between twenty-four colors when hue, luminosity, and saturation are varied (Feallock, et al, 1966). The ability of displays to show differing colors and the ability of the human operator to associate those colors with a meaning allows for the full use of all visual spatial channels (Thorell, 1983) This allows for more information to be collected using the visual channel than was possible when using monochromatic displays.

An additional advantage of using color is that the information contained in the color-coding is processed rapidly and relatively automatically after completion of some initial training (Dick, 1970; Ellis and Chase, 1971).

While the advantages of using color in display applications is significant, it is only effective when used properly. Color-coding which is irrelevant or which varies independently of other features may actually interfere with processing (Carter, 1979) Color-coding may be most effective when the symbol density is high, the legibility degraded, where relevant information must be discriminated, and where prevailing population stereotypes are utilized (Krebs, et al, 1978). Clearly, the choices that are made pertaining to what colors should be used are critical. Three different types of color have been found to be best in representing different display elements: environmental, traditional, and based on population stereotypes (Reising and Calhoun, 1982). Environmental colors suggest the actual appearance of objects as they appear in the natural world. Blue for the sky, brown for the earth, and green for vegetation are examples of environmental color use. Traditional colors are colors that have been used in cockpits for many years. Red for warnings or fire, amber for cautions, and green for advisories are examples of traditional color usage. Population stereotype colors are hard to quantify, as they are specific to each user population. Designers must try to quantify through research the stereotypes of the user population Aircrew advisory panels are often used during the system design stage to assist in this task.

Opinions for the optimum number of colors to use in a display have ranged from as many as ten (Teichner, 1979) down to three or four (Murch and Huber, 1982). MIL-

STD-1472F identifies seven colors with dominant wavelengths that should be used However many colors are used, it should be recognized that color differences will also be accompanied by some apparent brightness differences. Different colors will appear to have different brightness levels on the same background (Thorell, 1983). This characteristic can be beneficial if accounted for properly since it makes further use of the visual channel's capacity.

Color-coding must be consistent throughout each display and between displays to take advantage of its full potential. Flight test has shown that redundant color-coding significantly reduced both response time and error rates of the operator. Redundant color use was especially effective as the display density increased, resulting in almost eliminating the time gap between the least and most dense display (Kopala, 1979).

One final issue involving the use of color in displays is the use of night vision goggles (NVGs) in military tactical aircraft. The Type I class B NVGs used in fixed wing aircraft today (MIL-L-85762A, 1988) are not meant to view the displays, other than a heads-up display, directly through the goggles Rather, the aircrew must look under the NVGs at the displays This allows for the use of color in heads-down displays providing the radiance levels do not exceed those specified in MIL-L-85762A and the spectral output of all light emitting from or illuminating a display is at wavelengths less than 600 nanometers.

DISPLAY POSITIONING

The definitive standard for display positioning in military aircraft applications is defined in MIL-STD-1472F and MIL-STD-203G The applicable portions of the military standards are reviewed in the following paragraphs.

Displays should be located and designed so that personnel in their normal operating positions may read them to the required degree of accuracy without the need to assume uncomfortable, awkward, or unsafe postures. To accomplish this, displays shall be perpendicular to the operator's normal line of sight whenever feasible and never less than 45 degrees from the normal line of sight, as shown in figure 2.

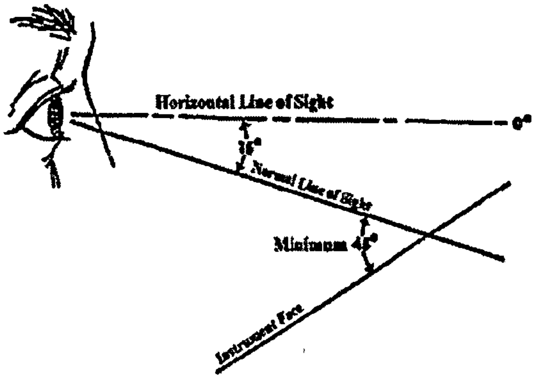

Figure 2: LINE OF SIGHT

The displays used most frequently should be grouped together and placed in the optimum visual zone, as shown in figure A-2. Information should be grouped functionally with priority placement being given to the displays that present the information critical to the primary mission of the aircraft. All displays, critical and non-critical, should be placed within the maximum visual zones shown in figure A-2. Displays should be arranged in relation to one another according to their sequence of use within a functional relationship. A visual flow of left-to-right or top-to-bottom should be provided.

A viewing distance from the design eye point (DEP), as defined in MIL-STD-1333, of the seated operator to a non-electric display should not exceed 25 inches, although up to 30 inches is allowable if used in ejection-seat aircraft. If using electronic displays, a maximum viewing distance of 20 inches is recommended. Displays that must be placed at viewing distances greater than 20 inches due to other considerations should be appropriately modified in aspects such as display size, symbol size, brightness ranges, and display resolution.

An additional factor to be considered is visibility of the displays for both crewmembers in side-by-side cockpits. If performing similar duties, either crewmember should be able to view all cockpit displays without assuming an uncomfortable, awkward, or unsafe posture while seated in an ejection-seat. Placement of all cockpit displays should fall within the maximum visual zones of either crewmember.

CONTROL DESIGN FACTORS

A control is any device or method with which the operator can transmit a message to a device or system (Hawkins, 1987). Historically, controls in aircraft have been of a mechanical nature, which has required the operator to impart a motion or a force in order to receive the desired action. Recently, some new technologies have emerged that may change the liveware-hardware interfaces in the future

The design and layout of controls in the cockpit is extremely important. For the operator to reach maximum efficiency in the execution of his/her mission, the controls must be arranged so as to maximize operator output while minimizing operator workload. Areas that should be considered during control design and layout include (1) arrangement and grouping, (2) control-display ratio, (3) direction of movement, (4) resistance, (5) coding, and (6) prevention of accidental activation (Hawkins, 1987; MIL-STD-1472F, 1999).

Controls which are operated in a task-driven sequence or which are operated together should be grouped together along with their associated displays. The most commonly used controls should be located in the easiest to reach areas. Adequate spacing between controls and any adjacent obstruction should be provided. When required, spacing allowances for operating with the applicable required handwear (gloves) should be provided for (MIL-STD-1472F, 1999).

Control-display ratio is how much the movement of a control affects the movement of the element that it controls on a display. It can be seen as the sensitivity of the control. Proper control-display ratio will provide for both fine and gross adjustments with minimal operator workload. Improper control-display ratio will severely degrade operator performance by requiring a high mental workload (Hawkins, 1987).

The direction of movement of a control should be in accordance with human expectation and physiology (Hawkins, 1987). In general, movement of a control forward, clockwise, to the right, or up should turn equipment on, increase a value, or move a related item in the same direction (MIL-STD-1472F, 1999). One exception to this rule is the "sweep-on" concept, which differs from the previously stated convention in that overhead mounted switches turn equipment on when moved to the rear (Hawkins, 1976) The sweep-on concept applies more to transport aircraft than tactical military aircraft. Another control direction convention, the Warrick Principle, states that if a knob is located next to the display which it controls, then an indication is expected to move in the same direction as the side of the knob closest to it (Hawkins, 1987). Whichever concept is applied, consistency throughout the controls in the aircraft is critical.

Control resistance can affect the speed and precision of control movement, the smoothness of control movement, and the tactile feel of the control movement (Hawkins, 1987). Each control must have enough resistance to prevent inadvertent operation but still be easy to operate for the entire range of operators. MIL-STD-1472F establishes minimum, maximum, and preferred resistance levels for every type of control presently used in military aircraft

Control coding by means of shape, size, color, labeling, and location are all designed to improve identification by the aircrew (MIL-STD-203G, 1991). The improved identification reduces the time required to select a control and minimizes control selection errors (Hawkins, 1987). Each type of coding has its advantages and disadvantages that must be considered before use. Like direction of movement, control coding for identical tasks should also be uniformly applied throughout the aircraft (MIL-STD-1472F).

Controls should be designed and located so they are not susceptible to inadvertent actuation, especially critical flight and weapons system controls (MIL-STD-1472F).

Design factors that can be utilized are physical barriers, proper resistance, mechanical locks, electrical cutouts, and recessed controls. Any design to prevent accidental activation must not interfere with normal operation of the control. Only those controls for which inadvertent operation will cause physical damage, equipment damage, or system performance degradation need be guarded Proper location and control resistance should provide adequate protection for other non-critical controls (Hawkins, 1987; MIL-STD-1472F, 1999; MIL-STD-203G, 1991).

The control design factors covered in the preceding paragraphs are a starting point for what should be considered when designing and implementing cockpit controls. Designers should work closely with the user population to ensure that the controls designed will meet the needs and desires of those individuals tasked to carry out the mission.

KEYBOARD DATA ENTRY

The use of keyboards for data entry has permeated every facet of our society. The entry of the personal computer into businesses and homes means most adults will interact with a keyboard at least once per day. Therefore, it is not surprising that the keyboard is the preferred method of data entry when alphabetic, numeric, or special function information is to be entered in a system (MIL-STD-1472F, 1999) The keyboard gives the operator the ability to give accurate detailed instructions to computerized systems (Hawkins, 1987). These detailed instructions are necessary with today's navigation systems, flight management displays, and data-links Keyboards are flexible and easy to implement (Hart, 1988). Once a keyboard is installed in an aircraft, many different systems can be made to interact with the one keyboard. This alleviates the need for each system to have a separate data entry device and saves valuable space in the cockpit. For inputting large amounts of data, especially alphanumeric sequences, keyboards are more rapid and accurate than discrete linear controls (Fenwick and Schweighofer, 1971). Both the rapidity and the accuracy are important as today's systems can handle large amounts of data that needs to be accurate to be correctly implemented. The choice of an input device predetermines most of the human errors in data entry. If a keyboard is used, traditional miskeyings which may occur can be analyzed and predicted from the keyboard layout. Design decisions can be decisions about the nature of the human errors that will occur (Hopkins, 1988). With proper human factors engineering applied, the human errors can be designed down to a minimum.

Keyboard use has several disadvantages when compared to other forms of data entry. Even with the best design, keyboards present opportunities for human error, especially during periods of high workload. The errors may not be recognized until much later in the flight, sometimes with serious consequences. In the case of Korean Air Flight 007, improperly entered navigational data led to a gross navigational error and the eventual shoot-down of the airliner by a Soviet interceptor (Hawkins, 1987). It is difficult for the operator to accomplish other tasks while using a keyboard. The operator must make the decision whether or not the data entry task is the top priority. If not, it must be deferred or passed to another crewmember. Most current cockpit keyboards require the operator to be heads-down while making entries (Baron, 1988). Typing in commands via a keyboard may not be the most efficient interface method in a complex and dynamic environment, especially where there are other concurrent manual and visual demands (Stokes, et al, 1990).

The standard typewriter-type keyboard in use today is known as the QWERTY keyboard, named for the 6 letters on the left side of the top row. It was designed in 1873 by Christopher Sholes who had the problem of the type-arms becoming jammed while typing on his manual typewriter. His keyboard design separated the most commonly used letters to keep the type-arms from jamming. Thus, the standard keyboard in use today was designed to be inefficient. The inefficiency is demonstrated by the fact that individual finger loading varies from 1% up to 20% and nearly 60% of the work is done by the left hand. Additionally, only about one hundred words in the English language can be produced by the center row of the QWERTY keyboard (Hawkins, 1987).

August Dvorak, a psychologist at the University of Washington, felt there was a more efficient layout than the standard keyboard. He developed the Dvorak simplified keyboard (DSK) which put all five vowels and the most commonly used consonants (D, H, N, T, and S) in the middle row where the typist's fingers would be resting. The layout allowed more than three thousand words in the English language to be typed using only the center row. The layout also shifted more work to the right hand and distributed individual finger loading from 8% up to 18% (Dvorak, 1943) Although more efficient than the QWERTY keyboard, the DSK has not broken the established QWERTY paradigm. The last one hundred years has seen more than twenty other unsuccessful proposals to rearrange the keyboard (Hawkins, 1987).

Typing alphabetical characters is not the only activity that keyboards are used for, especially in aviation applications. Data entry of numerical information is also quite prevalent. Commonly, one of two numerical layouts is used for number pads. Most calculators and adding machines in use are arranged in four rows with 7, 8, and 9 on the top row and so on. The layout commonly used on telephone number pads is four rows with 1, 2, and 3 on the top row and so on. The telephone-style is the layout standardized by the Society of Automotive Engineers (SAE). The SAE standard has been shown to be operated faster and with fewer errors than the calculator-style keypad (Hawkins, 1987).

The tactile interaction of the keyboard with the operator is an important factor. The possibility of turbulence, aggressive maneuvering, and increased load factors are all present in the tactical military aviation environment. Some of the recent trends designed to reduce the demand for cluttered cockpit space such as smaller keys, reduced tactile feedback, multifunction keys, and remote key legends may be counter-productive from a human factors point of view (Taylor and Berman, 1985). The possibility of errors increases if the operator has trouble accessing the keys or must search for the key's function in a dynamic environment. Factors such as when an entry is to be made, on key push or key release, and force required for key activation can have bearing on the number of errors. Minimum designed key resistance should be 9.9 ounces of force with a maximum resistance of 23.7 ounces of force (MIL-STD-1472F, 1999). The minimum designed key size for an operator wearing gloves should be 0.75 inches per side with a maximum size of 1.0 inch per side (MIL-STD-1472F, 1999).

TACTILE CONTROLS

Tactile controls can take many forms. Buttons, toggles, wheels, knobs, joysticks, thumbwheels, trackballs, force controllers, and touch pads are all examples of tactile controls. Only tactile controls used in data entry or cursor placement in conjunction with electronic displays will be reviewed in the following paragraphs.

Touch-sensitive displays and keypads may be used when direct visual reference access and optimum direct control access is desired (MIL-STD-1472F, 1999). Touch-sensitive displays use a matrix of infrared beams across the display surface to establish a x/y grid system. When an operator touches the display, the x/y grid system is broken at a defined spot that corresponds to a pre-programmed operation Surface acoustic waves can also be used in a similar manner (Collinson, 1996) Advantages of touch-sensitive displays are their flexibility, the pre-programmed operations can easily be changed in software, and their durability Unlike mechanical entry devices, the touch-sensitive controls do not require mechanical actions that lead to failures over extended periods of time. The up-front-control (UFC) in the new F/A-18E/F aircraft uses infrared touch-sensitive technology in place of the mechanical keys used on the older F/A-18 A-D models. The new Boeing 777 airliner has instituted a touch-sensitive device that allows the flight crew to interact with software-generated buttons programmed on the displays (Arbuckle, et al, 1998) Touch-sensitive controls should be regular, symmetrical, and equilateral in shape. For alphanumeric entry the actuation area should be 0.5 inches by 0.5 inches, separated by a minimum of 0.2 inches, and require 0 9 to 5.3 ounces of force for activation. A positive indication of touch activation should be provided with a response time of not more than 100 milliseconds (MIL-STD-1472F, 1999). To reduce the opportunity for errors, the pre-programmed operation should be executed when the operator lifts his/her finger, instead of when the touch-sensitive surface is initially touched (Spitzer, 1993). This allows the operator to verify the selection is correct prior to execution.

The widespread use of glass displays in cockpits has resulted in the need for pointing devices capable of controlling on-screen cursors The cursors are used for data pick-off, targeting, target tracking, data field selection, text editing, and software command selection. Several types of pointing devices are used in aircraft today Isotonic (displacement) joysticks, isometric (non-displacement) joysticks, and ball controllers are the pointing devices most commonly used.

Isotonic joysticks are good for tasks that require precise or continuous control in two or more related dimensions and when positioning accuracy is more critical than positioning speed. Data selection from display screens and rate control applications may be performed using isotonic joysticks Isotonic joysticks can either be hand-operated, finger-operated, or fingertip-operated. The more precise the pointing requirements, the lesser number of fingers should be involved. The isotonic joystick should return to the center position when released. Handgrip length should be between 4 3 to 7.1 inches and grip diameter should not exceed 2 inches. Clearances of 4 inches to the side and 2 inches in the rear should be provided for hand movements. If fingertip isotonic joysticks are mounted on handgrips as a steady rest and to damp vibrations, the handgrip should not also serve as a joystick controller. A concave circular controller with a diameter of 0 75 to 1.0 inches requiring 10 to 40 ounces of force for displacement should be used for a fingertip isotonic controller (MIL-STD-1472F, 1999).

Isometric joysticks are pointing devices that use a force controller instead of a displacement controller for sensing operator inputs. The isometric joystick has no perceptible movement. Isometric joysticks are good for tasks requiring precise or continuous control in two or more related dimensions and when positioning speed is more critical than positioning accuracy. Operator feedback is required to be visual rather than tactile. Isometric joysticks should not be used for tasks that require a force to be maintained over long periods of time due to operator fatigue. The physical attributes of the isometric joystick mirror those of the isotonic joystick (MIL-STD-1472F, 1999).

Ball controllers consist of a ball suspended on low-friction bearings When the ball is moved, the bearings move and the direction and displacement of the movement is transferred to the controlled item. Ball controllers are good at controlling cursors on a display for data selection and for applications where accumulative travel in a given direction is desired. Ball controllers are not good for use in a high load factor or turbulent environment due to the limited friction being available to stop uncommanded control travel. Control ratios and dynamic features should be designed to meet the dual requirement of rapid gross positioning and smooth precise pointing. The minimum diameter of the ball should be 2 inches with a diameter of 4 inches being preferred Smaller diameter ball controls should be used only where space availability is limited and the need for precision positioning is low (MIL-STD-1472F, 1999).

Activation push buttons are often used in conjunction with tactile controllers to effect an action on a display. Push buttons are excellent for commands that only require momentary actions. When used, a fingertip pushbutton should be concave in shape if possible or provide a high degree of frictional resistance. A diameter of 0 75 to 1.0 inches, a resistance of 10 to 40 ounces, a displacement of 0.08 to 0.25 inches, and a positive audible or tactile feedback should be provided for (MIL-STD-1472F, 1999).

DIRECT VOICE INPUT

Direct voice input (DVI) of commands using speech recognition technology offers the potential of a new form of control in the cockpit Using DVI, the operator can enter data into a system by voice command without diverting his/her attention from whatever other tasks are simultaneously being performed DVI requires the establishment of a standard vocabulary and a set of standard command templates. The operator can use these standard templates to voice commands that are recognized by a computer and converted into data The data is sent across the data bus to the correct aircraft subsystem in the same manner as any other control command.

DVI technology has been pursued for decades, but only limited functionality is currently available on the market (Arbuckle, et al, 1998) Experience has shown that DVI is best applied to non-critical tasks due to the technology not yet being mature (Spitzer, 1993). Additionally, research has shown that operators may not be able to use both voice and visual channels concurrently for some tasks (Grossman, 1983) The high background noise levels present in aircraft, coupled with voice changes in times of physical and mental stress make using DVI technology with a high degree of confidence a difficult challenge. Flight tests of DVI in the USAF Advanced Fighter Technology Integration F-16 in 1988 routinely achieved 95% correct word recognition during low load factor flight. However, under high load factor conditions the correct word recognition was reduced to less than 80% (Dickerson and LaSaxon, 1988). A word recognition accuracy of around 99% would be required to minimize having to repeat commands (Collinson, 1996). Repeating commands would severely degrade the usefulness of DVI since it would raise the operator's workload and lengthen the time required to accomplish a task.

DVI technology is seen as a future technology that could eventually revolutionize the interaction of humans with machines. The explosive growth of personal computers and the potential of using DVI technology leads many people to think that an inexpensive and robust speech recognition capability is only a few years away (Arbuckle, et al, 1998).

SUMMARY

The study of human factors engineering in relation to controls and displays used in the cockpit has been extensive over the last several decades The discipline of human factors engineering and the benefits it can bring to a system are becoming better understood as another tool available to the system designer. In the aviation design community, the desire to increase mission effectiveness and safety has led designers to focus on the interfaces between the operator and the hardware, software, and the environment in which the system must operate. If these interfaces can be optimized, many of the problems encountered today in aviation may be eliminated.

CHAPTER 3: METHODOLOGY

GENERAL

Operator-centric cockpit design is a methodology that places the focus of the design effort on how to optimize the interaction of the human operator with the system under design. Operator-centric cockpit design is based upon two separate but equally important engineering disciplines Human factors engineering utilizing the S-H-E-L conceptual model and the systems engineering process approach to problem solving are combined to capitalize on the synergistic effect of these two disciplines. The S-H-E-L conceptual model and systems engineering process and how they support the operator-centric cockpit design methodology is explained in the following paragraphs. An example of how the author utilized the operator-centric cockpit design methodology to design system hardware that will solve the problem statement is described in detail Although only described for one particular system modification, the same process was repeated by the author for each separate hardware item and for the system as a whole

S-H-E-L CONCEPTUAL MODEL

Human factors engineering as a discipline is still relatively new when compared to other more traditional engineering disciplines The concepts used in human factors engineering relies less on the laws of mathematics and physics, and more on the concepts of physiology and psychology. Difficult to clarify with words, human factors engineering and how it is applied in practice is best explained using the three-dimensional S-H-E-L conceptual model introduced in the early 1970s (Edwards, 1972). The model, shown in figure 3, pictorially shows the resources available to the human factors engineer, how the resources interface with one another, and the environment in which the resources must perform.

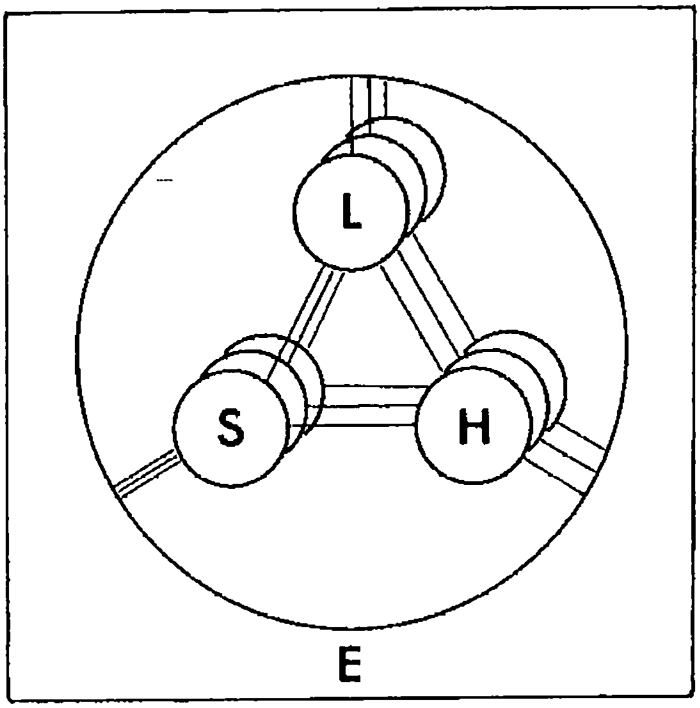

Figure 3: S-H-E-L CONCEPTUAL MODEL

The most critical member of the model is the human operator, or liveware, represented in the model by the letter L The liveware is the most important and most flexible component of the model. While the liveware is the most flexible, it is also the most prone to errors and displays the most variations in performance Due to human nature, the liveware cannot be counted on to act identical every time the same situation is encountered. The S in the model is the software. Used in the context of the S-H-E-L model, software does not only refer to computer commands executed by a program but also refers to other non-physical aspects such as procedures, manuals, checklists, symbology, conventions, regulations, customs, and practices. The H in the model is hardware Hardware is the physical system components such as controls, displays, gauges, coding, and equipment. The E in the model is the environment in which the liveware, software, and hardware must operate. The environment in which military aviation systems must operate can be harsh. Extreme temperature differences, humidity differences, vibration levels, salinity levels, pressure differences, varied oxygen levels, and varied load factors are some of the factors that the liveware, software, and hardware components of a military aviation system must be able to operate in.

The lines between the separate components of the S-H-E-L model represent the interfaces, or interactions, of the components It is at these interfaces where conflicts can develop that lead to a reduction in the overall efficiency of the system Therefore, it is at these interfaces where the human factors engineer must apply his/her trade in order to adapt and match the other components to the central component, the liveware. It is critical that a system never be designed with the idea that the liveware will adapt to match the other components. While the liveware is the most flexible component of the system and can often accommodate for design deficiencies, it does not always recognize the deficiencies in time to avoid a disaster.

The focus of this thesis is to design and select hardware which optimizes the L-H interface in order to assist the liveware in coping with the large amounts of information present in air combat operations. While the complete breakdown of a single L-H interface is unlikely, the possibility of small friction points developing along the interface is more likely. Friction points lead to a reduction in the efficiency of the interface and eventually a reduction in overall system efficiency. If compounded by multiple friction points in multiple systems, the possibility of a complete system breakdown rises By applying a human factors engineering approach to each component and interface present in the system, the possibility of a complete system breakdown can be minimized.

No cockpit system can operate without involving all of the interfaces presented in the S-H-E-L model. Whatever hardware is used must also be made compatible with the additional hardware and software present in the system and must operate within the environment specified by military standards These factors have been observed throughout the design and selection of the cockpit components presented in this thesis.

SYSTEMS ENGINEERING PROCESS

The systems engineering process is a methodical approach to problem-solving that attempts to break down the larger requirements of the customer into smaller identifiable pieces that can be dealt with at a subsystem level. The goal of the process is to optimize the system's components, attributes, and relationships in order for the entire system to operate at peak efficiency During the course of this thesis, an eight step systems engineering process was developed and implemented by the author. The process consisted of the following eight steps: problem statement, requirements and constraints analysis, alternatives generation, alternatives analysis and selection, system design, system testing, system implementation, and system control.

The systems engineering process begins with identifying the problem that the system under development seeks to solve It is important that the problem is well defined and clearly stated, allowing the problem to be bounded so as to avoid the costly "unknown unknowns" that may arise later (Sheridan, 1988). If the problem is not well bounded, the system design may head in a direction other than that intended. Once identified, the problem statement should be revisited throughout the process to ensure that the focus of the process is kept on solving the problem.

An analysis of the requirements and constraints of the system under design is performed in order to ensure that the needs of the customer will be met Areas to be analyzed include mission, cost, schedule, performance, environmental, and programmatic requirements. Additionally, constraints imposed by the customer, the environment, military standards and specifications, and technology must be analyzed for their impact on the system. The requirements and constraints analysis step takes place at the beginning of the process but is continuous throughout the systems engineering process. Each following sequential step should be traceable back to a stated requirement and should not violate any of the constraints deemed pertinent during this step Continuously performing the requirements traceability and constraints analysis will ensure that the system focus will be maintained throughout the design.

Alternatives generation involves developing all of the alternatives that may potentially solve the problem statement. The focus during this step is to generate as many alternatives as possible. At this stage, no possible alternative is discarded. Extensive research and study is performed to explore alternatives that have been used in similar systems. Additionally, advanced concepts are researched to determine if they may be applicable to the system under design All alternatives are recorded for possible future use.

The alternatives analysis and selection stage is where all of the previously generated alternatives are weighed for possible use in the design. The advantages and disadvantages of each are investigated and weighed. Important factors to analyze include technological risk, life cycle costs, availability, compatibility with other system components, producibility, supportability, and performance If necessary, studies may be conducted to select the best solution among many possible solutions. During this stage the systems engineering perspective must be maintained. The intent is to optimize the performance of the overall system, even if that means some individual components of the system operate at less than their optimal performance

The system design stage is where all of the individual alternatives previously selected are formulated into a system. It is at this point that the physical architecture of the system is defined. The physical architecture must be constructed so that each component will satisfy at least one or more of the requirements stated for the system. If it does not satisfy one or more of the requirements, it should be eliminated from the design Additionally, each component must be capable of operating within the constraints analyzed previously. Failure to do so will lead to overall system failure.

Once designed, the system must be tested to ensure that it can meet the stated requirements and that it can operate within the imposed constraints. System testing will take place at many levels. Subsystem testing should be performed to ensure that the subsystem has met its requirements and can operate within the specified environment Environmental, stress, vibration, electromagnetic compatibility, electromagnetic vulnerability, and performance are some of the tests to be done. Full system testing must also take place. Early testing may involve modeling, simulations, mock-ups, demonstrations, and analysis. Finally, testing of the full integrated system in the operational environment must be conducted.

Weaknesses in a system's design are often identified during the system test phase. Any deficiencies identified during test will return the design to the alternatives analysis and selection step. A new alternative may need to be selected and passed to the system design step for modifications in the design The concept of test, analyze, and fix ensures that the final system design will meet all of the requirements and design constraints placed on the system. A system should never be allowed to proceed to the implementation stage with deficiencies found in the test stage still outstanding Failure to fix known deficiencies guarantees that the system will operate at less than an optimal condition.

Manufacturing and fielding of the system take place during the system implementation phase. If the systems engineering approach has been properly employed, the system fielded will satisfy the stated requirements, operate within the design constraints, and perform at an optimal level.

System control is a concurrent activity that takes place throughout the systems engineering process. The purpose of system control is to provide balance to the process It provides the program manager with a tool to track progress and identifies problems early. Areas monitored include risk management, configuration management, interface management, and data management. Effectiveness analyses, trade studies, and performance based progress measurements are developed and tracked to ensure that the system design will satisfy performance requirements while staying within the cost and schedule mandated by the customer.

SUMMARY

Human factors engineering and systems engineering form the methodology used in operator-centric cockpit design By using these two separate disciplines together, the cockpit designer can build a system that conforms to the needs of the liveware operator while at the same time satisfies the design requirements and constraints placed upon him/her by the customer. The positive synergistic effect of the S-H-E-L conceptual model used in conjunction with the eight-step systems engineering approach will be shown in the author's proposed hardware selection and cockpit layout.

CHAPTER 4: RESULTS AND DISCUSSION

GENERAL

The current cockpit design being proposed by the prime contractor for the ICAP III aircraft is inadequate in several areas and will not fully solve the previously defined problem statement. Using the systems engineering approach, the overall problem statement was further broken down to six separate sub-areas where the current proposed design is inadequate Specifically, the design falls short in the following areas: (1) critical weapons system failure alerts can go unnoticed by the ECMOs, (2) a limited display area is available for the presentation of weapons system information, (3) a high operator workload is required to monitor the status of the AN/ALQ-99 jammer pods, (4) navigational situational awareness in the rear cockpit is extremely poor, (5) the current rear cockpit pointing devices increase logistical support requirements and enforce negative habit transfer, and (6) alphanumeric character entry into the integrated weapons system is inefficient. In order to solve these problem sub-areas, the operator-centric cockpit design methodology was utilized by the author. An example of how the methodology developed by the author was used to solve one of the six problem sub-areas is given in the following section

OPERATOR-CENTRIC COCKPIT DESIGN PROCESS EXAMPLE

GENERAL

Throughout the development of this thesis, the operator-centric cockpit design methodology described in the previous chapter was followed. Specifically, the eight-step systems engineering process was utilized while simultaneously keeping the focus of effort on the interfaces of the S-H-E-L conceptual model. Although eight steps are identified in the process, the author did not carry out the system test and system implementation steps during this academic exercise System testing was limited to paper fit-checks and cockpit mock-ups. System implementation was beyond the scope of this thesis due to the requirement to actually build and field an aircraft system. System control was performed by the author concurrently throughout the process to ensure that all of the proposed hardware systems satisfied the stated design requirements and constraints, could interface with the established data bus architecture, and focused on the interface with the liveware operator

An example of how the systems engineering process was utilized by the author to design the weapons system voice warning system in order to solve one of the sub-area problem statements will be given in the following paragraphs. Each of the steps will be explained. All other sub-area problem statements were solved using the same systems engineering approach.

SYSTEM DESIGN REQUIREMENTS AND CONSTRAINTS

A requirements and constraints analysis for the overall system was first performed to ensure that any hardware selected would meet the needs of the customer without violating any of the imposed constraints. A list of design requirements and design constraints for the overall system was generated and is detailed in the following paragraphs

Design Requirements

The hardware used in the cockpit design must satisfy the following requirements

1. All controls and displays must be usable by the ECMOs throughout the entire EA-6B flight envelope as defined in the Naval Air Training and Operating Procedures (NATOPS) flight manual for the EA-6B aircraft
2. All mission functions currently performed in the rear cockpit of the ICAP II aircraft must be present in the rear cockpit of the ICAP III aircraft.
3. The ability to control the USQ-113, MATT, and IDM must be available on the integrated cockpit displays
4. All controls and display lighting must be NVG compatible
5. The ability to store and use the laptop computer during ground and flight operations must be maintained
6. All weapons system displays must be cross-cockpit viewable. Any navigational displays that are present at both crew stations are not required to be cross-cockpit viewable.

7. All controls must be accessible from either the ECMO 2 or ECMO 3 position when properly strapped in. Exceptions are lighting, environmental control, ICS, and radio controls that affect only one ECMO position.
8. An effort will be made to reduce the number of separate controls and displays whenever possible.

Design Constraints

The hardware used in the cockpit design must operate within the following constraints:

1. All military standards and specifications pertaining to environmental stress, vibration, electromagnetic compatibility, electromagnetic vulnerability, and carrier suitability shall be enforced.
2. All technology used must be commercially available by mid-2001.
3. No hardware shall be allowed to extend into the previously validated ECMO 2 and ECMO 3 ejection envelopes.
4. Pointing devices at each crew position shall be identical to lessen the logistical support requirements.
5. Physical modifications to the console and panel support structures shall be kept to a minimum.
6. Total power and cooling requirements for the aircraft shall not increase.

WEAPONS SYTEM VOICE WARNING SYSTEM

Problem Statement

The overall problem statement of needing new control and displays to serve as interfaces between the ECMOs and the integrated weapons system was further broken down to six separate sub-areas where the current proposed design is inadequate. One of the sub-area problem statements was defined as " critical weapons system failure alerts can go unnoticed by the ECMOs." Constant manual or automatic monitoring of the jammers during offensive combat operations is critical for the success of the EA mission. A further bounding of the problem identified the following situations as critical failures that require an alert: power degrades to an unacceptable level on any jammer transmitter, antenna steering of a jammer transmitter varies by more than 5 degrees from the commanded steering, electrical power from the pod RAT is interrupted, or antenna beamwidth limitations are exceeded. The identified failures were only deemed critical when the MASTER RADIATE switch was in the RADIATE position, allowing the jammers to transmit.

Requirements and Constraints Analysis

The hardware and software proposed for use in the warning system had to satisfy all of the applicable overall system design requirements and design constraints that had been identified. Additionally, an analysis of the EA mission identified the requirement that the system under development had to present timely and accurate failure alerts to the rear cockpit ECMOs in a manner that was immediately noticeable with no manual input required. An additional constraint identified was that the warning system could not significantly interfere with the normal operation of the weapons system due to missions other than EA being simultaneously performed. A failure in the EA mission area should not interfere with other mission areas whenever possible

Alternatives Generation

Generating alternatives for how to monitor the weapons system and identify critical weapons system failures was not required due to an ICAP II legacy capability In the ICAP II aircraft, the AYK-14 central mission computer (CMC) monitors each of the critical weapons system parameters When the CMC detects any power or antenna steering degradations, a message is sent via the 1553B EW databus to the ECMO display for visual presentation The same 1553B databus message can be sent in the ICAP III aircraft to any remote terminal on the EW or navigation databus for presentation to the ECMOs. Passing of the message from a remote terminal to a mechanical device for presentation is also possible

Alternatives were generated on how to best alert the ECMOs to a critical weapons system failure. The alternatives generated were: (1) use of non-voice aural alerting tones, (2) use of voice aural messages, (3) use of flashing worded messages on the ECMO MFD, (4) use of flashing symbols on the ECMO MFD, (4) install a separate weapons system alert panel, (5) use of color distinctions of symbols and/or words on the MFDs, (6) install foot-pedal shakers on the microphone pedals, (7) overwrite all displays with failure messages, (8) disable the movement of the pointing device cursor and/or keyboard entry,

(9) inflate the ECMOs' anti-g suit, and (10) halt the flow of oxygen to the operator's mask. All of the alternatives generated were recorded and no alternatives were immediately discarded as a possibility.

Alternatives Analysis and Selection

An analysis of the alternatives generated in the previous step was performed to determine which possible solution would best solve the sub-area problem statement but not violate any of the system design requirements or constraints previously stated. The advantages and disadvantages of each alternative were investigated and weighed. Alternatives requiring a mechanical interface with a separate aircraft system were disqualified due to complexity and reliability concerns Microphone pedal shakers were disqualified as ineffectual since they would require the ECMO to always have his/her feet on the pedals. Inflating the ECMO's anti-g suit as a possibility was disqualified since it would only be effective under conditions in which the suit was not already inflated and would require further investigation by the ECMO to determine why the anti-g suit had inflated. Halting the flow of oxygen to the ECMO's mask was disqualified due to safety requirements Alternatives that required the ECMO to be looking directly at a display or warning panel to notice a visual alert were disqualified due to past experience of visual-only alerts Visual-only alerts are often missed during periods of high workload or while maintaining an out-of-the-cockpit scan in an environment with an air threat. Disabling of the pointing device and/or keyboard was disqualified since it violated the constraint of not significantly affecting the normal operation of the weapons system.

Three alternatives remained as a solution to the problem statement. Either a non-voice aural alert, a voice aural alert, or a combination of the two could be used. By referring to the literature reviewed in Chapter 2 and based upon the author's flight experience, the alternative selected was the combination of a non-aural alerting tone followed by a voice warning.

System Design

Once the alternative for how the warnings would be identified and presented to the ECMOs was selected, the physical architecture of the system was defined based upon the literature and military standards reviewed in Chapter 2. The following paragraphs specify the physical architecture of the weapons system voice warning system

The AYK-14 CMC will monitor each of the critical parameters as it currently does in the ICAP II aircraft. When the CMC detects any power or antenna steering degradations, a message will be sent via the 1553B navigation databus to the ECMOs' receiver audio select panel for aural presentation A similar message will be sent by the CMC via the 1553B EW bus to the pod status display for visual presentation. Voice alert presentation priority will be first detected, first alerted and will match the priority of the visual alerts. Any newly detected degradation warning will have a higher priority than a repeated warning for an already detected degradation.

The voice warning system will use synthesized speech technology to present a non-gender, distinctive, mature voice that will present the messages in a formal and impersonal manner. Construction of the messages will be in accordance with the characteristics previously reviewed in Chapter 2. Messages will consist of a 0.5 second non-voice aural alerting tone followed by a voice message consisting of three to four syllables with a duration of not less than 1 second or more than 3 seconds. No single word will be repeated throughout all of the warning messages. Each message will be initially repeated twice and then repeated twice every minute as long as the system degradation exists. Messages will be presented at an auditory frequency between 500 and 3,000 Hz.

The receiver audio select panel will be altered by re-labeling the currently unused lower left switch from VOR/ILS to WARN, as shown in figures A-4 and A-6 The WARN switch will be a receive-only selection switch allowing each rear cockpit ECMO to select or deselect weapons system voice warnings. Control of the warning volume will be individually controllable through the master volume switch on each receiver audio select panel. Volume of the voice warnings will be at least 20 dB above all other receivers but not greater than 115 dB. Design specifications for the voice warning system are shown in table 1.

Table 1: VOICE WARNING SPECIFICATIONS

Characteristic	Minimum Value	Maximum Value
Message Duration	1 sec	3 secs
Message Content	3 syllables	4 syllables
Aural Alert Duration	0.5 sec	0.5 sec
Frequency	500 Hz	3,000 Hz
Volume	Volume+20 dB	115 dB

ADDITIONAL HARDWARE ITEMS

The preceding example outlined how one of the six identified sub-area problem statements was solved using the operator-centric cockpit design methodology Solving of the remaining five sub-area problem statements was accomplished by the author utilizing the same process. In each case, the process arrived at either a hardware modification or a hardware addition to the contractor's current design. Each proposed hardware component and the sub-area problem statement it solved will be addressed in detail

For the purpose of explanation, the proposed hardware components addressed will be· (1) the ECMO 2/3 MFDs, (2) the ECMO2/3 pod status displays, (3) the rear cockpit electronic horizontal situation indicators (EHSIs), (4) the ECMO 2/3 pointing devices, and (5) the ECMO 2/3 data entry keyboards. The ECMO 2/3 MFDs and ECMO 2/3 pointing devices that will be addressed are modifications to items already included in the prime contractor's cockpit design. The remaining four items are additions proposed by the author to correct identified design inadequacies. Changes to the baseline cockpit layout that arise as a result of the new hardware will be briefly addressed and shown in figures A-3 to A-6. The ICAP II Block 89A rear cockpit, shown in figures A-7 through A-10, is the baseline upon which all proposed ICAP III modifications will be made.

ECMO 2/3 MULTIFUNCTION DISPLAYS

The primary interface between the ECMOs and the integrated weapons system will be the MFDs located at each of the ECMO crew stations. Using these visual displays, the ECMOs will be able to access the information and enter the commands needed to accomplish the various assigned missions. The current design proposed by the prime contractor specifies the use of an 84 5 square inch AMLCD display for the ECMO 2/3 MFDs While large compared to the displays currently in use in the ICAP II aircraft, the displays do not take full advantage of the available cockpit space. By implementing the displays specified by the author in the following paragraphs, better use will be made of the available cockpit space and the problem statement of a limited display area being available for the presentation of weapons system information will be solved.

AMLCD displays capable of full color presentation and protected from the environment by a glass covering piece will be used for the ECMO MFDs The use of color AMLCD displays will provide the levels of brightness required without imposing large electrical and cooling requirements on the aircraft. A day operating mode allowing for manual control of the brightness in excess of 200 footlamberts (fL) will be provided to provide for full sunlight readability. A night operating mode allowing for manual dimming from 0.05 fL to 3 0 fL will be provided for NVG compatibility. Each display will be 8.5 inches wide by 11 0 inches tall (93 5 square inches) and will be mounted on the ECMO panel directly in front of each crew station at a distance of 18 to 20 inches from the ECMO DEP. The mounted ECMO MFDs are shown in figure A-3. By choosing this size display, the available cockpit space can be fully utilized with no changes being made to the current support structures. Power, operating mode, and brightness control knobs will be mounted on the bottom of the display. Display resolution must be a minimum of 1,024 by 768 pixels and a minimum display refresh rate of 60 Hz will be provided as required in the System Performance Specification. The 60

Hz refresh rate has been demonstrated to be adequate throughout the EA-6B flight envelope by the electronic flight instrumentation system (EFIS) currently being flown in the front cockpit of the ICAP II aircraft. The display must be viewable at horizontal angles of plus or minus 55 degrees from the DEP-to-display line-of-sight. Interchangeability of the displays between the ECMO 2 and ECMO 3 crew positions requires that the displays be viewable from either the left or right half-angle.

Auxiliary heaters and cooling fans controlled by an internal thermostat and capable of operating on either aircraft or ground power will be mounted inside the displays in order to operate in the environment required by military standards. Heating and cooling of the display backlights and liquid crystal material will be automatically activated whenever power is available and the thermostat senses a temperature outside of the normal operating limits. Design specifications for the ECMO 2/3 MFDs are shown in table 2.

Table 2: ECMO MFD SPECIFICATIONS

Characteristic	Specified Value
Viewing Area	8.5 by 11.0 inches (93 in^2)
Sunlight Readability	Maximum luminance>200 fL
Nighttime Dimming	0.05 fL to 3.0 fL, controllable by operator
Night Vision Goggle Compatibility	Compatible with Type 1 Class B NVGs
Display Refresh Rate	60 Hz minimum
Display Resolution	1,024 x 768 minimum
Cross-Cockpit Viewability	Plus or minus 55 deg minimum
Color Availability	256 colors minimum, 64 shades of gray in each primary color

ECMO 2/3 POD STATUS DISPLAYS

Real-time monitoring of the AN/ALQ-99 jammer pods during the execution of a mission is essential. As the primary offensive weapon of the EA-6B, the jamming pods must be automatically or manually monitored continuously to ensure that transmitter power is being maintained and that the transmitter antenna steering commanded by the mission computer is being maintained In the current ICAP II aircraft, these tasks are performed manually using mechanical controls and displays resulting in a full-time task for one of the ECMOs during offensive EA missions. No reduction in the high operator workload required is included in the contractor's current cockpit design. Incorporation of the author's proposed pod status displays at each ECMO crew station will eliminate the need for constant manual monitoring of the jammer pods. By reducing the workload required , the operator can increase his/her attention to another critical mission area.

Simultaneous software presentation of transmitter power, antenna steering, pod RAT output power, and pod status (off, standby, or radiate) for each weapon station occupied by a jammer pod will be shown on the pod status display. The status of the MASTER RAD switch (off or radiate) will also be shown to eliminate the need for the operator to divert his/her visual scan out of the optimum field-of-view mentioned previously.

Glass protected AMLCD displays capable of full color presentation will be used for the pod status displays. Each display will be 7.5 inches wide by 6.5 inches tall (48.75 square inches) and will be mounted on the ECMO panel directly below the MFD. The specified display size and mounting position, shown in figure A-3, will allow for the maximum use of available space. Although within the optimum horizontal field-of-view, the mounting position will require a DEP-to-display distance of 21 to 23 inches. The symbology presented on the display will be adjusted in size so as to be easily readable by the ECMO at that crew position. Power, operating mode, and brightness control knobs will be mounted on the right side of the display. Requirements for the luminance, resolution, refresh rate, off-angle viewing capability, and auxiliary heating and cooling will be identical to the requirements for the ECMO MFDs. Design specifications for the pod status displays are shown in table 3.

Table 3: POD-STATUS DISPLAY SPECIFICATIONS

Characteristic	Specified Value
Viewing Area	7.5 by 6.5 inches (48.75 in^2)
Sunlight Readability	Maximum luminance>200 fL
Nighttime Dimming	0.05 fL to 3 0 fL, controllable by operator
Night Vision Goggle Compatibility	Compatible with Type 1 Class B NVGs
Display Refresh Rate	60 Hz minimum
Display Resolution	1,024 x 768 minimum
Cross-Cockpit Viewability	Plus or minus 55 deg minimum
Color Availability	256 colors minimum, 64 shades of gray in each primary color

ELECTRONIC HORIZONTAL SITUATION INDICATORS

Navigational situational awareness (SA) in the contractor rear cockpit design is severely limited. The navigational information available in the rear cockpit consists only of aircraft heading and the tactical aircraft navigation (TACAN) aid bearing and distance. Navigational information provided by the INS and the embedded GPS/INS (EGI), which serve as the primary means of aircraft navigation, is not available in the rear cockpit. The proposed incorporation of two EHSIs in the rear cockpit will increase the rear-cockpit navigational SA, and result in the reduction of the inter-cockpit (front to rear) verbal workload.

A 3.9 inches wide by 3.3 inches high (12.87 square inches) multicolor AMLCD EHSI identical in size to the one located at the pilot crew station will be added to both the ECMO 2 and ECMO 3 crew stations. Each display will be protected from the environment by a glass cover piece. The rear cockpit EHSI displays will be simple repeaters of the front cockpit EHSI. By using the same signal generator, the same control panels, and an AMLCD display, the addition of the rear cockpit EHSIs will have a minimal impact on the cockpit layout, power requirements, and cooling requirements of the aircraft. All control of the EHSIs, with the exception of day/night operating mode selection and brightness, will be managed by the pilot or ECMO 1 using the EFIS control panels located in the front cockpit. Day/night operating mode selection and brightness will be controlled at the individual display level and will conform to the same luminance requirements as the ECMO MFDs. The auxiliary heating and cooling requirements will be the same as for the ECMO MFDs. Display resolution will be a minimum of 800 by 600 pixels, identical to the ICAP II pilot station EHSI.

The rear cockpit EHSIs will be mounted on the ECMO 2/3 panel, shown in figure A-3, in the area previously occupied by the receiver control panel. The mounting locations will place the EHSIs within the optimal visual zones of the ECMOs and will group them with the weapons system geographic information presented on the ECMO MFDs. A DEP-to-display distance of 18 to 20 inches will be provided at that location. Design specifications for the EHSIs are shown in table 4.

Table 4: EHSI DESIGN SPECIFICATIONS

Characteristic	Specified Value
Viewing Area	3.9 by 3.3 inches (12.87 in^2)
Sunlight Readability	Maximum luminance>200 fL
Nighttime Dimming	0.05 fL to 3.0 fL, controllable by operator
Night Vision Goggle Compatibility	Compatible with Type 1 Class B NVGs
Display Refresh Rate	60 Hz minimum
Display Resolution	800 x 600 minimum
Color Availability	256 colors minimum, 64 shades of gray in each primary color

ECMO 2/3 POINTING DEVICES

Digital pointing devices will serve as the primary tactile interface between the ECMOs and the weapons system. All cursor movement control and on-screen software selections on the ECMO 2/3 MFDs will be accomplished using the pointing devices. Additionally, the identical pointing devices used by the pilot and ECMO 1 will be the only liveware-software interface present at those crew stations. Therefore, the design of the pointing devices is critical for the system to operate at its maximum potential. Currently, different pointing devices in the front and rear cockpits are incorporated in the contractor's cockpit design resulting in increased logistical support required for additional parts and the loss of positive habit transfer for the ECMOs that fly in both cockpits. The pointing device and the rear cockpit mounting positions proposed by the author in the following paragraphs eliminates the need for separate devices and maximizes the positive habit transfer between crew positions.

Compatibility of the pointing device commands when used either in conjunction with the data entry keyboard or as a stand-alone controller will be made possible by both being standard PS/2 devices. The use of standard PS/2 devices allows for future growth and/or modifications using commercial-off-the-shelf keyboards and tactile controllers.

An isotonic (displacement) concave circular constant-rate controller will be used for the pointing device. A small amount of tactile feedback will be provided to the operator by the displacement of the controller from the centered position. Displacement of the controller will result in a constant-rate movement of the on-screen cursor. The controller will be mounted on a fixed, rectangular, pistol-grip type handgrip with two top-mounted circular activation buttons and one bottom-mounted circular activation button. A top and back view of the pointing device is shown in figure A-11.

The physical design of the proposed pointing device, associated handgrip, and activation buttons are specified in accordance with the military standards previously reviewed in Chapter 2. Length of the rectangular handgrip parallel to the console will be between 3 and 4 inches but will not obstruct any of the panel located immediately to the rear of the pointing device. The rectangular handgrip will have a diameter of 1 to 1.5 inches, and a vertical clearance of 2.5 to 3.5 inches from the console panel, allowing the operator to wrap his/her fingers fully around the handgrip. The isotonic controller and top-mounted activation buttons will be mounted on a flat surface tilted at an angle of 10 to 15 degrees from the vertical. A circular concave controller with a diameter of 0.75 to 1.0 inches and requiring 15 to 20 ounces of resistance for activation will be used for the isotonic controller. Upon release, the controller will return to the centered position. Manipulation of the controller and the top-mounted left and right activation buttons will be accomplished using the operator's thumb. Activation of these buttons is for making on-screen software selections. A resistance of 15 to 20 ounces will provide the operator a positive tactile feel while preventing inadvertent operation. A diameter of 0.5 inches will make the buttons easy to locate tactilely and operate while wearing flight gloves. An upward movement using the index finger will activate the bottom-mounted activation button. Activation of this button is used for re-centering the cursor on the ECMO MFD. Size and resistance of the bottom-mounted button will be the same as for the top-mounted buttons.

The ECMO 2/3 pointing devices will be mounted on the right and left consoles, as shown in figures A-4 and A-6. The mounting of the pointing on the consoles will make valuable space available on the pedestals for the data entry keyboards. Positioning on the right console will require the relocation of the laptop computer stowage bin to the center console. Although the laptop computer will no longer be necessary to operate the USQ-113, MATT, and IDM, the design requirements dictated by the customer called for the retention of the storage space and interface panel. Positioning on the left console will require a relocation of a data storage bin to the right console. Design specifications for the ECMO 2/3 pointing devices are shown in table 5.

Table 5: ECMO 2/3 POINTING DEVICE SPECIFICATIONS

Characteristic	Minimum Value	Maximum Value
Software Compatibility	Must be PS/2 Compatible	
Controller Resistance	15 ounces	20 ounces
Controller Diameter	0.75 inches	1.00 inches
Horizontal Handgrip Length	3 inches	4 inches
Horizontal Handgrip Diameter	1.0 inches	1.5 inches
Handgrip Vertical Clearance	2.5 inches	3.5 inches
Activation Button Resistance	15 ounces	20 ounces
Activation Button Diameter	0.5 inches	0.75 inches

ECMO 2/3 DATA ENTRY KEYBOARDS

Keyboard Display

A means for the ECMO to quickly and accurately enter alphanumeric data into the integrated weapons system is required during the execution of missions. Specifically, a means of entering data is required in the ICAP III aircraft for the ECMOs to interface efficiently with the IDM. The IDM is used by the ECMOs to pass and receive HARM targeting data and to pass free-text messages between aircraft. Future proposed uses call for integrating the IDM with other tactical data-links for the flow of battlefield information. The current contractor cockpit design omits a hardware data entry device and provides for a software-generated keypad displayed on the ECMO MFD to be used in conjunction with the pointing device. This form of data entry is inefficient and prone to mistakes. The data entry keyboard proposed by the author will allow for the timely and accurate input of data. Additionally, it provides a secondary controller to be used in conjunction with the pointing device or in place of a failed pointing device.

The mechanical pushbutton keyboard found in the Block 89A aircraft will be replaced by a PS/2 compatible touch-sensitive AMLCD display horizontally mounted in the ECMO pedestal positions, as shown in figure A-3. Instead of mechanical pushbutton keys, the keyboard will use software-generated keys displayed behind a protective glass covering over the AMLCD display. By using a software-generated keyboard layout, maximum flexibility will be maintained for future changes to the keyboard layout.

The keyboard display will be 4.75 inches wide by 5.75 inches tall (27.3 square inches) in order to take full advantage of the available area on the ECMO pedestals without intruding into the validated ejection envelope. Display power, operating mode, and brightness will be controlled by the pod status display control knobs. The proposed physical dimensions and required activation forces are specified within the requirements of MIL-STD-1472F. Square keys with sides of 0.5 inches separated by 0.2 inches will be displayed in green video on a black background. Activation of the keys will require 2.5 to 5.0 ounces of force, will be shown within 100 milliseconds by the key being displayed in inverse video, and the command will be executed when the ECMO's finger is retracted from the display. Infrared beams of a frequency greater than 880 nanometers will be used to establish the pre-programmed x/y display grid. This frequency is above the response cutoff wavelength of the Class B Type I NVGs The keyboard display design specifications are shown in table 6.

Table 6: KEYBOARD DISPLAY SPECIFICATIONS

Characteristic	Value
Software Compatibility	PS/2
Display Size	4.75 by 5.75 inches
Infrared Beam Frequency	>880 nanometers
Key Size	0.5 by 0.5 inches
Key Separation	0.2 inches
Required force for Activation	2.5 to 5.0 ounces
Key Activation Response	< 100 msec
Key Activation Indication	Inverse video

Layout Assumptions

ECMO 2 and ECMO 3 will interface with the ICAP III integrated weapons system through their individual pointing devices and data entry keyboards Due to the lack of space for a keyboard interface at the forward cockpit ECMO 1 position, the display software has been optimized such that the majority of actions can be accomplished via software and the pointing devices. In an effort to optimize the liveware-hardware, liveware-software, and hardware-software interfaces the following assumptions were developed and adopted during the development of the keyboard layout.

1. The primary liveware-software interface will be the ECMO 2/3 pointing devices for all tasks with the exception of alphanumeric character entry.
2. The keyboard will be the primary liveware-software interface for alphanumeric character entry. Alphanumeric character entry will be used when entering navigational and targeting waypoints, when composing data-link targeting messages, when composing data-link free-text messages, and to enter responsive radar and communications jamming parameters The average length of an alphanumeric entry will be less than 100 characters, based upon mission requirements.
3. Less than 25% of tasks performed by an ECMO will require alphanumeric character entry
4. The non-alphanumeric hard keys on the keyboard will be for functions that can be accessed via software but which accessing would result in excessive cursor movement. Excessive cursor movement will result in an increase in the time to complete a task.

5. All alphanumeric entries will be presented on the display in either a scratchpad form or in a specific data field prior to entry into the weapons system. Full editing capability will be needed for the scratchpad form. Entry will only occur after the operator selects a software-generated APPLY or ENTER button.
6 The most commonly used letters in the English language are the five vowels and D, H, N, T, and S (Dvorak, 1943). It is assumed that these letters will also be commonly used during messaging with the addition of W and E being frequently used for waypoint entries.

Keyboard Layout

Figure A-12 shows the keyboard layout developed using the assumptions previously listed, researched human factors issues, and the input of experienced ECMOs. The primary function of each key is indicated by the type centered on the key while the alphabetical lock function of each key is indicated by the type in the upper left corner. Any key showing only one character means the button has the same primary and alphabetical lock function. Pressing the ALPH LOCK key located in row 7 accesses the alphabetical lock functions. Pressing the button once enables the alphabetical character entry functions. Pressing the ALPH LOCK button a second time disables the alphabetical character entry functions and enables the primary functions The currently active function will be highlighted using an increased brightness on the keyboard display. When selected by the operator, only the currently active function will be represented by inverse video on the keyboard display.

Access to the eight main working pages and the four working windows will be accomplished using the six keys in row 1. The left to right layout matches the left to right layout of the corresponding keys on the software display. Since both functions are primary functions they will both be highlighted on the display. Pressing of the key once will access the page or window listed on the top of the key while pressing the key a second time will access the bottom function. Selection of any other key will reset the key to the top function. The software is designed such that the main working pages are displayed in the large center part of the ECMO MFD while the working windows are displayed in the bottom portion of the ECMO MFD. Only one working page and one working window can be accessed at a time The layout of a generic software display is shown in figure A-13.

The F1 through F9 keys in rows 2 and 3 will serve two separate primary functions depending on whether the ECMO is using the USQ-113 working page or is using one of the other main working pages. Due to the USQ-113 software being a re-host of separately developed software, it becomes the only working page available once selected. Rapid navigation between the separate software pages available on the USQ-113 software will be the primary functions of the F1 through F9 keys. By pressing these function keys, the operator can quickly access the separate pages without moving the cursor out of the working area to select the page and then back into the working area to select fields for data entry. If the ECMO is using one of the other main working pages, the F1 through F9 keys correspond to the software-generated function keys available at the bottom of the ECMO display.

The primary function of the other keys in rows 3, 4, 5, and 6 will serve varied purposes. Navigating within large blocks of text or moving around separate data fields will be done using the up, down, left, and right arrow keys. The keys will allow the operator to quickly move about and make changes prior to entry into the system. A SAE standard telephone-type layout will be used for the number keys. Familiarity with this layout should increase operator speed and decrease operator errors when making numerical entries. Text entries containing sentences and numerical entries using a decimal point will use the period key The CLEAR button will be used like a backspace button on a standard keyboard. Pressing the CLEAR button once will clear the last character entered on a scratchpad or in a data field. Repeated pressing of the CLEAR button will be required for deleting multiple characters. Activation of the SPACE button will enter a blank character into alphanumeric entries.

The alphabetical lock function will provide the capability for the ECMO to input alphabetical characters using the keys of rows 2, 3, 4, 5 and 6 Optimization of alphabetical character entry will dictate the key layout. The vowels and most commonly used consonants will be laid out in rows 3, 4, and 5 and weighted towards the right-hand side. This layout will allow the operators to complete most of their typing with the dominant hand and require minimal hand movement. The large circles present on the N, E, S, and W keys and their geographically oriented layout will highlight the keys' positions for ease of waypoint entry. Letters that are used infrequently will be located in rows 2 and 6.

The keys of row 7 have primary functions only. Rapid navigation through multiple data fields will be accomplished using the TAB key. Cycling through data fields that have six or less available options will be done using the CYCLE key. Expeditious closing of a window or data field will be possible using the ESC key. An explanation of the ALPH LOCK key function has been covered previously.

The keyboard layout described in the preceding paragraphs will allow for future growth in the system. As new capabilities are added to the weapons system, the requirements for keyboard use will grow. Many of the keys in the planned layout lack primary functions allowing for their future use. However, careful consideration must be taken to ensure that the implementation of primary functions does not require the operator to cycle frequently between the primary and alphabetical lock functions. The optimal design for reducing data entry error will be a keyboard that rarely uses the primary and alphabetical lock functions simultaneously.

COCKPIT LAYOUT CHANGES

Implementation of the weapons system hardware proposed by the author will result in some physical changes to the layout of the rear cockpit. As mentioned previously, the ICAP II Block 89A rear cockpit, shown in figures A-7 through A-10, is the baseline upon which all ICAP III modifications will be made. Physical modifications to the current support and mounting structures have been kept to a minimum in the proposal to reduce cost and to reduce the amount of time required to modify each aircraft into the ICAP III configuration Keeping the modification time as short as possible is important due to the limited numbers of EA-6B aircraft available to fulfill worldwide military commitments Several legacy controls for non-weapons system functions have also been carried forth into the ICAP III aircraft as another cost and time saving measure. Figures A-3 through A-6 show the ICAP III physical cockpit layout changes required to implement the weapons system hardware changes proposed by the author. Any control or display panels present in the ICAP II Block 89A cockpit but not shown in the ICAP III cockpit layout have been eliminated The functions the controls and displays fulfilled in the ICAP II aircraft are either no longer required due to weapons system changes or have been assumed by other hardware or software controls. Table 7 describes the cockpit layout changes required to implement the author's proposed design.

Table 7: COCKPIT LAYOUT CHANGES

Panel Name	Panel Location	Change Description	Panel Function
ECMO Pointing Device (2)	ECMO 2/3 consoles	Install new pointing device on ECMO 2/3 consoles instead of on pedestals Replaces ICAP II data and laptop computer storage areas	Provide interface with displays for ECMO 2/3
Receiver Audio Select	ECMO 2/3 consoles	Re-label VOR/ILS selector switch to WARN	Allow ECMOs to monitor voice warnings
EHSI (2)	ECMO 2/3 panels	Install EHSI at each position Replaces ICAP II receiver control panels Moves ARC-105 HF radio	Provide navigational SA
ECMO MFD (2)	ECMO 2/3 panels	Install an MFD at each position Replaces ICAP II digital display indicator (DDI)	Provide interface between ECMOs and the weapons system
Pod Status Display (2)	ECMO 2/3 panels	Install at each position Replaces ICAP II video scope	Provides visual display of jammer pod status
Data Entry Keyboard Display (2)	ECMO 2/3 panels	Install at each position Replaces ICAP II keyboard	Provide interface between ECMOs and the weapons system
Master Control Panel	Center panel	Modify to eliminate ICAP II specific functions Eliminate pod power meter Add TJSR audio control	Provide function control of TJSR power, CMC reset, TJSR audio, and master radiate
Crypto Load Panel	Center console	Install new eight-position panel in the same position as the ICAP II three-position panel	Provide crypto loading to all onboard systems
Laptop Computer Storage	Center console	Move from ECMO 2 console	Provide storage for laptop computer
Data Storage	ECMO 2 console	Move from ECMO 3 console	Provide storage for MRU card caddies

CHAPTER 5: CONCLUSIONS

The importance of the EA-6B aircraft and the tactical EW support that it provides to strike aircraft has grown over its thirty years of service to the U. S Navy and Marine Corps. Today, with the recent retirement of the U. S. Air Force EF-111A tactical EW aircraft, the role of the EA-6B as the Department of Defense's sole support jammer aircraft requires that it be updated to stay a potent force on the battlefield of the future. This requirement has been acknowledged and the ICAP III upgrade program was undertaken to develop an integrated weapons system capable of detecting, denying, and degrading the enemy's use of the electromagnetic spectrum. While the weapons systems upgrades of the ICAP III program represent a leap forward in capabilities, the maximum effectiveness of these increased capabilities will not be realized unless the system design optimizes the controls and displays that provide the interface between the operator and the weapons system

The rear cockpit system design currently being proposed does not optimize the interfaces between the operators and the weapons system Specifically, the author has identified six areas in which modifications or additions must be made if the system is to operate at its optimum level

Critical weapons systems alerts must not be allowed to go unnoticed by the ECMOs during active EA operations By relying on visual alerts only, the contractor's design creates a situation where critical alerts may be unnoticed during periods of high workload or when an outside-the-cockpit scan is required Inclusion of a voice warning system at the ECMO 2 and ECMO 3 positions will ensure that critical alerts will not go unnoticed during periods of high workload or when the ECMOs' visual channel is saturated.

The display area available for the presentation of weapons system information to the ECMOs must be as large as the available cockpit space will allow As the primary interface between the ECMO and the weapons system, large amounts of information will be present on the MFD. The available cockpit space not utilized in the contractor's design will limit the area available to present the information, resulting in an increased visual workload for the operator to obtain the information required to execute the mission. By increasing the size of the display to fill the available cockpit space, the information can be spatially separated for visual distinction

The operator workload required to monitor the status of the AN/ALQ-99 jammer pods in the current ICAP II aircraft is too high No changes to the monitoring procedure are proposed in the contractor's cockpit design. An automated system that simultaneously presents all of the pod status information to the operator, coupled with the previously mentioned voice warning system, would allow the ECMO to devote his primary attention to other mission tasks.

Navigational situational awareness in the rear cockpit is required for the successful execution of a mission. The failure of the contractor design to make the pilot's navigational information available to the rear cockpit results in poor situational awareness and increases the verbal workload required between cockpits. Inclusion of an EHSI repeater at the ECMO 2 and ECMO 3 positions would significantly enhance their navigational situational awareness, reduce inter-cockpit verbal workload, and increase crew coordination.

The pointing devices used in conjunction with the MFDs should be the same for both the front and rear cockpit. By not using identical devices, the contractor cockpit design increase the logistical requirements to support the aircraft and enforces negative habit transfer for the ECMOs that fly in both cockpits By using the same device and mounting it in the same relative position to the operator, only one part will need to be maintained in the supply system and the ECMOs will feel comfortable switching between crew positions.

Efficient and accurate entry of alphanumeric character entry into the weapons system is required during combat operations. Incomplete or inaccurate information may result in the employment of a HARM missile against an incorrect target or the failure to jam a threat emitter properly. The on-screen software-generated keyboard planned for by the contractor will be slow to use and prone to error. Installation of a keyboard in the ECMO pedestals will provide a means for the quick and accurate entry of alphanumeric information into the weapons system

The introduction of the ICAP III aircraft will be a dramatic leap forward in the world of tactical EW For the first time ever, a highly capable receiver system will be coupled with the combat-proven EA-6B jamming system, producing a "precision" jammer capable of locating, identifying, degrading, or destroying multiple radar and communication threats. If accepted by the designers of the ICAP III program, the proposed cockpit hardware and layout design recommended by the author will ensure that the maximum capabilities of the integrated weapons system are available when needed most.

CHAPTER 6: RECOMMENDATIONS

Based upon the research performed during the course of this thesis and the extensive personal EA-6B flight experience of the author, the cockpit layout changes proposed in Chapter 4 and summarized in table 7 are recommended for inclusion in the EA-6B ICAP III rear cockpit design. Specific recommendations are:

1. Install a synthesized weapons system voice warning system to provide aural alerts to the ECMO 2/3 crew stations in the event of jammer pod degradations during active Electronic Attack operations.
2. Install 8.5 inches wide by 11 inches tall (93.5 in^2) color-capable AMLCD Multifunction Displays at each of the ECMO 2/3 crew stations to provide for operator visual interaction with the weapons system.
3. Install 7.5 inches wide by 6.5 inches tall (48.75 square inches) color-capable AMLCD Pod Status Displays at each of the ECMO 2/3 crew stations to provide an automated real-time simultaneous status display of the ALQ-99 jammer pods.
4. Install 3.9 inches wide by 3.3 inches tall (12.87 square inches) Electronic Horizontal Situation Indicators repeaters at each of the ECMO 2/3 crew stations to assist in navigational situational awareness.

5. Install pointing devices on the ECMO 2/3 consoles that are identical to the pointing devices installed in the forward cockpit to provide for operator tactile interaction with the weapons system

6 Install 4.75 inches wide by 5.75 inches tall (27 3 square inches) touch-sensitive data entry keyboards on the ECMO 2/3 pedestals to serve as a primary alphanumeric entry device and secondary tactile interface with the weapons system.

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REFERENCES

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APPENDIX

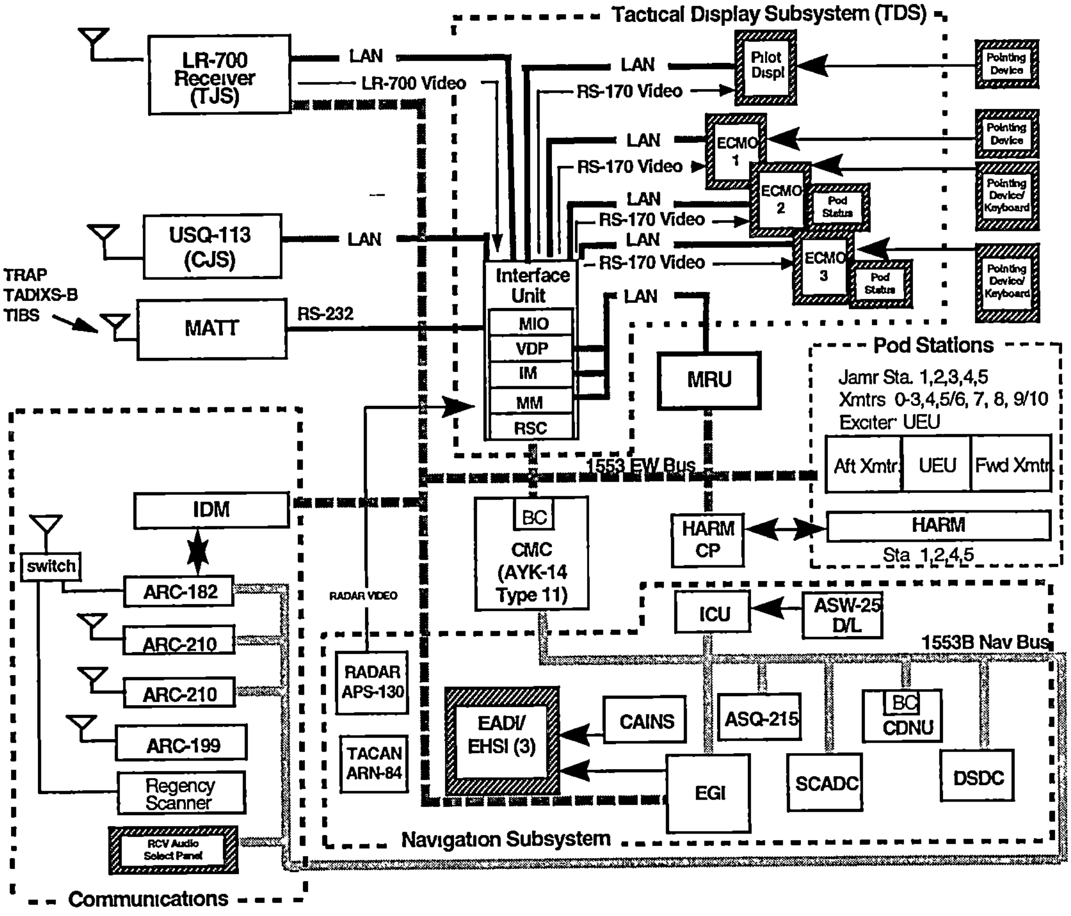


Figure A- 1: PROPOSED ICAP III IWS ARCHITECTURE

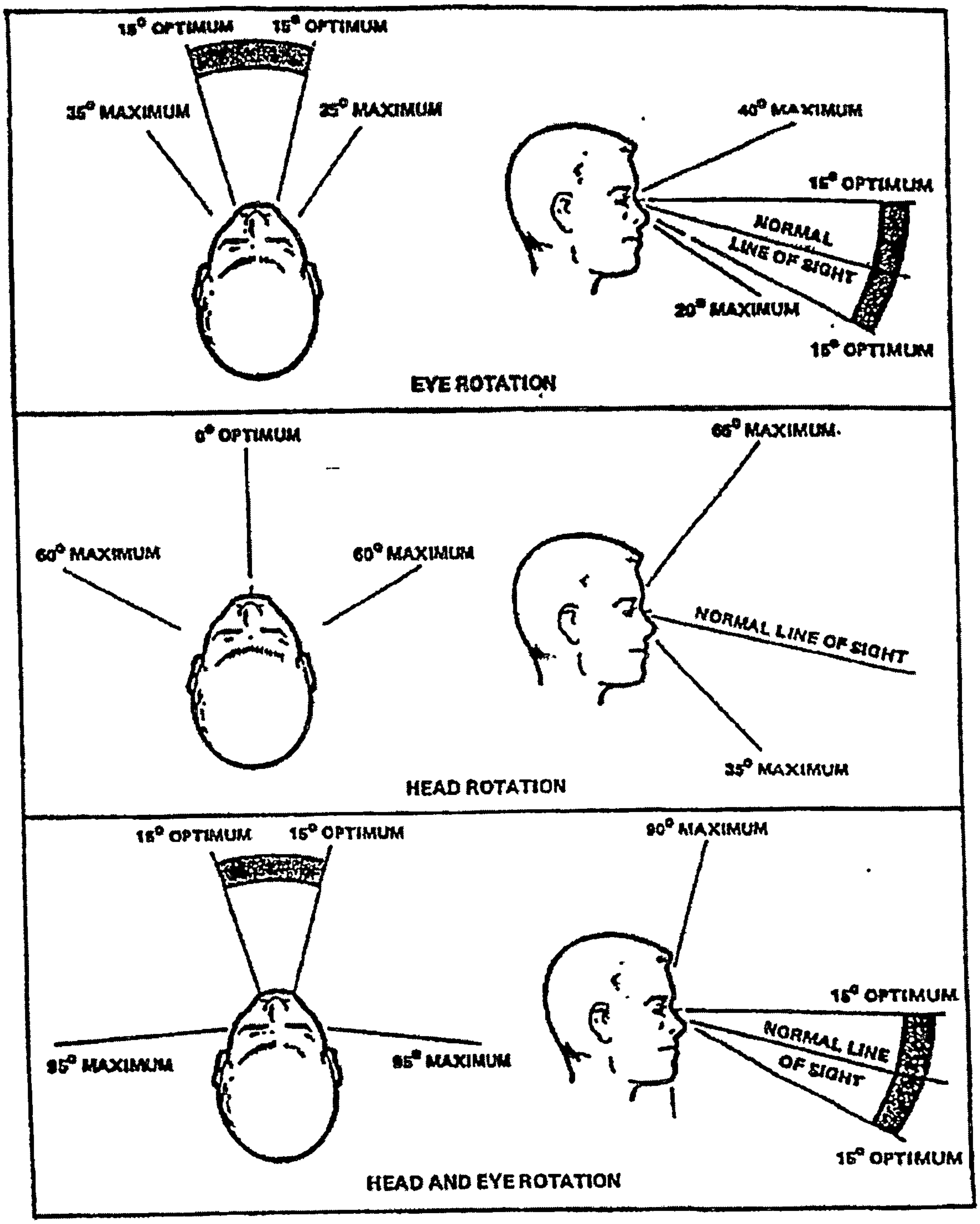


Figure A- 2: VERTICAL AND HORIZONTAL VISUAL FIELDS

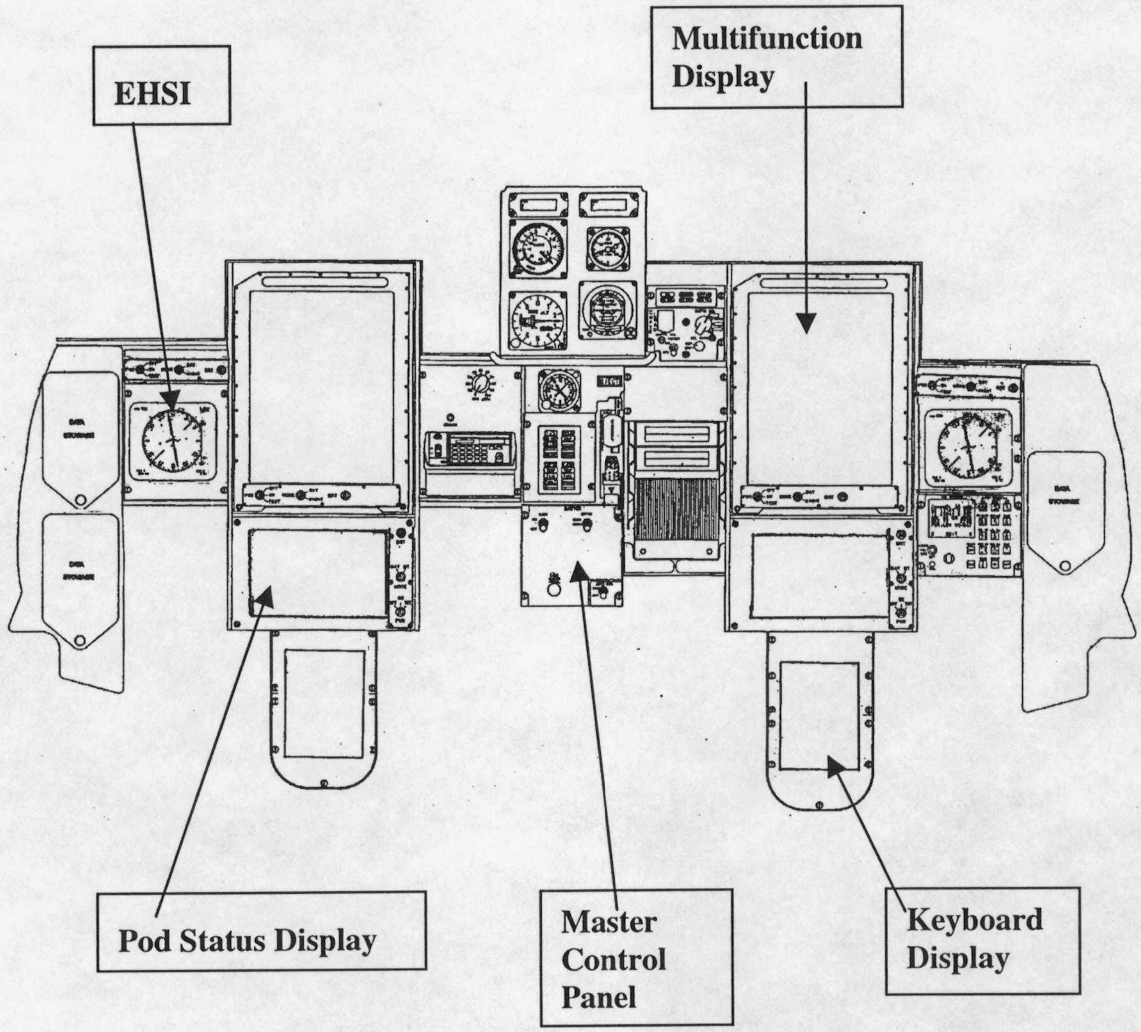


Figure A- 3: PROPOSED ICAP III ECMO 2/3 PANEL

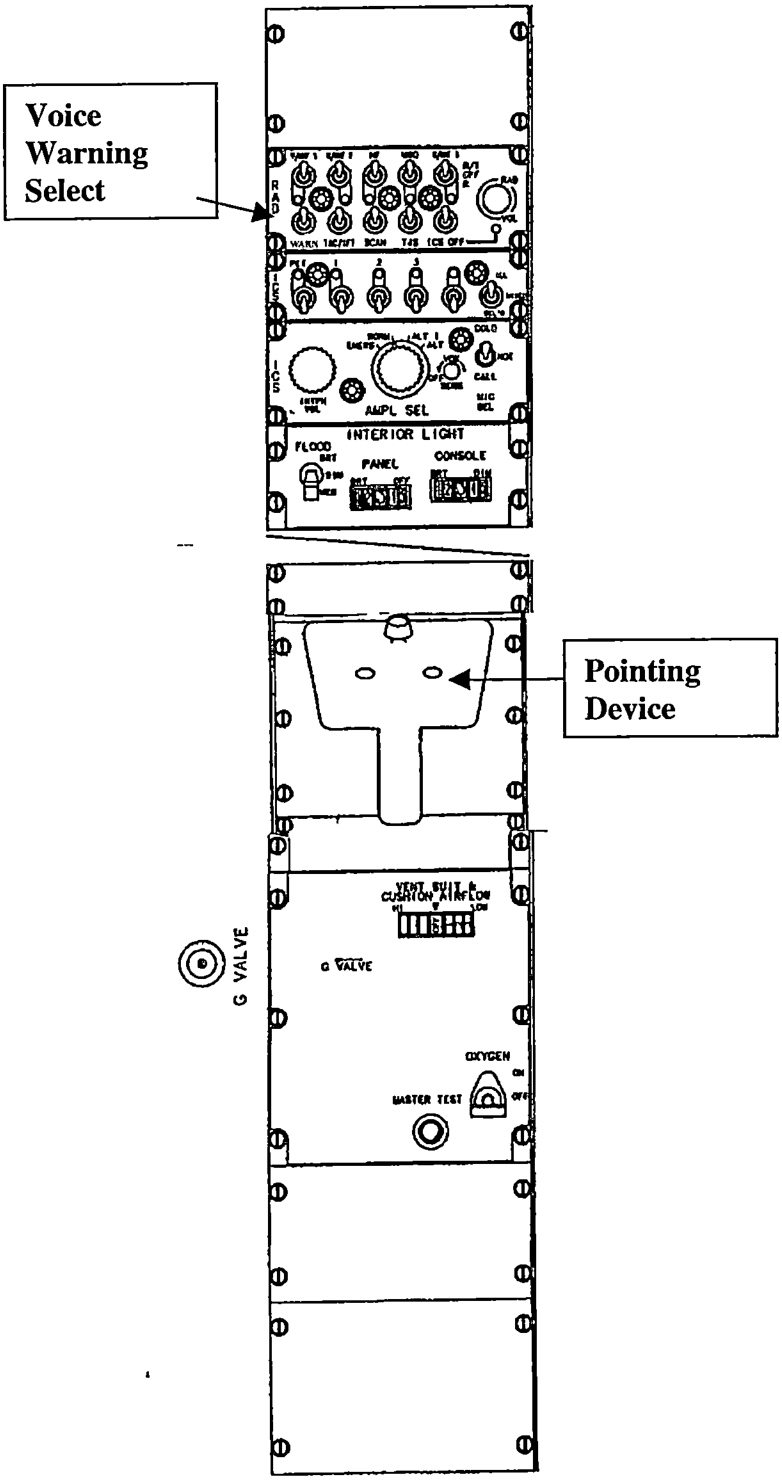


Figure A- 4: PROPOSED ICAP III ECMO 3 CONSOLE

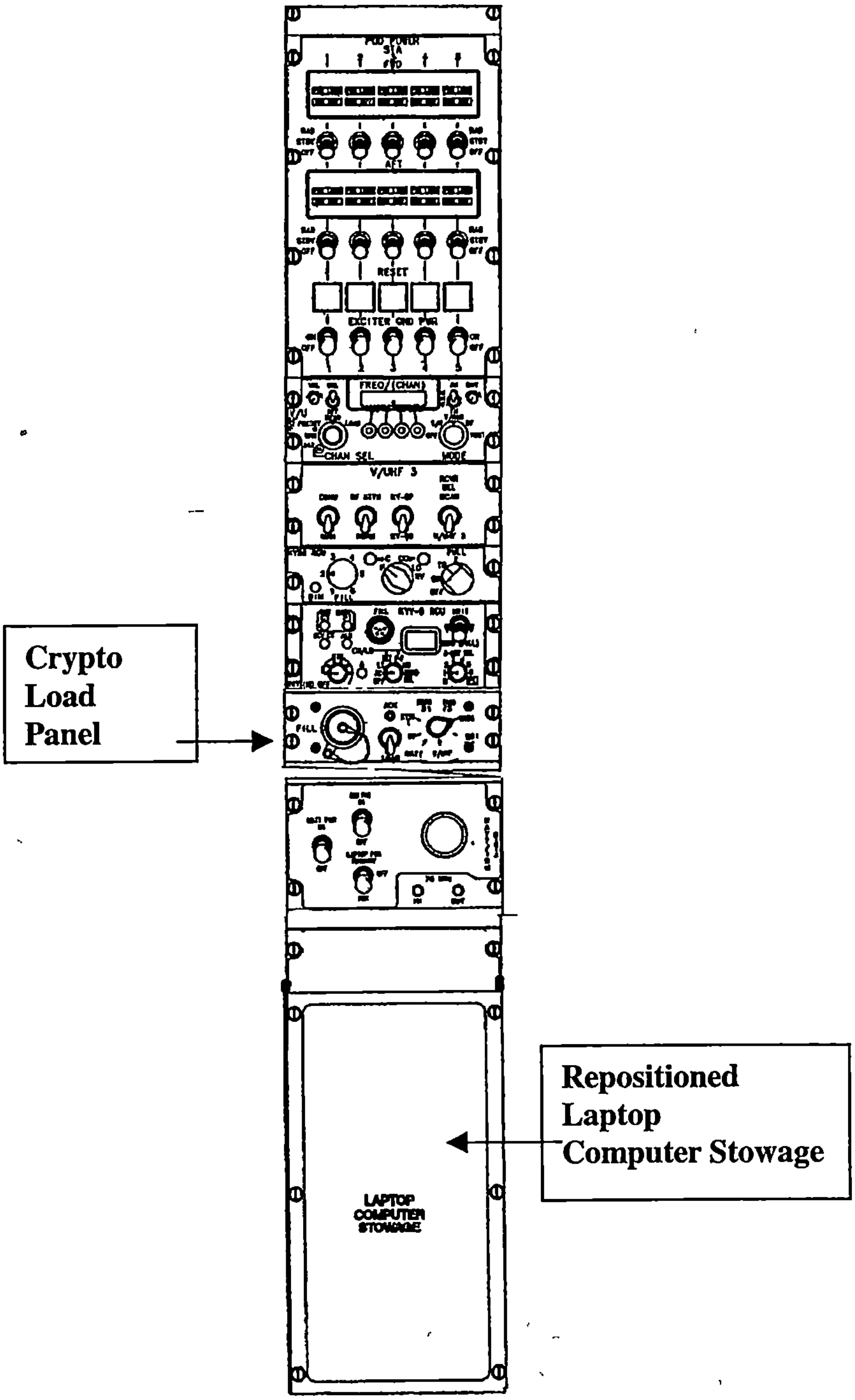


Figure A- 5: PROPOSED ICAP III REAR COCKPIT CENTER CONSOLE

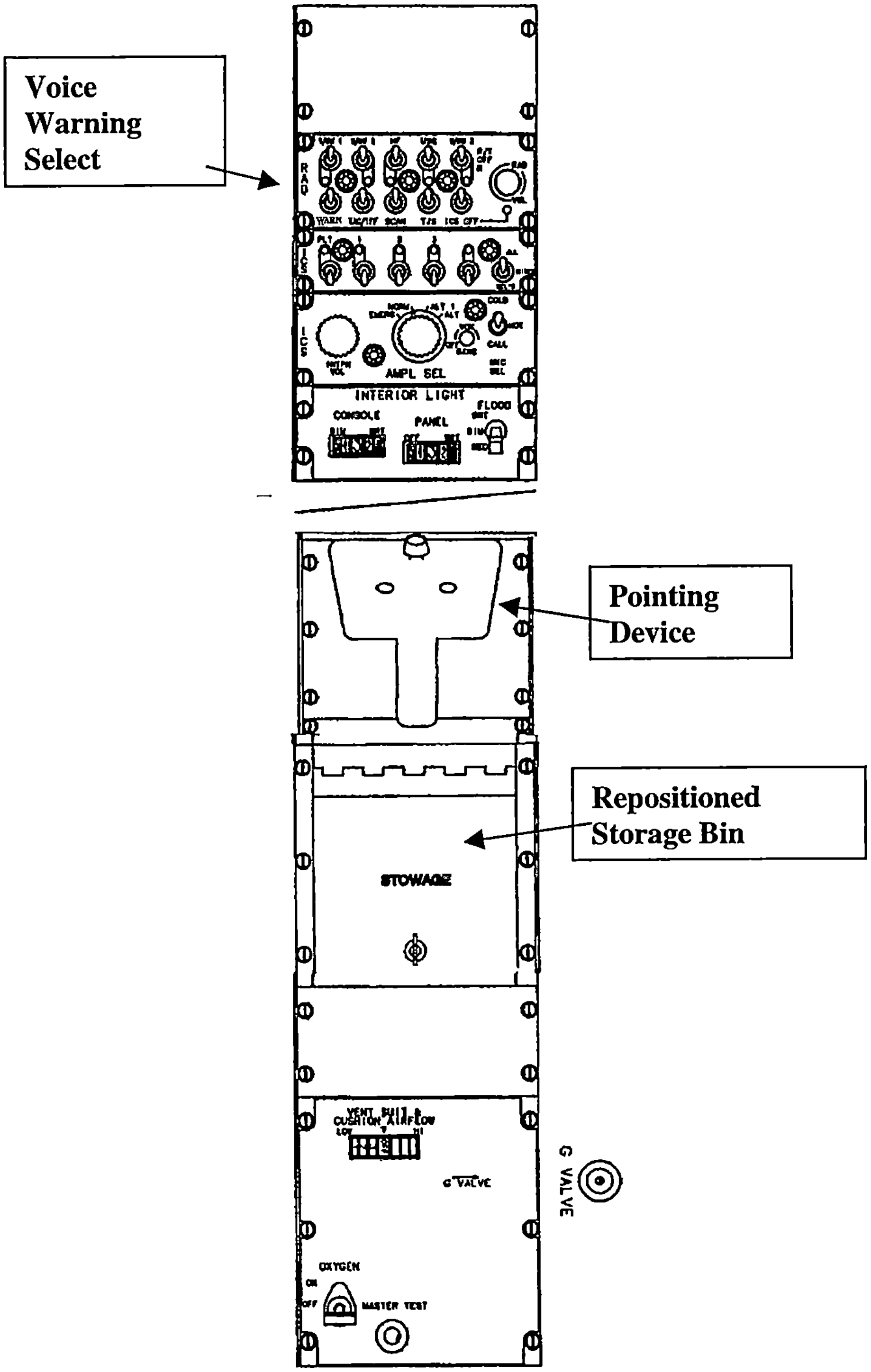


Figure A- 6: PROPOSED ICAP III ECMO 2 CONSOLE

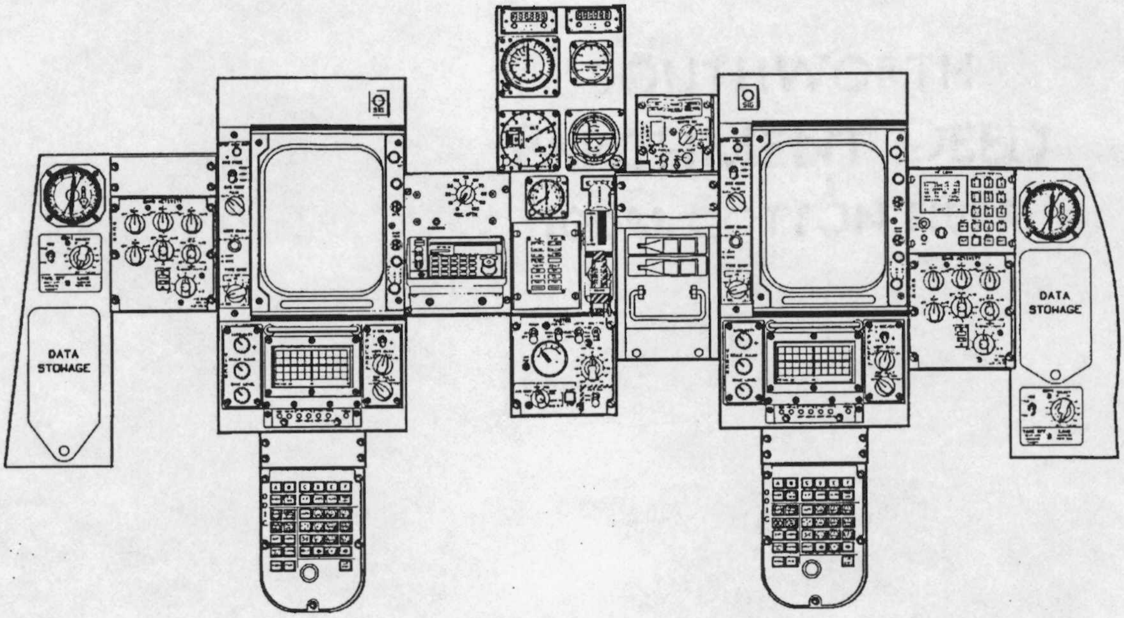
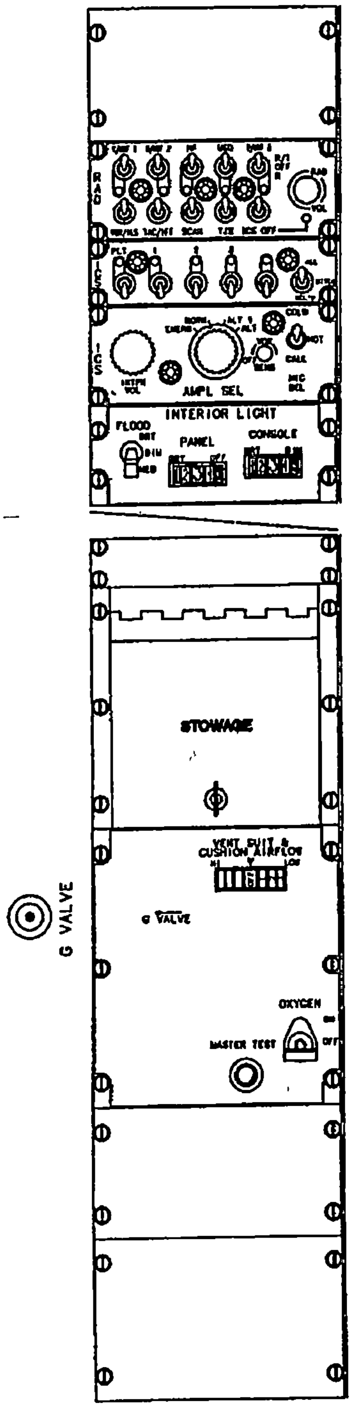


Figure A- 7: BLOCK 89A ECMO 2/3 PANEL



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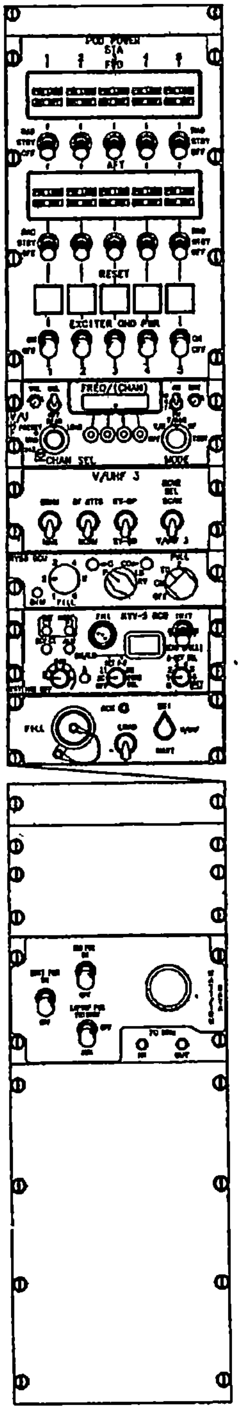

Figure A- 9: BLOCK 89A REAR COCKPIT CENTER CONSOLE

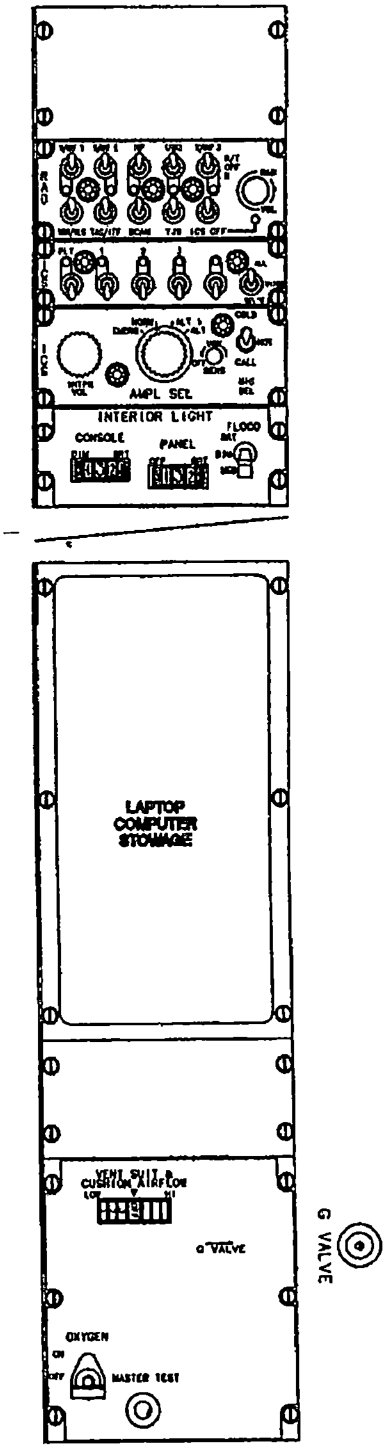

Figure A- 10: BLOCK 89A ECMO 2 CONSOLE

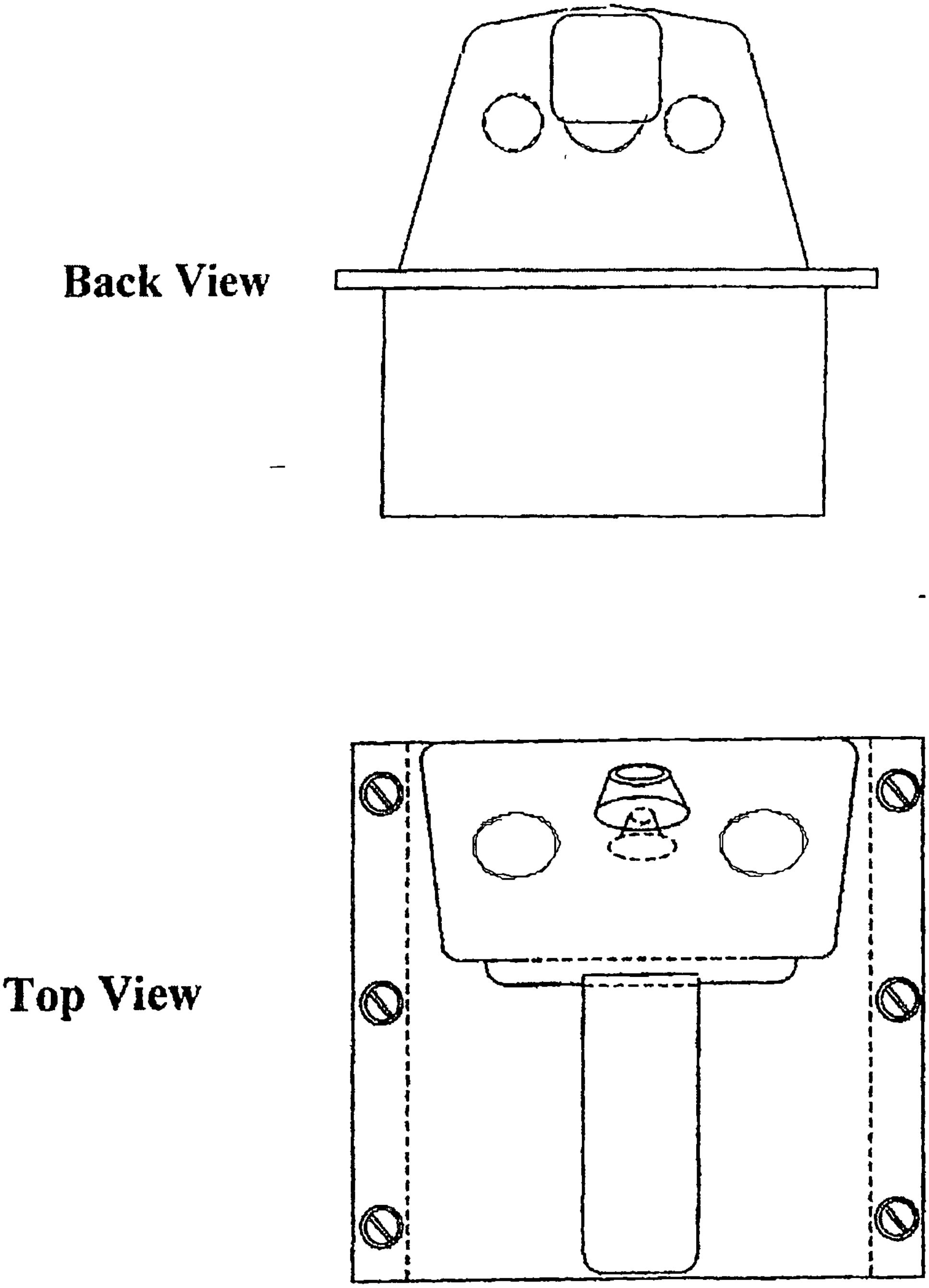

Figure A- 11: PROPOSED POINTING DEVICE

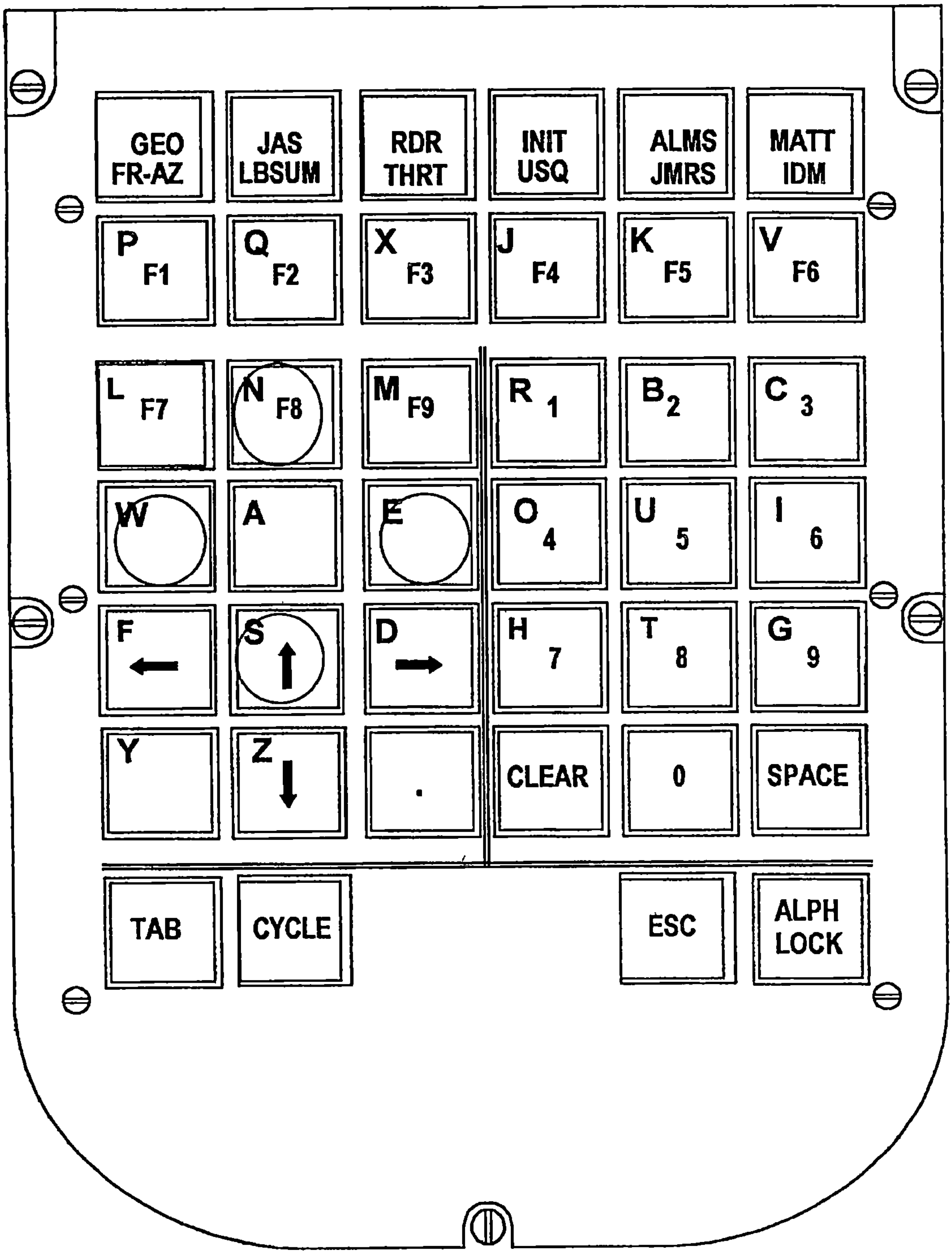

Figure A- 12: PROPOSED DATA ENTRY KEYBOARD LAYOUT

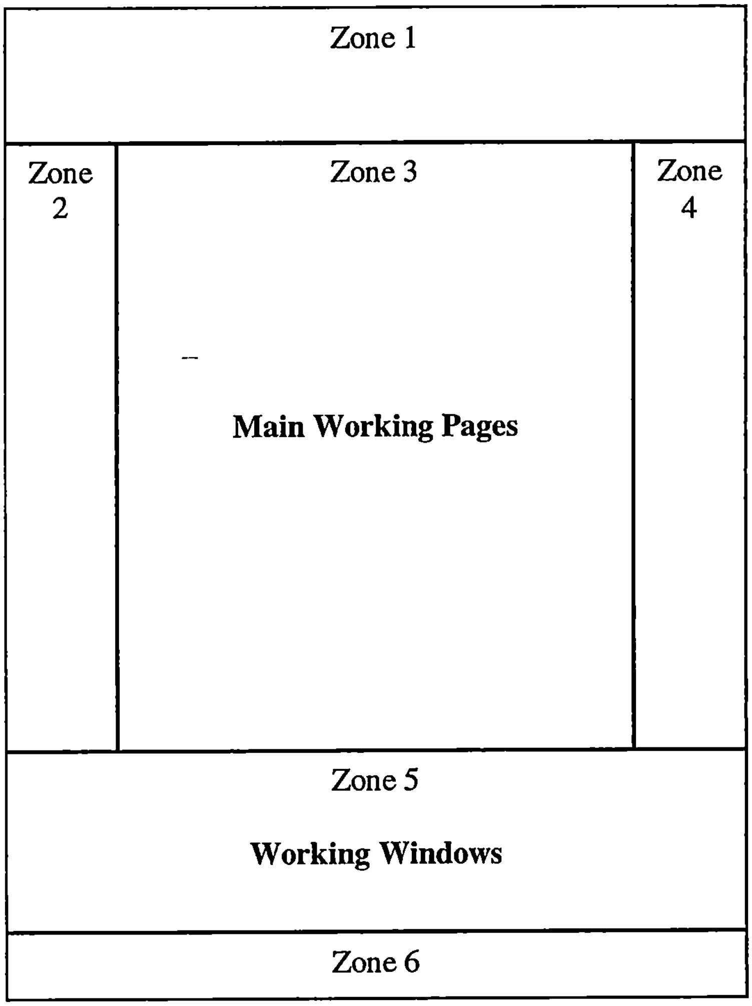

Figure A- 13: ICAP III GENERIC SOFTWARE DISPLAY

VITA

Thomas W. Hofer was born in Ames, Iowa on December 20, 1967. He grew up in Ames and graduated from Ames High School in May of 1986. He entered the United States Naval Academy at Annapolis, Maryland in July of 1986. He received his Bachelor of Science degree in Mathematics upon graduation in May of 1990, and was commissioned a Second Lieutenant in the United States Marine Corps. After initial Marine Corps ground officer training at Quantico, Virginia, he moved to Pensacola, Florida to begin flight training as a Student Naval Flight Officer. After receiving his wings in January of 1993, he was selected to be an Electronic Countermeasures Officer in the EA-6B Prowler community. After completing initial EA-6B training at Naval Air Station Whidbey Island, Washington, he served an operational tour at Marine Corps Air Station Cherry Point, North Carolina. During this tour, he deployed once to Marine Corps Air Station Iwakuni, Japan and twice to Aviano Air Base, Italy. In June of 1997, he reported to the U.S. Naval Test Pilot School at Patuxent River Naval Air Station, Maryland, and graduated with class 113 in June 1998. He currently is serving as an EA-6B Prowler developmental test project officer at the Naval Strike Aircraft Test Squadron in Patuxent River, Maryland.