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ARMSTRONG LABORATORY

PILOT-CENTRIC DESIGN METHODOLOGY AND CONCEPTS PROGRAM: TECHNICAL ANALYTICAL STUDY PROGRAM (U)

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JANUARY 1992

FINAL REPORT FOR THE PERIOD OCTOBER 1987 - NOVEMBER 1991

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FOR THE COMMANDER

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This report describes the work performed by MacAulay-Brown, Inc. (MacB) to support the Armstrong Aerospace Medical Research Laboratory (AAMRL) Pilot-Centric Design Methodology and Concepts (PDMC) Program. The PDMC Program was established to respond to the need for operator-centered crew stations. The conceptual development of virtual-world technologies, providing a spatial coupling to the visual, aural, and tactile senses, was emphasized during the program. This report details studies, analyses, simulations, and hardware/software prototype evaluations performed by MacB and various subcontracted personnel, in order to develop measurements and models of human performance in tactical and/or strategic environments. In addition, the report describes assessments of state-of-the-art human/machine (sub)systems relating to pilot-centered cockpit interfaces and various conceptual and hardware/software development efforts conducted within the PDMC program.

Auditory signals, cockpits, display, man-computer interface, performance, visual signals

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List of Abbreviations

2–D	Two–dimensional
3–D	Three–dimensional
AAMRL	Armstrong Aerospace Medical Research Laboratory
AIHS	Advanced Integrated Helmet System
AL	Auditory Localizer
ANOVA	Analysis of Variance
AOI	Acoustic Orientation Instrument
AS–HUD	All–Aspect Head–Up Display
ASE	Aircraft Survivability Equipment
AVCS	Audio Visually–Coupled Airborne Systems Simulator
AVL	Aviation Vision Laboratory
CCD	Charged Coupled Device
CDL	Color Display Laboratory
CLIN	Contract Line Item Number
CRT	Cathode Ray Tube
DADS	Data Reduction, Analysis, and Debrief System
DIRAD	Directional Audio Display
DMA	Defense Mapping Agency
EDB	Environment Data Base
EMD	Electromagnetic Deflection
ESFL	Electrostatic Focus Lens
FIP	Flight Instrument Package
FOV	Field of View
GRIN	Gradient Index
HMD	Helmet–Mounted Display
HMOF	Helmet–Mounted Oculometer Facility
HMI	Human–Machine Interface
HRTF	Head–Related Transfer Function
HUD	Head–Up Display
IDL	Interface Design Language
IHS	Integrated Helmet System
IPD	Interpupillary Distance

List of Abbreviations (cont)

KEMAR	Knowles Electronics Manikin for Acoustic Research
LH	Light Helicopter
LOS	Line of Sight
LOSA	Line–of–Sight Angle
LPCDC	Low–Power Consumption Dispenser Cathode
MacB	MacAulay–Brown, Inc.
MMI	Man–Machine Interface
MTF	Modulation Transfer Function
PDMC	Pilot–Centric Design Methodology and Concepts
RMS	Root Mean Square
SAT	Situational Awareness Technology System
SBIR	Small Business Innovative Research
SDB	Scenario Data Base
SOW	Statement of Work
SVU	System Verification Unit
TAC	Tactical Air Command
TDB	Type Data Base
TDLNS	Tactical Data Link Network Systems
USAFSAM	U.S. Air Force School of Aerospace Medicine
VCASS	Visually–Coupled Airborne Systems Simulator
VCS	Visually–Coupled Systems
VPD	Virtual Panoramic Display

1.0 INTRODUCTION

This report describes the work performed by MacAulay–Brown, Inc. (MacB) to support the Armstrong Aerospace Medical Research Laboratory (AAMRL) Pilot–Centric Design Methodology and Concepts (PDMC) Program. This report details studies, analyses, simulations, and hardware/software prototype evaluations performed by MacB and various subcontracted personnel, in order to develop measurements and models of human performance in tactical and/or strategic environments. In addition, the report describes assessments of state–of–the–art man/machine (sub)systems relating to pilot–centered cockpit interfaces and various conceptual and hardware/software development efforts conducted within the PDMC program.

The PDMC Program was established to respond to the need for operator–centered crew stations. The development of a sound theoretical and empirical basis for matching the perceptual, psychomotor, and cognitive characteristics of the pilot to the layout, displays, controls, and portrayal of information within the crew station was viewed as crucial. This matching implied the development of a synergistic pilot/aircraft system, for which the requirements for and packaging of controls and displayed information were determined on the basis of systems effectiveness criteria. The conceptual development of virtual–world technologies, providing a spatial coupling to the visual, aural, and tactile senses, was emphasized during the program.

The role of MacB was to provide an independent assessment of the various conceptual and hardware/software development efforts being conducted within the PDMC program, as well as the integration and application of the various PDMC program results. The products of the PDMC program include:

a. Emperically–based principles and methodologies for the management and measurement of virtual pilot/system information processes.

b. Virtual display concepts.

c. Pilot performance and information processing models that enable accurate predictions of pilot/system performance for the design and evaluation of virtual aircraft crew stations.

d. Human operator simulations.

e. The design and development of prototype virtual control/display hardware concepts.

f. The test/performance requirements for virtual cockpits containing visual, aural, and tactile interfaces, based on engineering tests and human operator simulations.

1.1 Background

Modern operational aircrews continue to be saturated with task workloads, despite the infusion of advanced technology. Aircrews face this workload because a large portion of the variance in system effectiveness depends on the operator's ability to acquire, process, and implement task–critical information. Human operators have a remarkable capacity for handling spatial information, as long as it is portrayed effectively, based on the nature of the sensory and perceptual processes of humans. Existing cockpits constrain the transfer of information from machines to human operators. Panel–mounted displays in the cockpit and limited field–of–view (FOV) head–up displays (HUDs) provide a two–dimensional (2–D) view into the three–dimensional (3–D) world in which the pilot must operate. Therefore, the pilot must search several displays in the cockpit to construct in his mind the overall 3–D combat situation.

In contrast to existing cockpits, a virtual cockpit can capitalize on the enormous human capacity to process visual and auditory information by presenting it in a natural 3–D way. A virtual cockpit would eliminate the need for conventional panel–mounted and head–up displays by projecting information directly into the pilot's eyes, using miniature components incorporated into the helmet. This approach allows a total spherical world to be generated for the pilot, so that information is conveyed in spatially relevant directions. A 3–D auditory display also conveys sound that contains directional information. Other monitoring devices incorporated into the headgear measure the instantaneous direction of the pilot's head and eyes. This, together with voice commands, facilitates the aiming of weapons and the selection of switches projected in virtual space. Since both the audio and visual interfaces use information projected into virtual space, the need for a myriad of instruments and controls in the cockpit is eliminated.

1.2 Scope

This document describes all of the AAMRL in–house and contractual efforts performed by MacB and subcontracted personnel toward establishing the technology base, empirical data, and applicable computer models required for the development of a virtual cockpit design technology. During the course of the PDMC Program, MacB provided on–site research support to several AAMRL in–house laboratory facilities, and task assignment support.

This report covers the contract activity from program inception in October 1987 through the completion of technical support in November 1991. Contract activity achievements for contract line item numbers (CLINs) 0001 and 0002 have been divided into two sections. Section 2.0 identifies technical and analytical support provided by MacB under CLIN 0001. This support consisted primarily of efforts performed at AAMRL. Task assignments for CLIN 0002 are described in Section 3.0. The CLIN 0002 tasks generally identify work performed by subcontractors and MacB management tasks.

2.0 AAMRL FACILITY SUPPORT EFFORTS (CLIN 0001)

This section describes the facility support efforts covered under CLIN 0001 and performed by MacB. The work performed includes technical data base development efforts and in-house AAMRL research support. The timing and tasking durations of these efforts are shown in Figure 2-1.

The technical data bases include the PDMC management support data base, Small Business Innovative Research (SBIR) data base, and Light Helicopter (LH) data bases. These data bases were developed to aid MacB's management and administration of the PDMC program, and to support AAMRL technical efforts.

The AAMRL facilities are made up of four laboratories. They are the:

a. Visually-Coupled Airborne Systems Simulator (VCASS).

b. Helmet-Mounted Oculometer Facility (HMOF).

c. Color Display Laboratory (CDL).

d. Aviation Vision Laboratory (AVL).

These laboratories are used to conduct human factors or theoretical visual perception research with human factors applications. The laboratories examine new cockpit/virtual display design concepts for implementation in future cockpits.

MacB provided human factors research support to the AAMRL research facilities. Support was focused primarily in the VCASS and HMOF laboratories. The laboratories and projects relating to the development of virtual display environments are depicted in Figure 2-2.

2.1 Technical Data Bases

2.1.1 PDMC Data Base

In accordance with Paragraph 4.1 in the Statement of Work (SOW), MacB initiated an effort early in the PDMC program to establish a data repository which would enable rapid retrieval of the large body of pertinent knowledge available in many diverse areas.

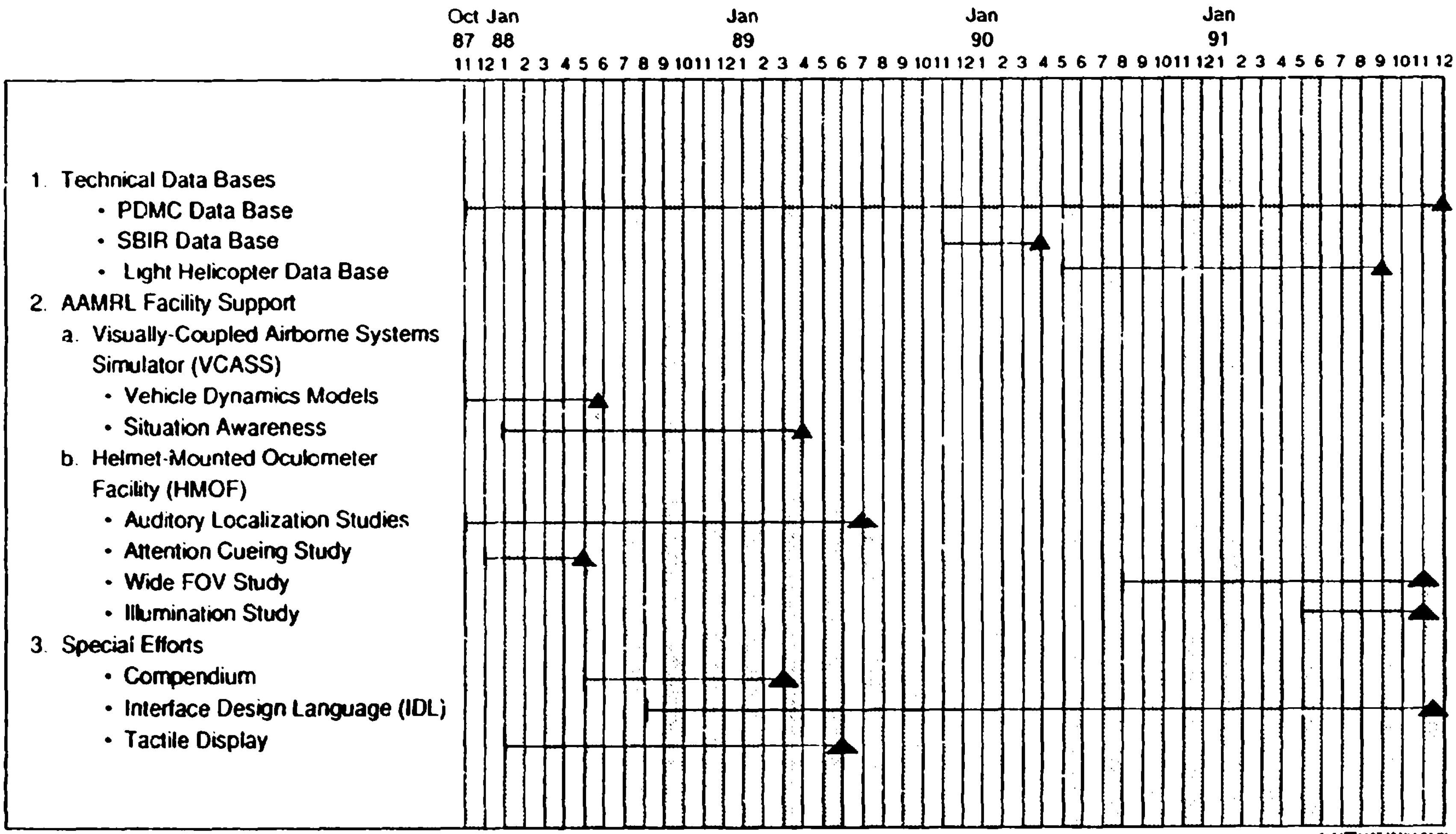

Figure 2-1. CLIN 0001 Support Efforts

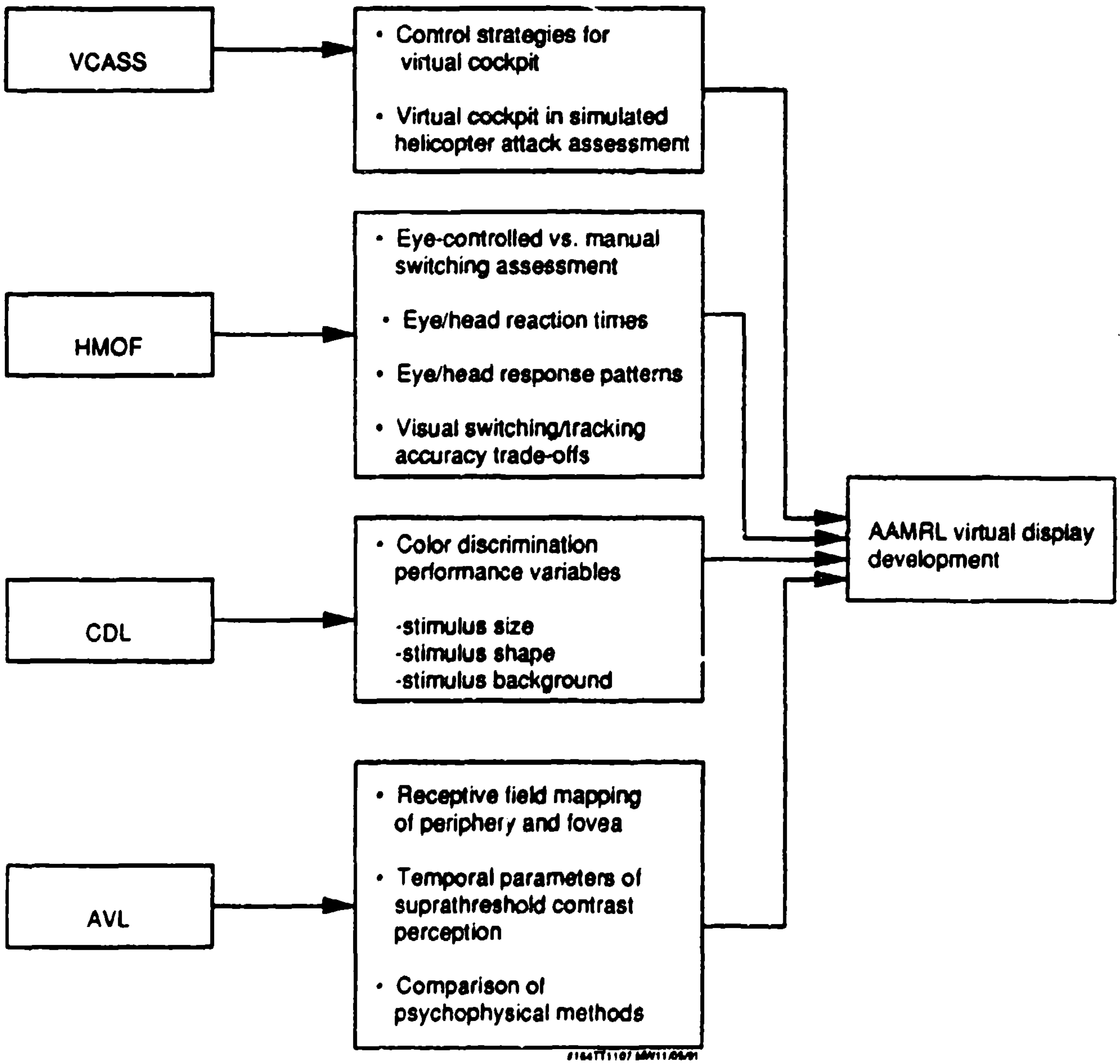

Figure 2-2. AAMRL Research Facility Virtual Display Support

A system was to be designed that would enable the data base to be hosted on a Digital Equipment Corporation VAX (MacIntosh and IBM—compatible computers serving as work stations) with Helix VMX, available through Odesta Corporation, as the supporting software package.

As a result of further scoping of the resources required to implement this data repository, it was determined that AAMRL did not currently have the funds available to begin the consolidation of technical data. Consequently, emphasis was shifted to establishing a management data base to support the PDMC Program Office. Data base formats for management reports, financial tracking, labor hour tracking, and property tracking were developed, tested, implemented, and updated.

2.1.2 SBIR Data Base

SBIR proposals are submitted each year to Wright Laboratory and to other Air Force laboratories. Several hundred proposals are submitted just after the calendar year begins. Each proposal must be recorded and tracked, a technical review team assigned, communications and coordination established, evaluations consolidated, funding decisions made, and announcements written. All through the process, schedules and deadlines must be assigned and maintained. This process puts a significant administrative load on the staffs of Wright Laboratory.

MacB was tasked to verify the process and implement a SBIR data base system to assist in managing the SBIR proposals and their evaluation process. The initial task was to assist the Avionics Directorate by developing a data base tracking system using DBASE III. As the resulting data base proved useful, the tasking was expanded to include the Propulsion, Flight Dynamics, Electronic Technology, and the Materials Laboratories.

The SBIR data base system tracks the SBIR proposals as they are received. It produces most of the form letters and status reports used throughout the proposal tracking process.

2.1.3 Light Helicopter (LH) Data Bases

During the fall of 1990, the U.S. Army was entering into the full–scale development and acquisition phase of the LH program. The LH is designed to provide Army Aviation with enhanced mission readiness and mission effectiveness beyond the capabilities of any helicopter currently flown. To accomplish this, the LH will incorporate the latest in aircraft technologies to provide superior performance capabilities for conducting armed reconnaissance, light attack, and support missions, while operating in a scout/attack role.

Under the PDMC program, MacB provided support for the Army's LH development program. The Army funded this effort to develop and deliver a SUPPRESSOR Simulation System data base for use during the LH source selection evaluation. The data base is used as input to the SUPPRESSOR simulation to define the scenario, the threat systems, terrain environment, and the LH. By exercising the SUPPRESSOR simulation, the data base will enable Army analysts to obtain insights into Aircraft Survivability Equipment (ASE) system impacts upon measures of mission effectiveness.

The goal of this effort was to guide the development of the SUPPRESSOR data base to ensure that it will accurately portray the LH aircraft and associated threat environment based on the most recent intelligence information. The data base delivered consisted of three individual data bases: the Type Data Base (TDB), Scenario Data Base (SDB), and Environment Data Base (EDB). The TDB contains descriptions of all communication systems, sensors, weapon systems, and platforms encompassed by the scenario. The SDB contains information characterizing the specific force laydown, planned flight paths, command and control hierarchies, communications networks, and areas of responsibility. The EDB consists of routines used to process the Defense Mapping Agency's (DMA) digital terrain elevation data.

The technical approach used is best viewed as a building block approach. The data base development started with the definition of a basic, working scenario, followed by enhancements in the area of tactics, mission objectives, and environmental influences. This approach permitted testing of the data base enhancements throughout the development cycle rather than just at completion. This resulted in more efficient testing of the data base, the avoidance of a lengthy test period at the end of the development phase, and the performance of parallel testing and information collection activities. In conjunction with a requirement for a consistent data base level of detail and format, this approach eased the burden of data base testing and debugging. The required consistency and building block approach enabled detection of data base errors early in the development cycle, and ensured that simil [illegible] were avoided in successive data base enhancement and modification efforts.

The technical approach, as realized through the completion of several individual tasks, allowed for the creation of the SUPPRESSOR data base in a timely and consistent manner in accordance with the development objectives. The result was the development of the TDB, SDB, and associated EDB for the portrayal of the LH aircraft by the SUPPRESSOR Simulation System. These data bases were used as an analytical tool to observe the influence of LH design parameters (vehicle signatures, ASE performance, and operational tactics) on the mission effectiveness of the LH in an armed reconnaissance mission.

A secondary result of this data base development is the existence of an intelligence source for future use. The data base, by itself, provides an excellent source for threat system hierarchy, command and control, and deployment projections, in addition to estimates of the performance capabilities of individual threat systems. The use of a source reference scheme throughout the data base provides the user with the identification of the intelligence source used in the specific system description. The user may then refer to the noted intelligence source for further details concerning the system of interest for verification or modification of the data base entry. Future studies involving the LH aircraft or the projected threat systems will benefit from the library of information contained in this SUPPRESSOR data base.

2.2 Visually—Coupled Airborne Systems Simulator (VCASS)

The VCASS facility is used to develop/integrate advanced hardware, software, and systems concepts for coupling a virtual panoramic display with aircraft systems. The ability to display 3—D information in real time during an airborne mission permits the exploration of 3—D display concepts not possible with other simulator systems. The VCASS virtual visual display is used for testing many of the new cockpit/crew station design innovations developed in the HMOF, CDL, or AVL facilities. VCASS provided a panoramic 3–D virtual display to investigate virtual cockpit concepts including head, eye, and voice control, as well as 3–D auditory presentation.

MacB support involved:

a. Improvement of the vehicle dynamics models which affect the tracking tasks used in the experiments.

b. Human factors support for several experiments examining situation awareness issues.

The following sections describe these two areas of support in more detail.

2.2.1 Vehicle Dynamics Models

Improvement of the vehicle dynamics models involved the F–15, the HH–60 helicopter, and the F–16 models. For the F–15, improvements included conversion to a generic model, and development of a new routine to transfer the proper initialization information from the console to the appropriate variables in the vehicle dynamics program. A speed brake function was added that allows the F–15 model to exhibit realistic flight through the stall. Further improvements included the addition of crash logic and ground dynamics.

Improvements to the HH–60 helicopter model included the conversion to a generic model form, the addition of crash logic, and the modification of ground dynamics to eliminate ground resonance. In addition, torque limiting was added to the model to prevent uncontrolled yaw motion in the hover mode. MacB devoted some effort to preparing the F–16 aerodynamic data for use in the generic simulation. A conversion routine was written to reorganize the linear data into 2–D and 3–D arrays.

2.2.2 Spatial Awareness

Both software and human factors support were provided for the Situation Awareness and Attitude Awareness studies conducted for the Spatial Awareness program performed in VCASS.

The software support provided for both studies involved developing block diagrams of all the software modules needed for each experiment as well as the requirements for each module. This effort also involved a coordination transformation based on quaternions to provide more realistic 3–axis motion in addition to 2–axis control and disturbance motions. Also, an algorithm to calculate the quaternion values for given Euler angles was developed to calculate proper initial conditions (unusual attitude) for the Attitude Awareness study. All software developed for this effort was checked out and revised, as necessary.

The human factors support for the experiments conducted in the Spatial Awareness program involved participation in experimental protocol development, data collection from subjects, and compilation of performance questionnaire data. This effort also involved software planning and preparation of performance data for computer analysis.

2.3 Helmet–Mounted Oculometer Facility (HMOF)

HMOF uses the Honeywell helmet–mounted oculometer system to study various eye/hand/head/voice integrated control techniques and multi–model attention cueing strategies. The research performed in HMOF includes eye/head tracking and visual switching studies.

MacB's support in HMOF involved two principal areas: auditory and visual research. The auditory research concerned the characterization and evaluation of 3–D auditory displays for integration into flight simulators and advanced crew station systems. The visual research addressed such issues as eye/head response measures as indicators of attention cue effectiveness, and the measurement of subject's eye gaze as a control interface for advanced crew station systems.

2.3.1 Auditory Research

MacB provided support for five auditory studies in HMOF. These studies involved characterization/evaluation of 3–D auditory displays.

2.3.1.1 Preliminary Evaluation of the Auditory Localizer AL–100

The objective of this study was to collect auditory localization data (horizontal plane targets only) with the AL–100, and to compare these data with that obtained in an earlier evaluation using a multiple–speaker configuration. The subjects' task was to point a hand–held sensor in the direction of the perceived sound stimulus. Head movement was permitted.

The AL–100 involves a single speaker presenting an audio signal, which is sensed by a Knowles Electronics Manikin for Acoustic Research (KEMAR) head (model of human head, torso, and outer ears), mounted on a servo–driven assembly enabling the KEMAR to be rotated 360 degrees in both azimuth and elevation. The entire system is contained within a 1.8 x 0.6 x 0.6 meter cabinet. Input signals are localized by changing the position of the manikin head relative to the speaker. Outputs of the microphones in the manikin's ear canals are amplified, and presented to the subject using stereophonic headphones.

In the multiple–speaker approach, the subject's head orientation is used to switch an audio signal among 36 speakers surrounding a KEMAR manikin in another room. The manikin head is fixed and the audio signal is transitioned in azimuth between speakers. Sound sources located between the speakers are simulated by simultaneously activating a pair of adjacent loud–speakers at reduced power. The audio signals are sensed by microphones in the manikin's ear canals, amplified, and presented to the subject using stereophonic headphones.

Similar results were obtained with the two different approaches for generating 3–D cues. There was little effect of azimuth on localization accuracy and performance improved over sessions. Root mean square (RMS) localization error with the AL–100 (3.4), however, was four degrees lower than that reported with the multiple–speaker configuration (7.4). These results could be attributed to either visual reference points (e.g., grid wall) being available for the subjects to correlate with the sound location in the AL–100 study, or to the fact that the response times in the AL–100 study were twice as long as in the multiple–speaker study, possibly reflecting a time/accuracy trade–off. The increased response time could also be related to the 30–Hz sampling rate of the AL–100, causing a delay in the time required to reposition the manikin head in response to the subject's head motion. This delay could increase the time required for the subject to "zero–out" the sound direction.

It was concluded that the AL–100 (single–speaker approach) is capable of generating 3–D aural cues that can be localized with good accuracy in the horizontal plane. Also, RMS localization error with the AL–100 was comparable to that found with the multiple–speaker configuration, thus providing a system without a large space requirement or the need to match frequency responses of multiple speakers.

2.3.1.2 Auditory Spatial Discrimination with 3–D Sound

The 3–D auditory presentation delivers to a listener, via headphones, audio signals that are perceived as originating from spatial locations outside the listener's head. One such presentation is the AL–100, which generates simulated 3–D signals by means of a single speaker and a movable manikin head with microphones placed in each ear canal.

The objective of this study was to evaluate localization performance at off–azimuth plane locations. Two tasks were used: a discrimination task to determine the spatial resolution of localization with the AL–100, and an absolute localization task to determine whether the correct location of the 3–D signals was perceived during the discrimination task.

Discrimination ability was measured by obtaining auditory discrimination thresholds using the method of constant stimuli in a two–alternative, forced–choice paradigm. The subject's task was to report "same" or "different" to indicate whether they perceived two successive audio signals as emanating from the same or different location. One signal originated from a target location, while the other originated from a comparison location displaced from the target in one of four directions and one of ten displacements (2 to 20 degrees) for each direction. Performance was summed across the four directions in calculating the threshold, defined as the displacement distance (degrees) at which subjects reported that the two signals (one from the target location, one from the comparison location) were in different locations for 75% of the trials. Thresholds were measured at eight target locations (azimuth, elevation in degrees): 45,25; –45,25; 45,–25; –45,–25; 135,25; --135,25; 135,–25; and –135,–25.

Results showed that auditory discrimination thresholds at the eight target locations ranged from 12 to 15 degrees, with significantly higher thresholds at the 45,25 and –45,25 target locations (top–front locations). Absolute localization accuracy was low (37% correct), especially for front targets. The higher thresholds in the top–front locations were due to decreased vertical discrimination ability, compared to horizontal discrimination.

It was concluded that the range of discrimination thresholds found in this study compared favorably to those found in studies with real sound, suggesting that the AL–100 delivers veridical localization cues at off–azimuth locations. There were two factors that may have influenced the discrimination pattern observed in the study (i.e., higher thresholds at the top–front target locations). One is the possible distortion of the acoustic signal inside the AL–100 cabinet; the other is the psychoacoustical effect of generating localization cues via the KEMAR manikin.

There are several possible reasons for the lower than expected performance on the absolute localization task. First, the subjects head motion was restricted during the discrimination task which could have limited performance. Second, subjects performed the absolute localization task using a small hand–held sphere which represented auditory space around them. They reported the perceived location of the signal by indicating the location on the sphere. Thus, they had to make a mental conversion from an "egocentric" perspective to a "God's eye–view" perspective, and some subjects may have been better at this than others. Last, the subjects appeared to be concentrating on the discrimination task more than on the absolute location of the signals.

2.3.1.3 Localization Performance with Two Auditory Cue Synthesizers

This study evaluated and compared auditory localization performance with two 3–D sound synthesizers, the Directional Audio Display (DIRAD) and the AL–204. A second objective was to compare interpolated versus non–interpolated targets generated by the AL–204 to determine whether interpolating between head–related transfer functions (HRTFs) results in decreased localization performance. The listeners' head movements were restricted in this study (fixed–head) and a verbal response method was employed (i.e., listeners provided angular estimates) to measure the listeners' perceived direction of the target stimulus.

Both the DIRAD and AL–204 synthesizers employ HRTFs recorded on a KEMAR in a free–field environment. These systems differ in the resolution of the measured HRTFs recorded along the azimuth plane (0 degrees elevation): one degree for the DIRAD and ten degrees for the AL–204. Thus, the AL–204 synthesizer contains 36 transfer functions per ear, one for each ten–degree increment, and employs interpolation routines to present sounds between ten–degree positions. In contrast, the DIRAD synthesizer contains 360 transfer functions per ear, one for each degree increment, and no interpolation routines are employed.

Results showed no significant differences in localization performance between the synthesizers for mean localization error, response times, or the number of front/back localization confusions. However, there was a significant interaction between synthesizer type and target sector, which indicates that localization performance differences did occur between the two synthesizers in certain areas of the azimuth plane.

In terms of target type within the AL–204, results indicated that interpolating between HRTFs did not result in increased mean localization error. In fact, in some sectors, subjects' mean localization error was lower when localizing interpolated targets compared to non–interpolated targets. However, interpolating between HRTFs did increase the number of front/back localization confusions. Thus, it was possible that employing algorithms to interpolate linearly between HRTFs may affect the localization indices in certain sectors of the azimuth plane.

It was concluded that additional research with different interpolating algorithms would help define the perceptual impact of interpolation on localization performance. If interpolation does not significantly affect localization performance, then there is little justification for devoting the additional resources required to measure HRTFs at every degree.

2.3.1.4 Evaluation of Two Methods for Measuring Auditory Localization Performance

The objective of this study was to examine localization performance with two response methods that subjects used to indicate the perceived direction of the auditory stimulus. The two methods were verbal response, in which subjects verbally reported the angular estimates of the perceived direction of the stimulus; and circle pointing, in which subjects estimated the perceived direction of the stimulus by pointing with a stylus pen to a position on a circle representing the azimuth plane surrounding them. In this study, the DIRAD synthesizer generated the localized stimulus, and subjects' head movement was restricted.

The mean localization error and response time obtained with each response method, circle pointing and verbal report estimate, were essentially the same. However, the percentage of front/back localization reversals was not. There appears to be no obvious explanation why significantly more reversals occurred with the verbal estimate method than with the circle pointing method.

The similar performance results can be attributed, in part, to the commonality of the procedures used with the two response methods. A circle diagram, marked with a line every degree and numbered every ten degrees, was placed on the response table in front of the subjects to assist in their angular estimate with the verbal response method. For the circle pointing method, a circle diagram marked and numbered at the 0, 90, 180 and 270 degree locations was used. Thus, each response method required the subject to complete a mental conversion by shifting from an "egocentric" perspective to a "God's eye-view" perspective while reporting the perceived direction of the sound. Perhaps if the subjects had not been provided the marked circle when using the verbal report method, greater differences between the methods may have been found due to errors in angular estimation.

It was concluded that both response methods were easy for the subjects to learn and employ. Additional research is needed to determine the best or most suitable method of indicating the direction of target sounds that vary in azimuth, as well as in elevation. The inherent error in the response methods should be investigated as well.

2.3.1.5 Evaluation of a Directional Audio Display Synthesizer

This study evaluated the effectiveness of the DIRAD synthesizer in providing auditory directional information in the azimuth plane. Performance was measured under two head–movement conditions: fixed–head (listeners' head movement was restricted to straight ahead, or the "0–degree" position, while determining the perceived direction of the target stimulus), and free–head (sound was repositioned, in real time, to provide a space–stabilized acoustical image); using four types of acoustic signals (wide–band pink noise, 4–kHz low–pass pink noise, 1–kHz tone, and recorded female speech).

Across all factors, mean magnitude error was 10 degrees, mean response time was 2.1 seconds, and mean percentage of reversals was 16.5. In terms of target location, the lowest localization error and fastest response times were found at side targets, with performance at the front and back targets exhibiting comparable, but less accurate and slower responses. The highest percentage of reversals occurred at the side targets.

The stimulus type significantly affected localization performance. The pink noise signal was localized with significantly greater accuracy than the 1–kHz pure tone. Also, significantly more front/back localization confusions occurred when localizing the pure tone compared to the pink noise and 4–kHz low–pass signals. In addition, the female speech signal required significantly longer time to localize than the other three stimuli.

In terms of the head–movement variable, localization performance generally improved when the subjects were free to move their heads. The mean localization error was lower in the free–head condition, although not significantly lower. The number of front/back localization confusions were significantly reduced in the free–head condition. However, the response times were significantly longer in the free–head condition.

This study demonstrated that auditory localization with synthesized directional audio can vary with the location of the target signal, the characteristics of that signal, and the listener's head movement. Such results can be used to determine how best to integrate a DIRAD synthesizer into flight simulators and operational cockpits. This may further enhance existing cockpit audio communication systems, as well as aid the pilot in target acquisition and situation awareness tasks.

2.3.2 Visual Research

MacB provided support for three visual studies in HMOF. The studies are detailed in the following paragraphs.

2.3.2.1 Eye and Head Responses as Indicators of Attention Cue Effectiveness

This study investigated whether eye and head reaction time can be used to evaluate the effectiveness of five methods of presenting attentional cues. Each cue directed the subjects' attention away from a central tracking task to one of four peripheral locations. The five cues were visual symbol, coded sound, speech cue, 3–D sound, and 3–D speech (speech signal given a directional quality by presenting it from peripheral locations).

The results for mean eye and head reaction time showed significant differences between all the cues, except for eye reaction time with the two speech cues. Also, eye and head reaction time showed similar trends across the four target locations and can be ordered, from fastest to slowest, as follows: right, left, up, and down. In addition, a significant interaction between target location and cue was found.

This study showed that both eye and head reaction time can serve as objective indicators of the effectiveness of candidate attention cues. Since these non–obtrusive measures were as sensitive to cue modality as Sternberg task completion time, the results suggest that such measures are not only valuable in the design of attention cueing systems, but also in overall cockpit design, since they may enable the detection of a pilot's awareness of rapid changes in information presentation.

The results also provide pertinent data on the effectiveness of candidate cue modalities. It was demonstrated that 3–D auditory signals can be effectively used as directional cues.

2.3.2.2 Wide Field of View (FOV) Study

The objective of this study is to compare eye control with head control in a dual–task paradigm. The central task involves maintaining level flight in the roll axis, and the peripheral task involves eliminating targets as they appear on the screen. In the peripheral task, subjects will use either eye control or head control (reticle on screen linked to helmet position) to select targets and weapons, and to position the weapon over the target to eliminate it. Both tasks will be presented on a wide 6 x 8 foot rear projection screen positioned in front of the HMOF cockpit. The primary goal of the study is to identify potential benefits/trade-offs between eye and head control in terms of speed, accuracy, and ease of performing these various operations.

MacB has provided support in accomplishing the following tasks in preparation for the Wide FOV study.

a. Experimental Procedure. The peripheral task was defined in terms of the number and size of targets to be presented, and the various specifics of the procedure, such as conveying to the subject that a target has been designated, or that a weapon has been selected. In addition, location and size/shape of the weapons were determined.

b. Target/Weapon Placement and Angles. Twelve targets and three weapons were presented simultaneously on the screen. A measure of the displacement between targets/weapons for each side of the screen showed some degree of asymmetry. Consequently, software manipulation was used to properly align these locations. Efforts were made to maintain a constant, yet comfortable, visual angle among the targets and weapons. The approximate horizontal and vertical visual angles for the targets are 1.5 degrees, while the weapons are approximately 1.5 degrees in the horizontal and 2.5 degrees in the vertical.

c. Identifying the Center of the Honeywell Dome Coordinate System. It is anticipated that knowledge of the dome center will not only provide a better understanding of the dome coordinate system geometry, but may also be useful in developing slewing algorithms for eye/head control applications.

   In summary, the approach to find the dome center involved locating a reference point on the screen such that a line drawn through this point perpendicular to the screen would pass through the dome's center in the cockpit. Once located, this reference point was then translated back to the cockpit to find the dome's origin. Additional measurements were then made from the dome center to the helmet transmitter, and from the helmet receiver to the helmet transmitter. These measurements provide a means for quickly identifying the dome center, and for validating the accuracy of Data General displacement data on which disclosure of the dome center was based.

d. Development of a Fixation Approach. The movement pattern during slewing of the eye-controlled cursor was characterized by large "jumps" off the intended path to the target, and also considerable jitter of the cursor when not being slewed. Thus, a new approach was developed in an attempt to reduce these problems. The approach involved basing the movement of the cursor on eye fixations rather than solely on raw eye data. Cursor control using the new approach demonstrated a more consistent and stable movement pattern on the screen. However, the accuracy of placing the cursor on the target was not improved.

e. Gate Radius Definition. Various gate radii were evaluated for the head–control mode. The gate radius defines how close to the target the helmet reticle must be positioned in order to select or designate it. The gate radii evaluated were 0.5, 0.75, 1.0, and 1.5 inches. In general, the selection and activation times were greatly inflated when the gate radius was 0.5. Conversely, these times were fastest at gate radius 1.5. The other two gate radii fell somewhere in between, as expected. Additional data will be collected before the final gate radius is selected.

2.3.2.3 Illumination Study

The objective of this study is to compare the tracking performance of two oculometers, the Honeywell (bright–pupil system) and the ISCAN (dark–pupil system), with the subject's eye exposed to various ambient illumination levels. Also, tracking performance with both systems will be evaluated with two types of ambient illumination: visible light (no infrared energy), and infrared energy only. Efforts completed on the first phase (evaluation of the Honeywell system with ambient visible light) are summarized below.

In preparation for the study, two pilot studies were conducted. The first was conducted to determine the illuminance levels for the experiment. Since the objective is to characterize system tracking response with different light levels, the range of illuminance levels should elicit a wide range of tracking performance. Specifically, the selected light levels should elicit tracking at the lowest level (baseline) and very little tracking at the highest level. The illuminance levels were generated via a monitor, and a luminance measure was used since a luminance meter was available. Illuminance measurements will be recorded prior to the study.

Initially, a range of luminances on a monitor was subjectively evaluated in terms of tracking (i.e., the experimenter watched the tracking of the eye displayed on another monitor). Tracking performance data was then collected with the Honeywell oculometer using this candidate range. The results showed that the percentage of data samples in which the Honeywell system tracked the eye ranged from 96 percent at level 1 (baseline) to 4 percent at level 4 (highest level). These data suggested that the levels would provide the desired wide range of tracking performance.

In the experiment, data will be collected in a transition phase, where the system's tracking is recorded during changes in illumination level; immediately followed by a fixation phase, where tracking is recorded while subjects fixate on squares presented on different locations of the monitor screen. In the fixation phase, the illumination level is constant.

The pupil diameter should be stable prior to the fixation stage, to avoid confounding a tracking change due to an effect of target location with a tracking change due to the pupil still being in transition in response to the change in illuminance in the previous transition phase. Thus, a second pilot study was conducted to determine the time required for the pupil diameter to stabilize following changes in luminance. The luminance levels from the first pilot study were used.

In-house subjects viewed a sequence of luminance levels presented on a monitor positioned in front of the cockpit. Each luminance level was viewed for three minutes. The video signal of the pupil was recorded from the charged coupled device (CCD) camera on videocassette and the pupil diameter was measured from the monitor during tape playback. It was concluded that the pupil diameter would have adequate time to stabilize in 60 seconds for a dark–to–light illumination transition, and in 90 seconds for a light–to–dark transition.

Following these two pilot studies and additional testing, data were collected from six subjects in three sessions each. Data analyses are currently being conducted and the next phase of the experiment is being planned.

2.4 Special Efforts

2.4.1 Compendium

The objective of this task was to review rejected (non–published) compendium entries and attempt to discern what types of information (e.g., insufficient methodologies) were missing. A data base containing certain parameters (e.g., titles, reviewer results, etc.) for each entry was created. Efforts for this task are summarized below.

MacB created a data–extraction form that contained the following compendium entry information: title, working number, publishing numbers, candidate entry listings information, and reviewer results. This form was completed for all published and unpublished compendium entries. Information from these data–extraction forms was used to create a data base. Data entry was completed, and a total of 1,866 files was created in the data base.

2.4.2 Interface Design Language (IDL)

Over the past several years AAMRL has been developing new technologies that can be used to enhance the coupling of the user with both system assets and an external environment containing the target problem. These technologies are known collectively as Virtual Technologies. Through the use of advanced imaging systems, computer graphics, and signal processing techniques, it is possible to create a panoramic 3–D synthetic environment in a manner that a person can interact with and perform actions in this "virtual environment." Interaction in the environment is made possible through head and hand position sensing and voice control systems. Virtual technology efforts, in the areas of 3–D continuous sound localization and 3–D tactile feedback, are directed toward extending the fidelity of this environment where it can be generated.

Virtual Technologies support the creation of a highly flexible medium for use in many applications as an interface between a systems environment and humans. For example, a perspective view of the external world can be displayed that depicts certain aspects of a problem situation (e.g., physical layout of threats, targets, planned route, etc.) as well as system states and the operational procedures a person must follow to deploy system assets during problem solution. Given the flexibility of the medium, including possible control mechanizations, anything that can be represented and stored in software code can be displayed or used to define the control mechanization. Thus, essentially any type of virtual environment can be generated which can provide information about a problem, the problem environment, and which supports multiple methods of user–interaction with the problem and system assets.

It should be clear that Virtual Technologies offer a wide range of possibilities for interface design but by themselves greatly underdetermine the form, content, and usability of the interface. Decisions must be made about what, where, when, and how, data should be portrayed; and when, why, and how data and system resources can be manipulated, etc. In short, the interface must be designed beyond simply specifying the availability of certain technologies that make available an interactive medium. Unfortunately, current approaches to interface design are inadequate during the early Conceptual Definition phase of development (Eggleston and Chechile, 1986; Chechile et al., 19889). The normal practice is to merely identify what technologies will be included in the interface. Almost all of the aspects of interface design are left to be completed much later in the Detail Design stage, after most system functionality and hardware decisions have been made, and interface options are highly constrained. Although flexible media like those offered by Virtual Technologies offer more degrees of design freedom during Detail Design, putting off the development of a well-formed interface concept until late in the development process still is not acceptable, since cost, schedule, and other pragmatic concerns at that stage force the designer to focus on making an interface work with little or no time available to consider broad conceptual design alternatives and other factors needed to adequately specify a point design interface concept.

The coupling of the Virtual Technology capability with functionality afforded by programs like the Pilot's Associate sets the stage for the possiblity of adaptive intelligent interfaces, providing the users of man–machine systems with the unprecedented flexibility and power. At the same time, however, these capabilities put additional pressure on the need for support of the design process, especially the user–system interface.

The IDL effort consisted of a series of efforts which represented a search through a variety of tools, processes, and approaches, for an appropriate set of methods and models sto support the design of intelligent interfaces. One characteristic of these interfaces is that they would be adaptive, that is, the interface itself could make appropriate, context dependent changes in its interaction with a human operator of a man–machine system.

No a–priori assumptions were made concerning the nature of the appropriateness of any methodolgy or model. This freedom led to the exploration of a number of approaches. While exploration of some individual methods may have led to dead–ends or proved unproductive, three important lessons were learned:

a. Linear design methods, i.e. those which proceed stepwise, with the completion of one step feeding into the initiation of another, tend to distort certain features of the design process such as the iterative nature of design.

b. Regardless of the approach taken, the structure of the job of the user returned time and again as a central theme.

c. In working with subject matter expertsd, we found that some are more useful in the knowledge acquisition phase of the design process than others.

The search for methods, principles, theoretical notions, and representational media that could be drawn upon for the formation of an integrated user–oriented framework for user–interface design concept exploration, analysis and decision making included:

a. Creating a language tool to support design;

b. reviewing of structural coupling from theoretical biology (Maturana and Varela, 1980, 1987) and Gibsonian notions from ecological psychology as a theoretical framework to support design of intelligent adaptive interfaces;

c. Creating a mobile office through a design effort;

d. Creating a model for an Adaptive Intelligent Interface;

e. Creating a model of job structure;

f. Generating Jobtool knowledge acquisition and analysis tools.

This was an initial exploratory effort, one that involved a considerable amount of conceptual and creative activity. When it appeared no longer fruitful to follow a particular line of inquiry, effort in that area was suspended until advances along other lines of inquiry suggested reasons for continued exploration. This "open–ended" and "free–flow" strategy encouraged the sampling of a wide and diverse variety of material and fostered creative problem solving. A negative consequence of this strategy was that suspended wotk that was not reactivated later effectively terminated without the production of a comprehensive interim report.

This summary presents a snapshot of all of the avenues explored in this effort. Paths receiving the largest attention, or developed most fully are given the widest coverage. While we cannot claim this work has produced a fully formed design framework and tool list, it has produced several valuable insights and novel ideas that should seed such a development. The interim documentation of the work consisted of a large collection of working documents, including working "thought" papers, concept papers, taxonomies , definitions, drawings of representations, etc.

Each of the following paragraphs cover one of the threads or activities that was pursued in the project.

The first activity, Interface Design Language, looked at language–based tools to support the design process. The purpose was to define a set of tools used to generate detailed design descriptions, and the tool set was to be useful over the complete development process. With this attempt at defining a tool set to support adaptive intelligent interface design, it became apparent that we had no theoretical basis from which to generate a consistent tools set. That led to the second activity, an exploration of existing interface design theory and/or work which could provide a beginning of such theory.

The second activity was undertaken to examine the current state of interface design theory. We took a step back from the problem of creating tools to support the design process to see if we could define a theoretical stance which would lend structure to our work. A literature review was conducted which provided us with some tentative constructs for a theory. A problem framing or definition tool was created using some concepts gleaned from the review, and several candidate architectures for adaptive intelligent interfaces were prepared. The problem framing tool and candidate architectures were prepared. The problem framing tool and candidate architectures were our methods for testing the viability of the fledgling theory. The problem framing tool, in particular, gave us additional insight into the influence of the structure of jobs on interface design. This interest in the structure of jobs led to the third activity, the mobile office design problem.

Activity three, the mobile office design problem, was undertaken with the thought that one way to understand the structure of jobs and their impact on interface design was to prosecute an actual design problem while maintaining as the primary goal an understanding of the design process. It was an attempt to represent the job structurally to determine whether and how affordances and effectivities would influence design decision making. This work clearly demonstrated the tangling of natural language analyses and explanations and pointed the way back to needed structure. We returned to an attempt to provide that structure in the fourth activity by working on an adaptive intelligent interface model.

The goal of the adaptive intelligent interface model activity (activity four) was to actually design an intelligent participant in the context of the support of pilot–pilot's associate communication. The model benefitted from language constructs gleaned from the literature search conducted in activity two and from emerging concepts concerning the influence of the structure of jobs on the design of interfaces. The focus on a cockpit application of our work on adaptive intelligent interfaces highlighted a need for additional, and much deeper, insight into the structure of the pilot's job.

Activity five, titled PNAMBC (PAY NO ATTENTION TO THE MAN BEHIND THE CURTAIN), was based on a series of interviews with pilots, in an attempt to understand the effects of context, aircraft state, and pilot state on expected adaptive behavior of the interface. A limited illustration was constructed for the adaptation of the interface for the fuel system only. Although the activity produced an interesting illustration, and the PNAMBC concept seemed to be well fitted to the task, it was still apparent that more insight into and understanding of the nature and structure of the job of pilots was needed before the design of an adaptive intelligent interface could begin.

The sixth and final activity of this series was designed to provide that insight and understanding. The Jobtool work was undertaken to provide a set of tools to be used with pilots to uncover not only the structure of knowledge (mental model) they possessed, but also to provide insight into the forces that shape the structure of the mental model in the first place. This was expected to give us an understanding of the ways in which we, as the designers of an adaptive intelligent interface, could influence the pilot/pilot vehicle interface interaction.

A number of these efforts have helped establish a baseline for understanding the requirements for and the development of tools to support the design of adaptive intelligent interfaces.

These individual efforts have examined language, model, theory, and tool approaches to provide structure and support to the design process. The chronological execution of these efforts is approximately in the order presented herein. In retrospect, this is reversed from the order in which the process would occur.

The Jobtool knowledge acquisition and analysis tools are now seen as the beginning rather than the end of the process. An integrated set of tools would require the further development of some of the issues addressed by the work under the present effort. For example, the designer would need a model of an adaptive intelligent interface as a structure in which to place the results of design efforts indicated by the design decisions required in an overall framework. This structure would also allow the evaluation of alternative designs in an overall framework.

The structure of the model of the adaptive intelligent interface would be determined in part by the design theory to which the process adhered (from the work on design theory), and in part on the descriptors used to identify job structure (from the mobile office interface design problem and PNAMBC).

This work constitutes a preliminary assembly of a tool set for the support of adaptive intelligent interfaces. Key lessons learned include:

a. Focus on the structure of the job as the binding tie from knowledge acquisition through conceptual and detailed design.

b. Provide for iteration/tradeoff analysis by embedding part–task designs in an overall framework or model to allow for the evaluation of design alternatives.

c. Use the simple action statement as the focus of the knowledge acquisition and analysis work with subject matter experts to clarify the Jobtool tools and techniques.

d. Gain a greater understanding of subject matter experts and their role in the process of the design of man–machine systems because subjects with prior experience in examining and expressing their expertise (teachers, book authors, etc.) will be of greater value with respect to input to the design process.

The key recommendation for further development of this tool set is fourfold:

a. Refine the Jobtool knowledge acquisition instructions with respect to focusing on simple action statements.

b. Reinspect the work structure categories in the Jobtool analysis to determine their acceptability.

c. Refine the model of the adaptive intelligent interface by careful consideration of the application of lessons learned in the present work and by reexamination of structural coupling—in light of the greater understanding gained by accomplishing the IDI tasks.

d. Utilize the refined tools to support a real crew system design effort.

2.4.3 Tactile Display

Under the Tactile Display program, MacB procured two experimental devices (the right and left data gloves manufactured by VPL Research), conducted a literature search, prepared a research plan, and began conducting experiments. In support of the Tactile Display program, a literature search was conducted and relevant articles were identified. Several articles on tactile pattern recognition were reviewed. These articles addressed paradigms in which subjects discriminated tactile patterns presented to the tip of the index finger via an array of vibrating pins. Several factors were shown to affect recognition, including display time of the pattern, and the mode of generating the tactile pattern.

A preliminary outline of a tactile display research plan was developed, focusing on two modes of tactile stimulation: pressure and vibration. This outline presented studies to be performed to evaluate pressure and vibrotactile stimulation, configured in a tactile stimulator glove as an information channel to the operator and to the virtual environment.

The VPL data gloves arrived in April 1988. The documentation accompanying the gloves was inadequate for easy system setup. VPL was consulted to ensure that the gloves were set up correctly. Simple testing of the equipment was performed to ensure that the systems were operational.

MacB developed a comprehensive research plan to investigate the data glove's capabilities. The plan consisted of a characterization of the accuracy and repeatability of the data glove on a human hand and a human factors assessment of its potential capabilities. An outline of a data glove evaluation plan (with visual feedback and integration into an Audio–Visually Coupled Simulator [AVCS]/VCASS), was included and approved with minor changes.

Pilot studies for experiment No. 1 were completed with some slight refinements to the procedure. Data were collected for the right hand using eight volunteer subjects; left hand data collection is currently in the planning stage. Data processing for analysis was begun using the Macintosh II. Independent variables were three hand–calibration positions and six orientation positions. The dependent variable was mean magnitude error, in degrees.

3.0 STUDY SUPPORT TASK ASSIGNMENTS (CLIN 0002)

Under the PDMC contract, MacB provided technical support covering such areas as: theoretical and analytical studies; development and application of diagnostic and measurement techniques; assessments of modeling activities and simulations; integration of test and simulation data; evaluation of new ideas, systems, and devices; and evaluation of prototype hardware/software products. The timing of individual tasks and their durations are provided in Figure 3–1. Summaries of these task efforts are described in the following sections.

3.1 Advanced Control/Display Concepts Tasks

This PDMC program was concerned with the development of innovative virtual control and display concepts for the presentation and portrayal of task–critical information in a workload–constrained environment. In support of this goal, MacB implemented conceptual studies and concepts for man/machine interface (MMI) designs provided by the PDMC office, and the hardware design and fabrication necessary to implement them. Emphasis was placed on conceptual development of virtual interface crew stations which enhance the spatial interface of pilots to advanced avionics subsystems.

3.1.1 Data Reduction/Analysis System for the Tactical Data Link Network System (Task 2)

AA' RL supports Tactical Air Command (TAC) requirements to demonstrate and evaluate the tactical utility of advanced control and display devices that increase a pilot's ability to acquire and maintain situation awareness, and offer increased weapon effectiveness in an increasingly complex mission environment. These control and display devices increase this ability by allowing the pilot to use natural psychomotor skills to communicate with and control his aircraft and environment. In support of a joint requirement from the Air National Guard, the Air Force Reserve, and TAC, this task was undertaken to evaluate the tactical utility and demonstrate the current performance of tactical data link network systems (TDLNS) in an operational environment.

The TDLNS is an avionics capability which allows the pilot of one aircraft to use information obtained from other aircraft. This sharing of information among cooperating

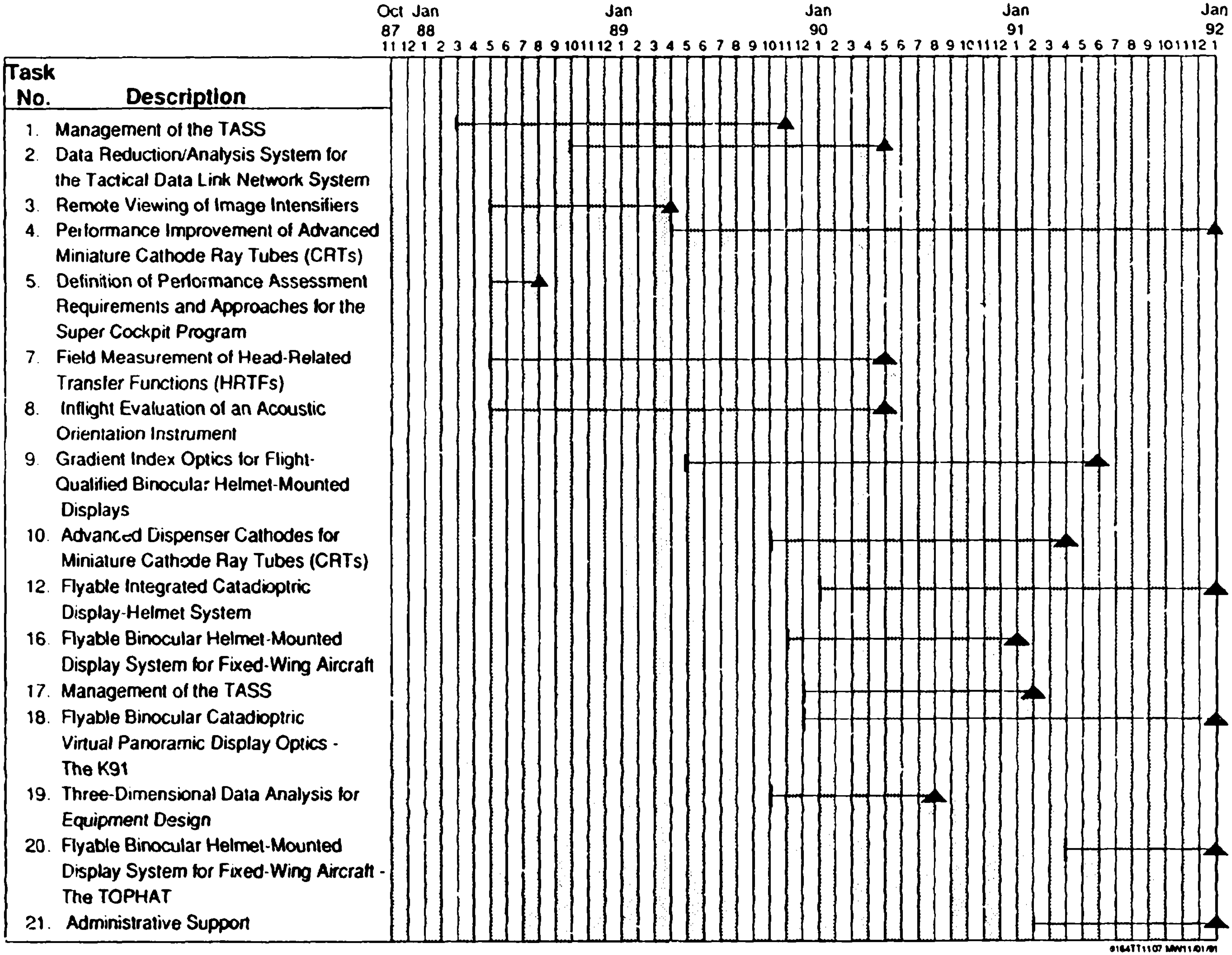

Figure 3-1. CLIN 0002 Tasking

M91-P401-1107-A

aircraft is essential to building improved situation awareness. Greater communication between aircraft through data channel transmissions and visual presentation increases lethality and survivability of each of the communicating aircraft by increasing the pilot's ability to coordinate their resources. This visual coupling of systems offered by the TDLNS provides a "closed–loop" control and display system with the human operator inserted into the "feedback loop". This MMI can be configured to provide many new capabilities, including visual control, hemispherical and/or space–stabilized virtual displays, and visual communications. It was the goal of this task to evaluate these functional capabilities and the performance of the TDLNS by developing a portable, stand–alone data reduction, analysis, and debrief system (DADS) to be used with the TDLNS.

This task was initiated in October 1988 and performed under subcontract to LTV/Sierra. The approach taken for the development of the DADS was based on analysis of the Sierra Situational Awareness Technology System (SAT), as the TDLNS being evaluated. The Sierra System Verification Unit (SVU) was used to generate test data and to provide flight paths for aircraft that would be equipped with SATs. The SVU also simulated the transmit and receive time delays between the SATs being tested. These time delays were used by the SAT to determine the relative position of each participant in the network.

The flight path data was perturbed to simulate inertial navigation data errors, transmission errors, and loss of the link. The perturbed data was then used as input to the SAT systems under test, which attempted to correct the data and generate the relative position of all participants in the net. The initial flight path data and the perturbed data were passed directly to the DADS. This corresponded to data available in the real world from some non–TDLNS, such as an instrumented range. The SAT solution data was recorded during the test and input to the DADS through a tape read system called a Raymond Tape Recorder. The solution data corresponded to the actual SAT data taken during test flights.

3.1.2 Remote Viewing of Image Intensifiers (Task 3)

Image intensifiers are electronic viewing devices that amplify dim ambient light reflected from objects and present these amplified images on a fluorescent screen. An image intensifier thus provides a means of multiplying the available reflected light so it can be seen by the human eye. Their primary application is in night vision devices to aid Army aviation. The technology used by image intensifiers to enhance night vision continues to be viable.

Image intensification, used alone or in conjunction with thermal imaging, provides adequate resolution acquisition during clear star–lit nights. Most current applications employ the image intensifier tubes in a direct–view mode in which the intensified image is presented directly to the eye through a series of magnifying optics. Newer applications and many future applications require the intensified image to be converted into a video signal and presented to the eye on an electro–optical display for remote viewing.

Past techniques employed to convert the direct–view image to a remote–view image were cumbersome and inefficient. One technique used a coherent fiber optic rope, with one end coupled to the intensifier and the other end mounted behind a magnifying lens in a remote viewing location. Another technique employed a television camera placed behind the direct–view intensifier and a television monitor plac[illegible] the remote viewing location. The intensifier's image quality was severely degraded [illegible] these conversion techniques, especially when the target and/or sensor were moving. One of the more recent approaches was to directly couple a CCD video camera directly to the image intensifier. However, this CCD/image intensifier approach produced a problem with image smearing.

This task was undertaken to investigate the capabilities and limitations of past and current techniques, and the viability of proposed techniques for remotely viewing intensified images. The capabilities and limitations were examined by conducting analyses, simulations, and evaluating prototype hardware. Additionally, a technical literature survey, technical data review, and a trade–off analysis were done in order to make recommendations regarding methods of coupling video imaging devices to image intensifier tubes used in visually–coupled systems (VCS).

The literature survey was conducted of past, current, and proposed techniques of remote–viewing image–intensified tubes and systems. The literature review was limited to primarily "open" literature. Unfortunately, most product manufacturers were unwilling to share their latest work, considering the competition in state–of–the–art technology. A detailed discussion of the design and/or analysis of the electro–optical imaging characteristics of specific system applications has not been adequately addressed in the open literature. Consequently, only the rather general information at the system level was obtained.

Findings indicated that previously used methods for remote viewing of image intensifiers, such as fiber optics and television interfacing, were very inefficient and tended to negatively affect image quality both for the static and dynamic image cases. A new technique for interfacing, perhaps one which integrates the image degradation interface directly into the intensifier sensor, will prove more viable for future systems.

3.1.3 Performance Improvement of Advanced Miniature Cathode Ray Tubes (Task 4)

Advances in miniature monochrome cathode ray tubes (CRTs) have demonstrated peak line widths on the order of 0.75 mils (19 microns), with a peak line brightness of 4000 foot–Lamberts. These improvements reflect a 70 percent improvement in brightness and a greater than 45 percent reduction in line width, over an earlier state–of–the–art helmet–mounted CRT (Type H–1380), operating at essentially the same drive conditions.

To bring about substantial performance gains in the CRT during the virtual panoramic display (VPD), helmet–mounted display (HMD) effort, an attempt was made through a number of studies to identify major problem areas, where improvements were needed. Improvements in miniature CRT performance were needed to address major performance–limiting problem areas, including CRT faceplate systems, electron optics, power voltages, and size considerations.

Improvements had to be made in the context of the design limitations imposed, by the electromagnetic deflection (EMD)/electrostatic focus lens (ESFL) system, which was found to be most suitable for miniature CRT applications. The overall resolution, for a given luminance level, is equal to the vector sum (square root of the sum of the squares) of the individual factors contributing to CRT spot size. For the VPD effort, the major design emphasis focused on maximizing the CRT's final anode potential, while remaining within safe operating limits; investigating the effects of increasing the G_2 voltage and G_1 cutoff; maximizing the effective cross–sectional area of the focus lens; improving deflection yoke characteristics; and optimizing phosphor grain size/composition/deposition techniques.

Raising the final anode potential effectively provided more luminance for the same beam current. Utilization of a lower–current, higher–voltage operating mode meant that, for particle phosphor screens, longer phosphor life was achieved. Also, at 12 kilovolts or more, space charge spreading effects became negligible for the beam currents and beam travel distances found in miniature CRTs. However, the higher anode potentials meant a stiffer beam for the magnetic deflection yokes to steer. Therefore, new higher–current, low–inductance/low–capacitance deflection yokes were designed. These new yokes were designed to run cooler at higher currents and are supported by appropriate, highly linear deflection electronics circuitry, that can support the high video line rates, often needed for VPD applications.

Maximum focus lens diameters and gun limiting apertures have been successfully implemented in an integrated CRT design. These improvements, coupled with shaped faceplates, the implementation of dynamic focus correction into the CRT drive electronics, and slight lengthening of the CRT so that the deflection yoke assembly does not overlap the focus lens element, have effectively reduced aberrational/astigmatism contributions to about 10 to 15 percent of the total spot size. This may represent a practical limit to a reduction of their contribution to spot size, and left only the first order contributions and phosphor screen effects, where further reductions might be obtained.

Improvements were previously realized by the use of a fine grain P53 phosphor and state–of–the–art electron optics, within the physical confines of the miniature tube specifications. To achieve the goal of 15–micron spot size with greater brightness, on the order of 5000 foot–Lamberts or more, becomes increasingly difficult. All the contributing functions within the confined physical limits have been improved and are approaching negligible values. The only major areas that are open to mprove the line width, luminance, and contrast (gray scales) are:

a. Reducing the G1 aperture and developing cathodes which can support increased current loading requirements.

b. Increasing the phosphor screen efficiency.

c. Enhancing the fiber optics by intagliation.

d. Using optical coatings.

Also, the improvements, that are achieved, must be able to be fabricated in reliable/reproducible packages that are qualified for operation in military environments. This requires the implementation of a modest qualification program and the documentation of manufacturing considerations, which must be considered to ensure that future miniature CRTs, exhibiting the same performance characteristics, can be procured with reasonable cost and lead times.

The tasking of this effort was initiated to provide the analytical, design, fabrication, and process engineering necessary to evolve miniature CRTs for operational use in monocular and binocular HMD systems. The task goals were the improvement of two separate image source systems. One was designed to emphasize vector graphic applications, where line widths may be somewhat larger, but whose gun design permits them to be operated at relatively large excursions of beam current, with minimal impact on line width. The other image source system was designed to emphasize high line rate, raster video applications, where smaller line widths, at somewhat reduced luminance levels, are needed.

3.1.4 Inflight Evaluation of an Acoustic Orientation Instrument (Task 8)

As modern aircraft have become more complicated, filled with sophisticated avionics, the capacity required to obtain and process data has become phenomenal. Experience has shown that there is much more information available and presented visually to the pilot than he may necessarily need or can handle. Thus, pilots are complaining of being saturated and overly task-loaded with visual information. When the workload in the cockpit becomes more demanding, the time that can be spent with the head down to gather attitude information becomes shorter. Since the visual channel capacity is already at or near its maximum, it may be possible to exploit the auditory channel as a means to unobtrusively convey vital aircraft attitude information to the pilot.

Researchers at the United States Air Force School of Aerospace Medicine (USAFSAM) have worked on the development of an acoustic orientation device that would, by changing various characteristics of the audio signal, convey aircraft attitude information. The first prototype had been designed and built. Preliminary examination of the device indicated that a second generation instrument was necessary.

The objective of this effort was to design and build a second generation Acoustic Orientation Instrument (AOI). This instrument encodes flight parameters (airspeed, angle of attack, vertical velocity, and heading deviation) by variations in an acoustic signal. A rigorous flight test evaluation of this device was undertaken to test its effectiveness in delivering continuous ambient auditory orientation information. In addition to the AOI, a Flight Instrument Package (FIP) was developed to acquire and format aircraft state data and transmit it to the AOI.

The Flight Instrument Package (FIP) was designed to translate inflight motion into digital and analog signals that can be used by the AOI. The sensor and data processing package provides real–time data corresponding to aircraft speed, altitude, vertical velocity, bank angle, pitch angle, heading, and angle of attack. Both digital RS–232 data and processed analog signals are available to the user.

The AOI and FIP were delivered to the USAFSAM in March 1990.

3.1.5 Gradient Index Optics for Flight–Qualified Binocular Helmet–Mounted Displays (Task 9)

During 1988, AAMRL took delivery of five binocular HMD breadboards as part of the VPD effort that was supporting a number of DoD programs including the Army LH helicopter program. Two of the breadboards were the catadioptric and the off–aperture designs, which had some operationally important characteristics, including large FOV, excellent eye relief/exit pupil size, and improved center of gravity. The major operational design deficiency for the catadioptric design was its relatively low transmission efficiency, while for the off–aperture design it was the weight of the relay lens optical elements. One relatively new technology area that was thought could help increase the system's total brightness (by increasing the system's spectral bandwidth), and effect a significant weight reduction while maintaining or improving other performance parameters, is gradient index (GRIN) optics.

The objective of this effort was to design custom GRIN optical elements that could demonstrate the ability to replace a correspondingly greater number of conventional optical elements in existing binocular HMD designs owned by the Government. The results of this effort were to be used to verify, to potential users in the Air Force operational commands and other DoD organizations, that significant weight reductions, and therefore improved operational viability, can be achieved for binocular HMDs with minimal or no reduction in the original performance of the optical system.

The goal of the proposed experimental development of the GRIN optical elements was to determine if any lens group within the catadioptric HMD and off–aperture designs could be replaced by GRIN to reduce weight and increase spectral bandwidth.

For the catadioptric HMD effort, the HMD system (referred to as K90) was redesigned to meet new specifications for FOV and overlap. In addition to these changes in specification, two additional constraints were imposed. These were color correction and the elimination of the extreme aspheric surfaces used in the original K90 design. The original weight of the K90 optical system could not be exceeded in meeting the new design specifications. GRIN materials were to be explored to determine their usefulness in meeting the new design goals.

The principle considerations in the design of a binocular HMD were color correction (because of transmission), light weight, cost and ease of fabrication, and optical performance. To achieve these goals, several different types of systems were investigated: all spherical systems, systems employing an aspheric surface, and systems using a shallow radial gradient. The performance of these three types were roughly comparable. Each of the systems were also comparable to the K90 design.

There were problems involved if either an aspheric element or a shallow radial gradient were included as part of the relay group. In the former case, an aspheric glass element is very costly and difficult to test. In the latter case, there were problems with the gradient index profile not being manufactured exactly as it was prescribed. The all–spherical systems had one or two more elements, but this was not detrimental to the weight restriction. The lenses themselves could be fabricated at a fraction of the cost, and testing would not be a problem.

The three systems that were designed met all of the design specifications as well as the optical performance requirements. Of the three systems, an all–spherical system seems to be the most logical configuration. It meets all the optical and mechanical restrictions and would be relatively simple and inexpensive to fabricate.

For the off–aperture system, the HMD design was examined to determine if GRIN materials could be used to reduce the weight of the optical system. The original system specifications were not changed during the design process.

The eyepiece portion of the off–aperture systems contained a triplet, two singlets, an aspheric corrector plate, and a thick prism. Axial gradient elements showed no significant reduction in weight. Use of a radial gradient element in the eyepiece reduced the weight by 60 grams, and the number of elements can be reduced from four to one while maintaining equivalent performance. However, the radial gradient required is not possible with current manufacturing technology. The maximum change in index that has been achieved in large radial gradient elements is approximately 0.1, while an index change of 0.255 would be required by this design. This large index change has been achieved in linear axial gradient materials with similar dimensions.

Conceptually, the reduction in weight that could be achieved in the off–aperture objective is very significant. Current design efforts have not resulted in a feasible configuration, due primarily to the difficulty of controlling the mechanical parameters of the configuration during optimization. Their effect on image aberrations is large, making the system unstable during optimization. Other configurations that use on tilted, on–axis lens elements are another possibility.

The off–aperture telescope portion of the system contained three off–aperture lens elements in the objective and a single aspheric partial reflector surface in the eyepiece. The telescope portion received most of the attention in this study, however no GRIN solutions were found that matched the optical performance of the original system.

3.1.6 Advanced Dispenser Cathodes for Miniature Cathode Ray Tubes (Task 10)

Today's limit of micro–CRT performance as concerns the compromise between resolution/brightness/life is imposed by the emission density on the cathode surface. Dispenser cathodes have therefore been suggested and tested, but led to disappointing results because this type of cathode needs to be carefully matched to the micro–tube environment.

It is widely recognized in the CRT field that conventional oxide cathodes can be employed in gun designs that impose a maximum of about 1 amp/cm^2 cathode loading if normal lifetimes (> 1000 hours) are to be obtained. If higher loadings are employed, beam current duty cycle must be reduced, or CRT lifetime will be seriously affected.

A well–known solution to higher current cathodes is to employ the so–called "dispenser" design, in which a porous tungsten matrix, impregnated with barium compounds, is heated to a sufficiently high temperature to "dispense," or release, barium (the active thermionic emission element) at a higher rate than practical in an oxide cathode, thus providing a higher emission current. A long lifetime is achieved through the large reservoir of available barium within the matrix. Such cathodes are widely used in microwave and high–power transmitting tubes.

In attempting to employ dispenser cathodes in CRTs where higher cathode current density would increase performance, a number of difficulties have arisen. These include electrode leakages and grid emission, arising from the higher operating temperature and rate of barium evolution, and erratic performance due to miniaturization problems.

The development work under this task was awarded to Thomson Electron Tubes and Devices Corporation. Thomson had successfully applied their dispenser cathode technology to a number of production programs, including an avionics CRT for advanced sunlight–readable cockpit color displays, and a large, very–high–brightness projection CRT for visual simulation displays in Daimler–Benz and F–14 trainers.

The objective was to perform CRT and materials analysis, design, fabrication, CRT integration, and testing necessary to develop improved long–life cathodes suitable for narrow–angle miniature CRTs that act as the image source for airborne–qualified HMDs used in military aircraft. Specifically, Thomson performed the manufacturing, assembly, and performance verification to:

a. Fabricate developmental cathode assemblies and define the procedure for activating them for use in working miniature CRTs.

b. Integrate one developmental cathode into a working CRT of Thomson's choosing.

c. Fabricate additional developmental cathodes for integration and test into third–party miniature CRTs to substantiate performance independently for general purpose use in miniature CRTs.

d. Test and evaluate the electronic performance of the developmental cathode in the working test miniature CRT of Thomson's manufacture.

Following an evaluation of commercially–available dispenser cathodes that exhibited the characteristic problems, Thomson performed a development program which led to:

a. Reduction of operating temperature from between 1050° and 1100°C down to 950°C, through the application of an osmium low–work function coating.

b. A materials and process study leading to a sequence of steps resulting in high–processing yields.

c. A miniaturization program resulting in a reduction of thermal power requirements.

Thomson delivered five developmental low–power consumption dispenser cathodes (LPCDC). In order to demonstrate the ability of the LPCDC to work correctly in a miniature CRT, Thomson incorporated their advanced dispenser cathode into an electron gun and a 1–inch diameter full–assembly CRT.

For this task, the small LPCDC was designed and has demonstrated a maximum power consumption of 1 watt, as is appropriate for a miniature CRT gun assembly. This low power level should solve grid emission and leakage problems that would otherwise arise. The LPCDC size is compatible for integration into a miniature 1–inch diameter helmet tube and has current densities of 5 to 10 amps/cm^2. The life tests have demonstrated that the emissive material (M–type with osmium) is able to deliver very high current densities during 1000 hours or more.

3.1.7 Flyable Integrated Catadioptric Display–Helmet System (Task 12)

The VPD may serve as the pilot's primary MMI in future high–performance aircraft cockpits. This is especially true for cockpits like that of the Army's LH helicopter, because the VPD will provide the primary interface to the pilot's mission equipment package, and because the mission will require very–low–level altitude flying where peripheral motion cues provided through a wide–FOV display are essential to maintain proper situational awareness. This new crew system concept for the LH requires a high level of system automation and integration supported by a wide FOV VPD that permits displaying superior fidelity sensor information while allowing acceptable "see–through" capability to the cockpit controls and to the "outside world". The panoramic feeling associated with the catadioptric breadboard has been demonstrated to support the above requirement well. However, its wide–FOV optical system places unique requirements on its associated flight helmet.

This effort was initiated in an attempt to provide a flight–worthy integrated helmet system (IHS). This system includes the HGU–56/P helmet and a removable unit that houses an improved catadioptric optics assembly and miniature CRTs capable of supporting flight test evaluation efforts for the LH helicopter program. The work, performed by Optical Design Service, was accomplished through an iterative process, because the exact optics layout depends on the configuration of the IHS hardware and the IHS depends on the optical design.

The objective of this task was to design a flyable helmet system so that the follow–on improved catadioptric display optics can be mounted and evaluated in the cockpits of USAF military test aircraft. Two complete IHS systems were manufactured and assembled based on the finalized optics/helmet integration design.

3.1.8 Flyable Binocular Helmet–Mounted Display System for Fixed–Wing Aircraft (Task 16)

AAMRL has been developing an advanced MMI concept employing an electronically generated all–aspect head–up display (AS–HUD). An AS–HUD is similar to the aircraft–mounted HUD, except that it is mounted on the helmet. Therefore, the information displayed is always within the pilot's FOV. The information processed for the display, using the capability of future advanced airborne graphics engines that can process and overlay digital avionics and map data with imaging sensor returns in real time, also takes into account the viewer's line of sight (LOS). The result is an interactive control/display system that represents a panoramic display of all cockpit information, organized both spatially and temporally in 3–D, so that the crew member's total situation awareness of the weapon system's state relative to the world, its threats, and targets is greatly enhanced.

This new crew system concept requires a high level of system automation and integration supported by a binocular medium–FOV HMD that permits displaying superior–fidelity sensor information while also allowing acceptable "see–through" capability. This technology supports and enhances the mission of future high–performance fixed–wing aircraft requiring low–level flying, in which the pilot must use peripheral motion cues to maintain proper situational awareness.

The objective of this task was to perform a preliminary design study for a flyable binocular medium–FOV HMD system that could be mounted on an advanced flight helmet (HGU–53/P or customized helmet). The study included detailed trade–off data across all design parameters, which impacted the likelihood that the resulting HMD would meet ejection requirements and flight qualifications in order to be evaluated in the cockpits of USAF military fixed–wing test aircraft.

The design effort was completed by Vis–O Displays and led to the preliminary design for a flyable binocular medium–FOV HMD system that will be mounted on an advanced HGU–53/P flight helmet. The design addressed AAMRL's concerns regarding ejection requirements and total system weight.

In an attempt to meet ejection requirements, mounting of the optics with the HGU–53/P helmet led to a "frangible" system that would be virtually blown away from the helmet during an ejection scenario. Any undue aerodynamic loading on the pilot's head would then be eliminated.

During the course of the design, it became apparent that the aerodynamic conditions expected in the cockpit during ejection were far from previous ideal estimates. The type of seat, location of the pilot tube, wind–blast pilot protection shields, and other related items were still in the developmental stages. For these reasons, it was premature to design and build a frangible visor display without knowing the actual environmental conditions. At the direction of AAMRL, the design was completed in which the ultimate goal was a frangible design including ejection hardware. The main thrust was to design and produce two light weight displays possessing excellent optical characteristics while maintaining a low profile relative to the helmet.

Total system weight, which was a major concern, was forecast to be at or below 1.66 kilograms. The weight of the display itself was calculated to be 503 grams. In contrast, the complete HGU–53/P size 6 helmet, excluding the oxygen mask, weighs 1162 grams.

This HMD design featured several improvements over the displays built for rotor–winged aircraft:

a. It is a fully–overlapped binocular system with see–through capability.

b. It has a very large exit pupil (– 5 to 95 percentile) compatible system.

c. The total system weight of 1.66 kilograms is below the recommended 1.8 kilograms.

The design developed under this effort was used during Task 20, entitled "Flyable Binocular Helmet–Mounted Display System for Fixed Wing Aircraft – The TOPHAT."

3.1.9 Flyable Binocular Catadioptric Virtual Panoramic Display Optics – The K91 (Task 18, Phase I and II)

The VPD will serve as the pilot's primary MMI in future high–performance aircraft cockpits. This is especially true for cockpits like that of the Army's LH helicopter, because the VPD will provide the primary interface to the pilot's mission equipment package, and because the mission will require very–low–level altitude flying, where peripheral motion cues provided through a wide–FOV display are essential to maintain proper situational awareness. This new crew system concept for the LH requires a high level of system automation and integration supported by a wide–FOV VPD that permits displaying superior–fidelity sensor information while allowing acceptable "see–through" capability to the cockpit controls and to the "outside world".

The panoramic feeling associated with the catadioptric breadboard has been demonstrated to support the above requirement well. However, it had several problem areas that needed to be improved. The problems were identified as an imperfection of the aspherical relay lenses, the lack of an integrated interpupillary distance (IPD) and depth adjustments, and the slight aft displacement of center–of–gravity obstructions at the center and around the oxygen mask. Several improvements were to be addressed during this effort to overcome these problems.

The objective of this effort was to design and fabricate two flyable binocular catadioptric virtual panoramic display systems that will be mounted on the Advanced Integrated Helmet System (AIHS) HGU–56/P. The improved catadioptric design, designated as the K91, was to allow the realization of a monocular and overlapped FOV within specified parameters, as well as mounting of the optics and image sources with headgear. A key aspect in the redesign of the catadioptric display system was an optical system that met the performance requirements resulting from a demonstration/evaluation conducted on the catadioptric breadboard K90.

The K90 was the first binocular HMD to feature a monolithic visor with adjustable IPD. This involved pivoting its relay optics and CRT on a virtual pivot about the focus of the visor.

The K90 was objectionable in several respects. First, it used two highly aspheric relay lens elements that proved excessively difficult to fabricate. Second, for weight reduction, it was not achromatic, and required supplemental filtering to eliminate the red and blue colors from the P53 phosphor used on its CRTs. Third, the miniature CRTs had to move, presenting concern for safety and durability.

The K91 developed under this effort was intended to eliminate the main problems of the K90, while improving its field coverage. Also, it was essential that the new design include aberrational, dimensional, and centering tolerances for each optical component, and predicted system Moduation Transfer Function (MTF). These tolerances were used to guide the mechanical design of the optomechanical adjustment mechanisms and to determine the acceptance limits and assembly instructions for each optical element. Also, the information is necessary to verify and calibrate the optical/mechanical performances of the entire display system.

The concept of using a monolithic visor for safety and minimum see-through obstruction remained paramount in the design effort. Any candidate design that required a divided visor was not considered.

Optically, the best solution appeared to be one similar to that used in the K90. Except for small amounts of coma and negligible field tilt/distortion, the image is remarkably stable as the IPD is adjusted. However, that solution was ruled out since it moves the CRTs.

The next best solution was the one that was adopted for the K91. The relay optics were divided into two groups. One remains fixed and attached to a fixed-position CRT. A second group, in this case a single lens element, moves and tilts to maintain focus and maximum image quality during IPD change. It also requires the motion and tilt of a small "wing mirror", or folding mirror. These motions were coupled together in linear fashion to approximate ideal motions. The image remains well-corrected for all IPD positions, but is optimum from the nominal 68mm.

The K91 HMD features several improvements over its predecessor, the K90. It is achromatic and uses only spherical lenses, and it has a slightly greater field overlap. Its miniature CRTs are rigidly fixed in space, with IPD adjustment being provided by a new method. Also, the pupil has been reduced to 19mm, and the CRT image area increased to 23mm. It is expected that the weight of the K91 would be similar to that of the K90, and perhaps even reduced slightly.

3.1.10 Flyable Binocular Helmet-Mounted Display System for Fixed-Wing Aircraft-The TOPHAT (Task 20)

AAMRL has been developing an advanced HMI concept employing an electronically generated AS-HUD. An AS-HUD is similar to the aircraft mounted HUD, except it is mounted on the helmet; therefore, the displayed information is always within the viewer's FOV. The information processed for the display, using the capability of future advanced airborne graphic engines which can process and overlay digital avionics and map data with imaging sensor returns in real time, also takes into account the viewer's LOS. The result is an interactive control/display system which presents a panoramic display of all cockpit information organized both spatially and temporally in three dimensions, so that the crew member's total situation awareness of the weapons system state relative to the world, its threats, and targets is greatly enhanced.

This new crew system concept requires a high level of system automation and integration supported by a medium–FOV HMD that permits displaying superior fidelity sensor information while also allowing acceptable "see–through" capability to the cockpit controls and "outside world". This technology supports and enhances the mission of future high performance fixed wing aircraft requiring very low level flying in which the pilot must use peripheral motion cues to maintain proper situation awareness.

This task was a follow–on to the effort performed under Task 16 entitled "Flyable Binocular Helmet–Mounted Display System for Fixed–Wing Aircraft." The previous effort led to the design for a flyable binocular medium–FOV HMD. The objective of the effort was to fabricate the optical components for two systems of the developed design.

First, the new design was verified to assure that it included an aberrational analysis and dimensional and centering tolerances for each optical component, as well as the expected system MTF. Both the geometric and diffraction MTF calculations were reviewed. This included the results using a wavelength of 540 nanometers for calculating the MTF performance and the results of geometric MTFs calculated on–axis and at +/– 10%, +/– 25%, +/– 50%, +/– 75%, and +/– 100% of full FOV range, in both the saggital and tangential planes. This data base was reviewed and used to:

a. Guide the mechanical design of the optomechanical adjustment mechanisms.

b. Determine the acceptance limits and assembly instructions for each optical element and mechanical housing.

c. Verify/calibrate the optical/mechanical performances of the entire display system.

Vis–O Displays Inc. oversaw the manufacturing of six sets of optical components which could, at a later date, be integrated with helmets and miniature CRTs to produce two flyable systems and two space and weight models. The components were manufactured according to the finalized optical design and optics/helmet integration report delivered during Task 16. The components included injection molded polycarbonate visors, visor coatings, aspheric lens elements, fiber optic face plates, filters, and prisms.

3.2 General Engineering Tasks

3.2.1 Definition of Performance Assessment Requirements and Approaches for the Super Cockpit Program (Task 5)

The objective of this effort was to define in detail the kinds of constructs and measurement requirements likely to be generated in the Super Cockpit program, and to develop an overall set of guidelines for the metrics likely to meet those requirements. The results of this effort are summarized below.

Extensive interviews were carried out with AAMRL and other researchers to determine the current status and plans for the Pilot–Centric Cockpit (Super Cockpit) program. Concepts involved in this program were analyzed. A creative effort then attempted to define any new requirements for performance assessment in such systems. These requirements were compared to existing performance assessment techniques (including techniques currently under development). Recommendations were made concerning both the scientific and organizational steps necessary to meet anticipated needs.

Based on these activities, it was concluded that AAMRL already possesses considerable capability to use state–of–the–art performance assessment techniques, and is particularly strong and current in the development of new techniques, especially in the cognitive area. Impressive efforts are also being carried out in the development of theoretical models. However, these capabilities are not being directed specifically to the Super Cockpit. Therefore, the following recommendations were developed to achieve this goal.

a. Develop new or expanded assessment techniques.

b. Increase emphasis on validation techniques.

c. Translate performance metrics to system metrics.

d. Develop a measurement integration technology.

e. Recommend organizational changes.

f. Integrate performance metrics into existing simulators.

g. Increase emphasis on theoretical models.

h. Explore clinical and phenomenological assessment techniques.

3.2.2 Field Measurement of Head–Related Transfer Functions (HRTFs) (Task 7)

A 3–D auditory display has been identified as one of the virtual technologies of interest to AAMRL. This panoramic display, in addition to a panoramic visual display, will provide information to the pilot from his aircraft avionics, weapons, sensors, and navigation updates in a manner that optimizes his spatial and psychomotor capabilities. Specifically, threats, targets, and other operators are heard as if they originated from specific locations in 3–D space. These signals will be directionally accurate and stabilized in space regardless of the pilot's head position.

To maximize location accuracy, it is thought to be necessary to take into account the human's unique HRTFs – the transformation of sound pressure from the free–field to the human ear canal as a function of the geometry of each listener's external ear. Obtaining estimates of these transfer functions in order to implement the digital filters required for spatial simulation presents several problems.

The first problem arises because measuring the HRTFs is technically demanding and is subject to numerous errors. The degree to which these various sources of error contaminate the RH measurements in a perceptually significant way is not clear. Second, since HRTFs are directionally specific, each direction to be simulated requires a different pair (left–right) of transfer functions. The extent to which economies can be achieved was not known. Third, the precision (resolution) with which the HRTFs must be presented in order to synthesize localization cues satisfactorily has not been established. Last, the inter–individual differences in HRTFs for numerous subjects is not well–known. The possibility of large differences suggests that the digital filters may have to be individual–specific for the simulations to be veridical.

The objective of this effort was to refine and simplify techniques for generating acoustical signals that could be used in 3–D auditory displays. Such signals are presented to the listener over headphones and create the illusion of a virtual sound source at a predetermined position in 3–D space. The signals are generated digitally, using algorithms based on the acoustical effects of human outer ear structures on sound waves reaching the ears. The main area of difficulty inhibiting development of practical 3–D displays is in obtaining estimates of these outer ear effects. That aspect was the focus of this effort.

The work was divided into three areas:

a. Acoustical measurements of free–field–to–eardrum transfer functions (HRTFs).

b. Analysis of HRTFs.

c. Psychophysical assessment of human performance in sound localization tasks involving stimuli presented both in real and in simulated (virtual) auditory space.

The focus in all three areas was on evaluation of means for making RH measurements faster and easier, thus simplifying synthesis of auditory stimuli for 3–D displays.

In the measurement phase of the work, HRTFs were obtained from 20 human sybjects at 144 positions in an anechoic sound field. A periodic pseudorandom noise – averaging technique (Wightman and Kistler, 1989) was used to make the measurements. Comparable RH measurements were also obtained from the KEMAR mannequin (using the same psuedorandom noise procedure) and from one of the original 20 subjects using a brief click as a measuring stimulus. The aim of obtaining HRTFs from KEMAR was to assess the need to base 3–D stimulus sythesis on individualized RH measurements. If acceptable measurements could be obtained from KEMAR, the time–consuming and somewhat risky measurment procedures involving real subjects could be elimated. The motivation for the click measurements was to evaluate the feasibility of making RH measurements in an ordinary room, with appropriate gating to remove echoes.

Analysis of the HRTFs revealed large inter–subject differences, substantial differences between the KEMAR HRTFs and those from any of the human subjects, and a minimum of 20 dB loss insignal/noise ratio accompanying the use for the click as a measuring suimulus. The magnitude component of the HRTFs from nearly all subjects included a deep notch, usually in the 8–12 kHz region, that was dependent on probe microphone position and independent of source directon. Further acoustical and optical measurements confirmed that this notch was a result of standing waves in the ear canal. A principal components analysis of the HRTFs was conducted with the aim of assessing the feasibility of constructing "model" HRTFs that would have the important features of real HRTFs. Unfortunately, available principal components algorithms do not accept complex data, so only the maginitude components of the HRTFs were analyzed. The analysis revealed that 90 percent of the variance [illegible] could be accounted for by five principal components. The first of these c[illegible] the overall similarity of the HRTFs across subjects in the low frequencies, and the next two revealed large differences across both subjects and positions in the important 5 to 15 kHz region.

Extensive psychological tests, using techniques developed and tested previously (Wightman and Kistler 1989), were conducted on 15 adult listeners. In these tests, stimuli were presented from 36 positions either in free–field (anechoic chamber) or in simulated free–field (over headphones). Listeners gave numerical judgements of apparent azimuth and elevation of the sources. The results suggested:

a. When simulated free–field stimuli are synthesized from RH measurements obtained from the listeners' own ears, the apparent positions of the stimuli are the same as in free–field.

b. The elevation components of the apparent position judgements of simulated free–field stimuli are very sensitive to distortions (in the 5 to 10 kHz region) of the HRTFs used to synthesize the stimuli.

The conclusions of the psychophysical tests were:

a. At the present time, the most veridical simulations of 3–D auditory space require synthesis to be based on a listener's own HRTFs.

b. Because of the sensitivity of the apparent elevation of simulated sources, great care must be taken to preserve RH information in the 5 to 10 kHz region.

c. Techniques need to be developed that offer high–frequency detail in the RH measurements while making the measurements in an ordinary room.

3.2.3 Three–Dimensional Data Analysis for Equipment Design (Task 19)

The Human Engineering Division of AAMRL has been applying anthropometric size data to the design of USAF equipment for over 30 years. Work in 3–D shape data (morphometrics) has only begun in the last few years. The apparent difference between these two methods is that previously, AAMRL could dictate only what size to make something; now AAMRL can also prescribe what shape or contour it should have. However, the analytical difference between the methods is staggering. Size data is typically a set of lengths, breadths, depths, etc. and the statistical analysis techniques used were well defined. Shape data, on the other hand, consists of hundreds of thousands of X, Y, Z coordinates, and statistical techniques are virtually non-existent. Therefore, a great deal of exploratory work has been undertaken to define analytical methodology and hardware necessary for using this new design enhancement. This task represents the first attempt to apply morphometric data to improve the shape of USAF equipment.

AAMRL has been developing a 3-D human body measuring system to fully quantify the shape of the body in fine detail. This information is being applied to the design of numerous items of equipment that must closely fit the pilot. The purpose of this effort was to improve the fit of the MBU 12/P oxygen mask and to develop prototype shape and sizing data for low-profile/ejection-compatible night vision goggles. The objective of the task was to define variability in shape of manufactured masks and face shapes.

The MBU 12/P oxygen masks have been produced by two separate manufacturing contractors. Due to the lack of detailed engineering drawings, the masks were different in shape with a resulting degradation in the mask's performance. This effort used high-density scanning techniques to define the proper shape for the masks and to provide the shape data in a format that would allow proper engineering drawings to be created.

The 3-D morphometric data on a large sample of USAF pilots was analyzed, and software was developed to characterize and summarize the shape of the head around the eye. This data was to be used to create prototype shapes for the development of low-profile night vision goggles.

3.2.4 Experiments to Determine the Line-of-Sight Angle (LOSA) for HMDs

The U.S. Air Force recently had a HMD vendor propose a design that calls for centering the symbology at -7.5 degrees (below the pilot's LOS) rather than at the conventional zero-degree position. The vendor justified this suggestion by citing human factors literature which recommends a -15 degree LOSA. Yet, the literature cited was a single source of expert opinion rather than empirical data. Experiments performed by Hill and Kroemer (1986) suggested that there is no single optimal LOSA, but that it varies with seating angle and decreases as viewing distance increases. However, in these experiments, Hill and Kroemer collected no data at distances beyond one meter. The appropriate LOSA for a pilot viewing a collimated image (i.e., at optical infinity) is unknown. Therefore, experiments were needed to determine the preferred LOSA for HMD images.

Since the specific purpose of the study was to gain information to be used in the design of HMDs to be worn by male fighter pilots, 10 male subjects were used. Their ages ranged from 19 to 25 years, with mean age of 21.3 years. To ensure that they had Snellen 20/20 near and far vision, all subjects were tested prior to the experiment on a Bausch and Lomb Orthorater. Subjects were also questioned to screen for diabetes or other medical problems that could affect eyesight.

The subjects' sitting eye height ranged from 71.8 cm to 83.9 cm, with a mean of 78.8 cm. This corresponds to a range of 1st to 82nd percentile, with the mean sitting eye height at approximately the 25th percentile, for 1967 USAF flight personnel.

The experiments were conducted in a specially built chamber with a modified barber–type chair. The ceiling and front surface of the chamber were curved with a radius of 1.75 meters and textured with plaster to remove external visual cues. The chair's head rest was removed and replaced with a single bar to which the helmet could be attached. The range of the chair back was extended so that it pivoted from 90 degrees (upright) to almost 180 degrees (supine).

Two light pens were mounted on a pivoting platform on the chamber wall at the center of the curvature. One light, the target, was controlled by a step motor that moved the light horizontally by seemingly random increments. The second light was controlled by the subject through a push–pull handle and cable. Both lights were mounted on the same platform, which could rotate through 360 degrees. A protractor was attached to the platform so that the experimenter could read the selected LOSA.

An Air Force pilot's helmet was modified to hold the lenses. Pairs of lenses were mounted in a Plexiglass frame. The lenses were 6.5 cm in height and 6.0 cm in width, allowing the eyes a pitch of approximately 60 degrees.

The subject was asked to perform two tasks. First, he was asked to set the light pens at a "level that was preferable and comfortable for his eyes". This determined his LOSA. Second, after the LOSA was selected, he was asked to track the moving light with the light that he controlled. The subject was asked to keep the controlled light arrow aligned with the moving target. During each session, the subject performed these tasks 32 times.

The main effects of chair position, image distance, preset image location, and selected interactions were examined using an analysis of variance (ANOVA) procedure on SAS. Chair position and preset image location had significant effects on LOSA, while image distance and simple interactions among these measures were not found to be significant effects. The mean LOSA values in each chair position are as follows: chair upright, −.46 degrees; chair at 111.6 degrees, −11.94 degrees; chair at 135 degrees, −11.60 degrees; chair at 158.5 degrees, −5.05 degrees; and supine, −7.59 degrees.

Interpreting the data for use with HMDs, the results seemed to indicate that the declination of the LOSA is fairly small, ranging from −0.5 degrees in the upright sitting posture to a maximum of −12 degrees in the declined postures (as measured against a line perpendicular to the seat back). Furthermore, there is no apparent dependency of preferred LOSA from perceived target distance. Yet, these results are probably a function of the experimental task and the experimental apparatus used. The task did not require focusing on the visual targets. Various image distances were produced by lenses, a condition not found with current HMDs. It was therefore strongly suggested that, before final recommendations were made for centering the symbology in HMDs, experiments be conducted that closely reflect the actual conditions found with HMDs.

The best experimental condition would be to use actual HMDs (together with other realistic cockpit conditions) and vary the LOSA within the HMD. The second choice suggested would be to actually project targets onto screens at varying real distances (instead of using lenses) and to require the subjects to perform visual tasks that are representative of actual HMD tasks.

3.3 Management and Administration Tasks (Task 1, Task 17, and Task 21)

The PDMC program consisted of a number of contractual and in–house efforts directed toward establishing the technology base, empirical data, and applicable computer models required for the development of a virtual cockpit design technology necessary for Super Cockpit. Overall program administration and supervisory support was given to:

a. Provide administrative guidance and integration of the on–site research support and the individual technical task assignments, as well as to provide the Air Force PDMC program manager with the necessary input on the program's progress to meet the overall objective.

b. Manage and control the task assignments that were issued over the duration of the contract, including milestone tracking, technical performance, and financial tracking.

c. Facilitate government research by requisite specialized instrumentation and personnel support.

d. Provide the mechanism for the exchange, assimilation, and dissemination of the PDMC technical data. The PDMC tasking cycle for initiating new efforts under CLIN 0002 is shown in Figure 3.2.

Specifically, MacB performed the following tasks throughout the duration of the PDMC program.

a. MacB provided administrative and supervisory support for personnel assigned to technical support under this contract. The administration included the review of work conditions, work progress, travel arrangements and approvals, report preparation, reproduction and distribution, as well as day–to–day support required by employees.

b. MacB provided continuous coordination with the contract and technical task monitors to insure a smoothly functioning contract, and provided for expeditious settlement of any problems evolving from the contract. MacB provided the Air Force program manager with the necessary input on program status, including expenditures, technical issues, schedules, independent assessment of tasks, financial status, and overall program status.

c. MacB processed all task assignments received to include the issuance and administration of required subcontracts.

d. MacB provided for the rapid acquisition of specialized instrumentation (i.e., prototypes) and related documentation needed to support in–house government simu lation/human factors studies.

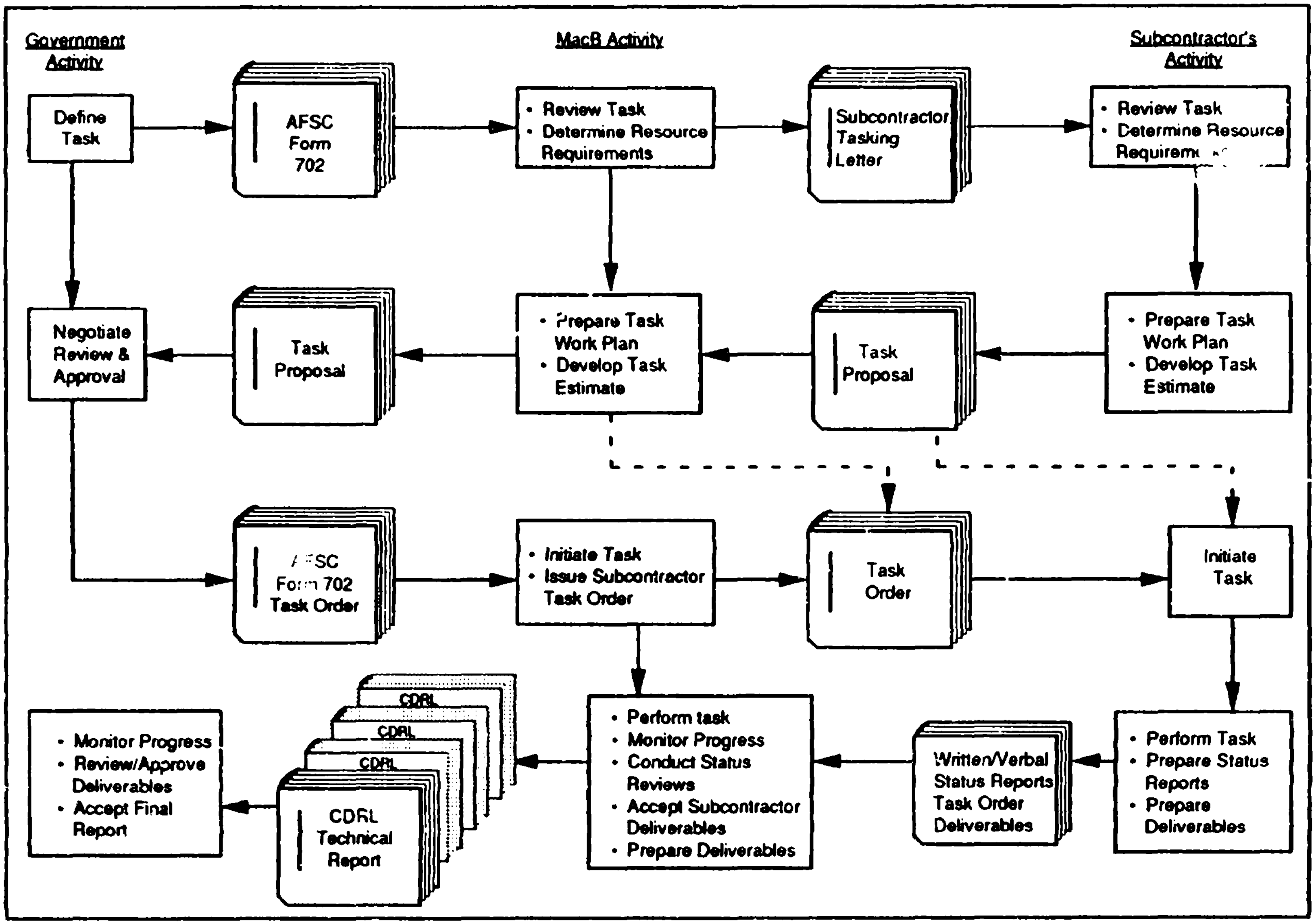

Figure 3-2. PDMC Tasking Cycle

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4.0 CONCLUSIONS

A Super Cockpit would provide virtual 3–D information in a pilot–centered spherical world in which information would be coupled with the real world. Visual graphics and sensor imagery would be magnified and projected into the pilot's eye using miniature binocular display electronics incorporated into his helmet. The realization of this virtual environment would require the development of innovative control methodologies and the integration of advanced display technologies. These technology areas were the primary focus of the PDMC program.

At its inception, the PDMC program was an ambitious, multifaceted program with the goal of developing pilot/aircraft systems requirements for the virtual man–machine interfaces necessary to support Super Cockpit. The PDMC program was established with the expectation of advancing the state–of–the–art in systems related to pilot–centered cockpit interfaces. Specifically, to build on existing technologies and facilities to develop and demonstrate new control and display concepts. Several of the in–house research studies and hardware prototype tasks performed under this program helped to define and analyze these concepts. However, the PDMC program was unable to fulfill all aspects of the original objectives because of a significant reduction in the level of funding.

Shortly after beginning the program, it was known that Super Cockpit program funding for the PDMC program would be greatly reduced. With the reduced funding, the areas of research and development, technology assessments, and types of research studies were reduced in scope. As a result, MacB's CLIN 0001 in–house support was focused primarily in the VCASS and HMOF laboratories. These laboratories were used to conduct auditory and visual perception research with human factors applications. In these laboratories, MacB's support helped to examine new cockpit/virtual display design concepts for implementation into future cockpits.

MacB technical support for the PDMC contract included support for task assignments covering advanced control/display concepts, engineering analysis/assessments, and hardware prototyping. Many of the task assignments involved the work of subcontractors with specialized expertise in the field of interest. MacB provided a responsive mechanism for issuing subcontracts and consulting agreements to initiate and complete the various task assignments. MacB worked with the subcontractors to establish virtual control and display concepts including the fabrication of hardware necessary to prove them.

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