TITLE: Pilot-Vehicle Interface

PILOT-VEHICLE INTERFACE

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SUMMARY
Agile aircraft introduce new requirements and performance standards for the pilot-vehicle interface. This lecture will address these ergonomic issues as they pertain to agile aircraft. Specifically, controls and displays will be discussed, followed by design issues relevant to intelligent interfaces. The concepts and technologies proposed as candidate solutions for creating pilot-vehicle synergy are, for the most part, untested at present. It is hoped that this lecture will provide the impetus for the research required to realize a pilot-vehicle interface that will enhance the operation of agile aircraft.

6.1. OVERVIEW

Agile aircraft have the potential to provide enhanced speed, range, flexibility, and lethality. In order to exploit these benefits, the warfighter must be able to assess situations, decide tactics to be employed, and execute responses under rapid, highly uncertain and temporally demanding combat conditions. Unfortunately, improvements to date have all tended to *complicate* cockpit design. This increased complexity may overload pilots' perceptual and cognitive processing capabilities, increase workload, and ultimately degrade mission effectiveness.

For pilots to realize the benefits afforded by agile aircraft, crew station designs must facilitate the potential synergy between situational awareness, the maneuverability envelope, and systems [1]. For instance, enhanced maneuverability will not increase survival rates if pilots do not realize that a change in flight path is recommended. Moreover, if pilots on a flight path ending with ground impact have real-time updates of their situation, they can choose when to alter their flight path – they can choose whether to change the path immediately, or wait until the final moment the envelop allows escape. Likewise, if pilots are cognizant of a threat, but weapon selection is time consuming, they may not be able to exploit the advantages of increased maneuverability. On the other hand, simple and direct means of changing weapon settings may achieve a tactical advantage without arduous maneuvering.

These examples show that it is the communication between the crew station and the pilot that is the limiting factor in the ability of pilots to exploit the advantages afforded by agile systems. Although there are some specific design issues presented by new capabilities, it is the *multitude* of systems that constitute agile aircraft that make the pilots' information management task the primary challenge and key determinant of successful deployment. Crew station design with the goal of pilot-cockpit synergy has the potential to provide the flexibility to maximum mission effectiveness.

6.2. AGILE AIRCRAFT IMPLICATIONS

The pilot-vehicle interface used in agile aircraft determines how fast and accurately the pilot can assimilate the required information and execute control procedures. Although the pilots interviewed indicated that special devices are not required to exploit the advantages of agile airframes, they did raise several interface design issues for agile aircraft systems. These are discussed below.

6.2.1. HIGH ANGLE-OF-ATTACK (AOA)

Conventional attitude displays can not simultaneously present both the nose position and vertical velocity during high AOA maneuvering. Moreover, when a pilot is recovering from a high AOA maneuver (e.g., over 45 degrees), there is an initial feeling that the aircraft is not reducing its AOA in response to nose down pitch commands. This makes it even more difficult for the pilot to maintain awareness of the flight path vector. Pilots need a display format that provides a rapidly interpreted indication of the flight path response for agile aircraft.

6.2.2. NEW COMBAT MANEUVERS

Agile airframes have enabled a new range of combat maneuvers (e.g., Herbst Maneuver), especially since pilots no longer have to point the aircraft's nose in the direction of the target. The ability to rapidly change flight path has also allowed an advantage during flat scissors maneuvers. These two exemplary maneuvers present corresponding display challenges. First, the pilot must receive a clear indication of the approach of a "terminal exit time" – that point in flight when the pilot must leave the post-stall domain to avoid reaching a hazardous altitude. Second, additional indication of yaw, in addition to flight path, is needed for the pilot to maintain spatial orientation. A visual reference that provides an accurate orientation cue is especially needed during automatic guns aiming or missile avoidance, to help avoid disorientation and sickness from the abrupt maneuver changes. Also, means of maintaining sight and situational awareness of the target during high angle-of-attack flight is required.

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6.2.3. HIGH SPEED/EXPANDED ENVELOPE

The anticipated speed that can be achieved by agile aircraft will mean that information in front of the pilot will unfold two to three times faster than in non-agile aircraft. Thus, some conventional symbology (pitch ladder and digital readouts) may change too rapidly to be useful to the pilot. The pilot has to "think ahead" more, given there is less turning time involved in getting in position to launch weapons. These agile operations require decisions to be made in "microtime" or less time than one typically would want to spend weighing options, making decisions, and executing actions. The ability of the system to provide the right information at the right time, and assist the pilot in determining the right course of actions, is the crux of the cockpit designers' challenge.

6.2.4. NEED FOR TAILORING

With increasing onboard processing capabilities, agile aircraft will have a concomitant increase in the number of systems and possible data views. The pilot's time can be consumed just programming the numerous options available. Cockpit design and standard operating procedures should focus solely on those options essential to mission requirements. One mechanism is to have one command or input automatically activate the systems and set up the tasks relevant to the current flight segment (e.g., air-to-air versus landing). Only those options required for that flight segment would be readily accessible.

6.2.5. TUNNELLING OF ATTENTION

It cannot be assumed that pilots will scan all available information sources in a timely manner. Presenting information on head up displays, together with the demanding agile aircraft mission, can result in a tunneling or channeling of the pilot's attention such that vital head down information is missed. It is also possible for a situation (e.g., changing threat scenario) that attracts the pilot's attention to head down displays and delays the pilot from returning to a head up posture. Therefore, some cueing mechanism is required to inform pilots of critical information or a change in aircraft or mission state that needs attention.

6.2.6. ENERGY MANAGEMENT

Given the complex maneuvers possible with agile aircraft, anticipated use of carefree handling, and decrease in sensory feedback (noise and buffet), the pilot needs to have precise timing and perception of any change in the aircraft's energy state. Moreover, the pilot needs information pertinent to energy management to weigh the advantages of different maneuvers that can be employed. For instance, the pilot needs information on the goodness of the launch condition to assess the tactical situation and determine whether to accept a low confidence launch or maneuver to a more favorable launch position. This is especially important since using the advantages of an agile airframe to point the nose at a target may leave the aircraft too slow to recover speed quickly for a missile defense maneuver.

6.3. HEAD UP CONTROLS/DISPLAYS

Providing and controlling information "head up" maximizes the amount of time the pilot spends looking out the canopy for threats. To date, this advantage is primarily realized with a head up control concept and a head up display (HUD). Head up control is achieved with the pilot's inceptors which can be operated with the head up. Agile airframes make a sophisticated system that integrates flight and propulsion control a definite requirement. With such a carefree handling system, the stick and throttle can be used to maneuver the aircraft inside the whole flight envelope, automatically taking into account aircraft limitations. Head up control is also facilitated with additional switches located on the flight controls; this hands-on-throttle-and-stick (HOTAS) concept enables selection of many sensor, navigation, and weapon systems without redirection of the pilot's gaze point.

A HUD presents symbology projected onto a transparent combiner. Some information, such as a pitch ladder that relates directly to the world, can be seen superimposed on the real scene to facilitate display interpretation. The display can also relay a sensor image, providing a view of the scene ahead at night or bad weather. Because the HUD combiner is fixed to the top of the instrument panel, the pilot must look forward along the aircraft longitudinal axis to see the symbology. Moreover, targets often lie outside its limited field-of-view.

Helmet mounted displays (HMDs) have been developed as one means of extending the advantages of the head up transparent display concept and overcoming limitations of current HUDs. An HMD can provide a wider area of visual information. Moreover, with a HMD, displayed information is within the pilot's field-of-view regardless of head movement and orientation. Because of their utility when the pilot looks both along and away from the fore-aft axis of the aircraft, HMDs are predicted to eventually eliminate the need for HUDs.

When implemented with a head/helmet position tracker, a HMD system can also provide target cueing and sensor guidance. In addition, these Helmet Mounted Display/Tracker (HMD/T) Systems have tremendous capability compared to earlier Helmet Mounted Sights (HMS) that combined a tracker with a sighting reticle to provide a simple aiming mark to pilots. HMD/T systems, along with other "head up" control and display devices (e.g., HOTAS and auditory systems), enable pilots to focus attention out the window and minimize manual control and head down glances which can cause disorientation and/or vertigo, especially in extreme

+/-G. This is even more critical for agile aircraft to support maneuvering, weapons launch, and evasion/survival.

The following describes candidate head up controls and displays. This presentation will focus on pilot usage of these devices for agile aircraft applications, rather than on the mechanics of each technology.

6.3.1. HELMET MOUNTED DISPLAY/ TRACKER SYSTEMS (HMD/T)

Candidate HMD/T systems have three major components: 1) a head or helmet mounted visual display, visually directed, 2) a means of tracking head pointing direction (based on the assumption that the pilot is looking in the general direction that the head is pointing), and 3) a source of visual information which is dependent on the head viewing direction [2]. Information displayed on the HMD can be referenced to head axes, aircraft axes, earth axes, or any combination of these three. Advances in several display technologies (miniature cathode ray tubes, etc.), make HMDs a definite candidate for agile airframes [3]. With further development, other hardware may provide additional advantages over conventional approaches. For instance, the Virtual Retinal Display™ scans a lower power beam of light to "paint" rows of pixels onto the retina of the eye, creating a high resolution, full motion image without the use of electronic screens [4].

The concept of HMD/T operation (Figure 6.1) is as follows: the pilot looks in a particular direction, the head tracker determines what the direction is, and the visual information source produces appropriate imagery to be viewed on the display by the pilot. The direction of the head can also be used as a control signal for a variety of aircraft systems, in addition to controlling what information is displayed. Thus, the HMD/T system serves as both a head up control *and* display, with an instantaneous field-of-view around 25-40 degrees subtended visual angle.

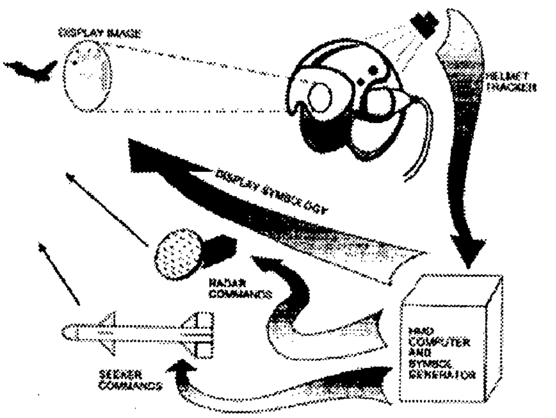

Figure 6.1. Schematic of Helmet Mounted Display/Tracker System Concept.
(Reprinted with permission from *Helmet-Mounted Displays and Sights*, by Mordekhai Velger. Artech House, Inc., Norwood, MA USA. www.artechhouse.com)

With a HMD, the pilot has a global view of information through the whole range of head positions [5]. Head up, visually coupled information will assist the pilot in looking out of the cockpit to maintain situational awareness in a highly dynamic flight environment. For instance, research has shown that an off-boresight HMD enhances the pilot's search capability, tracking performance and survivability in a simulated low-level, high-speed airborne surveillance/reconnaissance mission [6] and facilitates high angle target search and intercept during a simulated air-to-air engagement [7]. With a HMD, both the angle and duration of off-boresight visual scanning were increased. The extent to which this advantage can be realized depends on the information presented on the HMD, as the symbology can occlude the outside world view.

For combat, the combination of agile aircraft and HMD/T systems may offer important tactical advantages when used in conjunction with guided missiles. A tracker determines the position of the pilot's head as the target is followed through the display on the helmet visor. The tracker relays critical information to the computer that, in turn, communicates the location of the target to the missile system. When the weapons lock on the target, the pilot receives feedback and pulls the trigger located on the control stick to fire the missile. This scenario represents a total paradigm shift in the way within-visual range air-to-air combat is fought. The nose of the aircraft is no longer the sighting reference for cueing the weapon, but rather the pilot's helmet. As long as the target is within range and can be viewed by the pilot through the display in the helmet visor, the relative position of the aircraft to the enemy is not critical. Since a hostile contact averages only 30 seconds to 2 minutes, any time saved by not needing to repoint the aircraft helps give a quicker first shot capability to pilots. This capability also facilitates engagement of multiple adversaries. Using a HMD/T system, a pilot can designate and launch a missile or lock the radar and immediately turn to the next target, designating sequentially several targets within seconds without having to reposition the aircraft [5].

Another advantage of a HMD/T system is the ability to designate targets and hand off their location to other sensors and the theater communications system, in general. For example, the pilot can steer a FLIR system mounted on a steerable gimbal in the nose of the aircraft. Likewise, a threat detected by a sensor can be used to cue the pilot by showing directional information to the threat location on the HMD. The pilot can also designate a ground position and then call up cues to reacquire the target, should the pilot lose sight of it during maneuvering [5].

These potential tactical advantages were demonstrated in several simulated scenarios by operational F-15 pilots employing a HMD/T system [8]. The simulation pilots reported that the HMD/T: made it easier to accomplish within-visual range radar acquisition and get visual sighting of acquired targets, saved time in attacks, provided helpful weapon data while visually tracking a target, added tactics capability by easing simultaneous AIM-9 and AIM-7 attacks, and avoided sacrificing basic fighter maneuvers to launch an AIM-9 or perform a full system gun attack. The ability to accomplish a visual missile attack without sacrificing positional advantage was viewed a key advantage of the HMD/T. The pilots commented that the HMD/T provided as many improvements to air-to-air operations as weapons computers have provided to air-to-ground operations. There was also a marked exchange ratio advantage for the pilots with the HMD/T.

6.3.1.1 Visual Illusions with HMD/T Systems

Certain vision conditions (empty field myopia and accommodation convergence micropsia) can be problematic with HMD/T usage [9]. For example, even if symbology is presented on a HMD focused at infinity, overlaying the sky, some individuals' eyes will tend to focus two feet out from the display. Problems such as this can result in misjudgments of sizes and distances to external objects.

6.3.1.2 HMD/T Symbology Size/Location

Symbology size needs to be optimized for the HUD field-of-view viewing and the goal of minimizing obstruction of the outside view. Plus, the resolution of the HMD will impact the size and legibility of presented text and symbols. One study [10] has shown that recognition of symbolic aircraft presented on a collimated display deteriorated with increased eccentricity (5, 9, and 13 degrees). Aircraft in the periphery had to be displayed for a longer time than targets near the fixation axis, for viewers to classify them successfully. Response latencies were also longer in the lower and left visual fields.

6.3.1.3 HMD/T Symbology Format

Most of the information requirements for agile aircraft are the same as non-agile aircraft. For flight control, pilots need to know where the aircraft is actually going, rates of change, energy management, and how to recover to straight and level flight. Given the dynamic and expanded weapon envelopes realized by agile weapons, pilots will need enhanced estimations of the probability of detection and or launch as well as accurate information on the threat situation, ownship susceptibilities, and sensor ranges. Information is also needed to assess avoidance maneuvers and use of decoys.

Advances in display technologies make it possible to present pilots with formats that span from simple lines and symbols to high fidelity, geo-specific perspective scenes. Having the HMD format attempt to duplicate the organization and content of the real world is attractive in the sense that the pilot would have *everything* needed (Figure 6.2 [2]). The optical flow of objects could give natural cues as to altitude, attitude, and airspeed. For conditions in which view of the outside scene is poor or absent, such a display can provide a "virtual cockpit." [5].

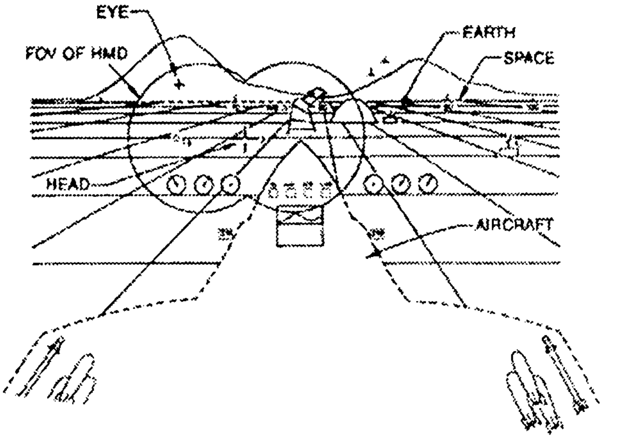

Figure 6.2. Example Candidate HMD Symbology.

For flights where the outside scene is visible, it remains to be determined whether providing this abundant amount of information is in the pilot's best interests. Contrary to viewing a HUD, the symbology remains constantly in front of the pilot's eye.

For any proposed format, systematic evaluations of candidate symbology sets are required. These evaluations should start by examining features of individual symbology elements. Indeed, experience has shown that the usefulness of elements depends on the pilot's current flight segment and information needs. For example, consider the use of digital, tape, and dial indicators of flight parameters. Some research has indicated that analogue displays are easier to process than digital displays since the analog information is extracted more intuitively, maps more directly on the response system (i.e., analog control inputs), and requires few mental transformations. Moreover, if the digits (e.g., vertical velocity) are changing very rapidly, the blurry readout is useless, especially when the pilot only needs to have a general indication of the rate and extent of change. It may be the case that a dial format (e.g., with arc scribing the outside of the altitude dial relative to changes in vertical velocity) is assimilated more easily than vertical formats [11]; however, initial results using a HMD presentation failed to support this notion [12]. With a perspective format, quantitative estimates are even more difficult to discern and adding scaled reference marks as a remedy tends to defeat the objective of providing the pilot the impression of flying into the perspective scene [13].

Besides the requirement to evaluate how conventional flight information should be presented for agile aircraft operation, the unique information needs for these missions also needs to be considered. For instance, pilots will need to monitor the more extreme angles-of-attack that can be achieved by agile aircraft. HMDs will help keep the flight path vector within view, except when the aircraft is at an extreme angle (e.g., 60 degrees). New symbology might be useful. One candidate HMD symbology set evaluated for the X-31 utilized two triangles, superimposed and appearing as one triangle for 0-30 degrees of angle-of-attack. For 30-70 degrees angle-of-attack, one triangle stayed fixed and the second grew to match a point on a scale inside the attitude reference symbology [14].

There have also been several evaluations to determine what symbology helps exploit the advantages affording by using a combination of HMD/T devices and precision weapons. One experiment investigated how the target location information should be related to the pilot [15]. Three symbology orientations were evaluated. In one, the symbology was relative to the nose of the aircraft, indicating the most efficient pursuit vector between the ownship and an airborne target location. A second orientation referenced head movement, indicating the most efficient line between the pilot's line-of-sight and a target. The third orientation evaluated included symbology that simultaneously presented ownship and head information. The results indicated that the ownship coordinate information may have more merit than traditionally believed and that pilots favored the combination which presented both "look-to" and "fly-to" locator lines when the target was outside of the HMD field-of-view.

Consideration of HMD symbology with respect to weapons needs to consider the exact flight mission anticipated, as information needs may differ depending on whether the pilot is engaged in air-to-air combat, air-to-ground attacks, or missile evasion (in addition to navigation and landing piloting tasks). The designer's objective is to provide the information required for each flight segment, yet minimize the pilots' training burden by keeping symbology sets as similar as possible. For instance, there have been several studies addressing how and when ownship information should be presented. One experiment [7] examined if ownship status information within the HMD symbology set is necessary for air-to-air applications. Several ownship status formats were evaluated, including the Standard Attitude Reference, the Arc Segmented Attitude Reference (ASAR) and the Theta Attitude/Direction Indicator (Theta). In the standard format developed by the US Air Force, the attitude set includes a helmet fixed inverted "T" climb/dive symbol oriented as an inside-out flight path reference, as well as an artificial horizon line and pitch bars.

The German-developed ASAR ("orange peel") includes a fixed climb-dive symbol that represents climb/dive angle by its relation to a half-circle arc surrounding the symbol [16]. The upper portion of the circle is invisible during straight and level flight. The visible portion of the circle represents the area below the horizon and the invisible portion represents the area above the horizon. The amount of visible orange peel translates to aircraft pitch (e.g., for positive pitch attitudes less than half the circle is visible, while for negative pitch attitudes more than half is visible). As the climb angle increases, the visible negative angle area of the arc begins to narrow in proportion to the climb angle. With an increase in dive angle, the arc closes to forms a more complete circle (Figure 6.3). At a 90-degree dive angle, the arc forms nearly a complete circle, leaving a small gap to cue the pilot of the most efficient direction to recover from the dive. During a roll, the arc rotates about the climb-dive symbol.

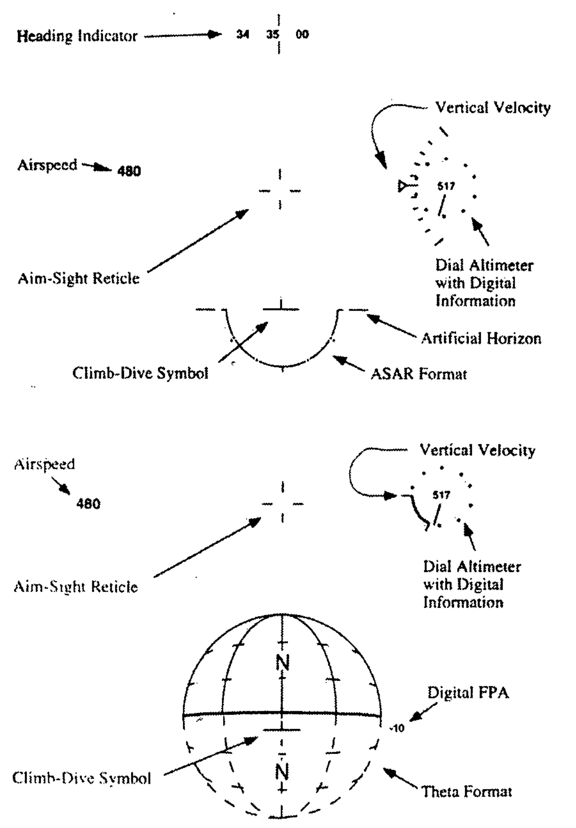

Figure 6.3. Example ASAR (top) and Theta (bottom) HMD Symbology [12].

Another format featured a Theta Attitude/Direction Indicator [16] developed at the Air Force Research Laboratory (Figure 6.3). The symbology integrates heading information and attitude symbology with a simulated three-dimensional, transparent, wire-frame half-ball consisting of arced lines. The longitudinal lines serve as an azimuth (heading) position reference in 45-degree increments. The ball is free to rotate about all three of its axes to represent rotation of the aircraft in those axes. Continuous lines on the upper portion and segmented lines on the lower portion represent climb and dive areas, respectively. Within the ball there is a climb/dive symbol and the cardinal headings are marked by letters. The format is mechanized like a standard, three-axis attitude direction indicator ball. The results of this experiment failed to show any interpretation or usability differences among the formats used to present ownship information. However, the pilots definitely preferred that ownship status be included in the HMD symbology set [7].

Another study specifically examined the ASAR and Theta symbology suites for a HMD used in the X-31 [17]. The pilots commented that for close-in-combat, attitude symbology was less critical, because the pilot flies relative to the opponent aircraft. Pilots found the ASAR useful as a large amplitude pitch reference for locating the horizon or recovering from an unusual attitude. This symbology is very compelling and effective for simple, instant instruction. However, they questioned its utility as a precision instrument. The Theta symbology was found easy to interpret and was the preferred attitude reference. The globe provided a good analysis of the situation. However, its utility in complex scenarios remains to be determined.

In a more recent effort at the Air Force Research Laboratory, a "non-distributed flight reference symbology" was designed to supplement HMD target acquisition information with ownship status information, the latter particularly useful during high off-boresight targeting tasks [18]. The key challenge was to ensure the presented information is useful without any associated clutter or disorientation incurred by its presence. This non-distributed flight reference symbol set presents ownship aircraft reference information close together and positioned within the attitude symbology (see Figure 6.4). The primary flight information is spatially arranged so that the conventional basic "T" layout is maintained with airspeed to the left of altitude and heading between airspeed and altitude. The information is presented digitally inside an outline designed to mimic the shape of aircraft wings and tail. Collectively, this compact information montage can be located anywhere in the HMD field-of-view (e.g., near the bottom during air-to-air applications).

The aircraft symbol is fixed relative to the HMD field-of-view and the attitude symbology moves about it. The flight path angle and roll of the ownship montage is represented by its relation to a half circle arc (using the ASAR approach described earlier). Heading tags appear at extreme climb and dive angle to give additional indication of ownship roll. This functionality was found useful in previous evaluations of the Theta attitude reference symbology and helps provide orientation information throughout the full aircraft-maneuvering envelope. During rolling maneuvers, the arc and artificial horizon rotate about the ownship symbol.

It is only through systematic evaluation of candidate symbology sets for specific flight tasks that optimal HMD symbology can be identified. Unfortunately, a format found to quickly provide pilots with an overall situational awareness and orientation perspective, may not provide the information required to precisely control the aircraft through a commanded mission. Also, the ideal format may depend on environmental factors, ground detail, and the availability of an outside reference. For instance

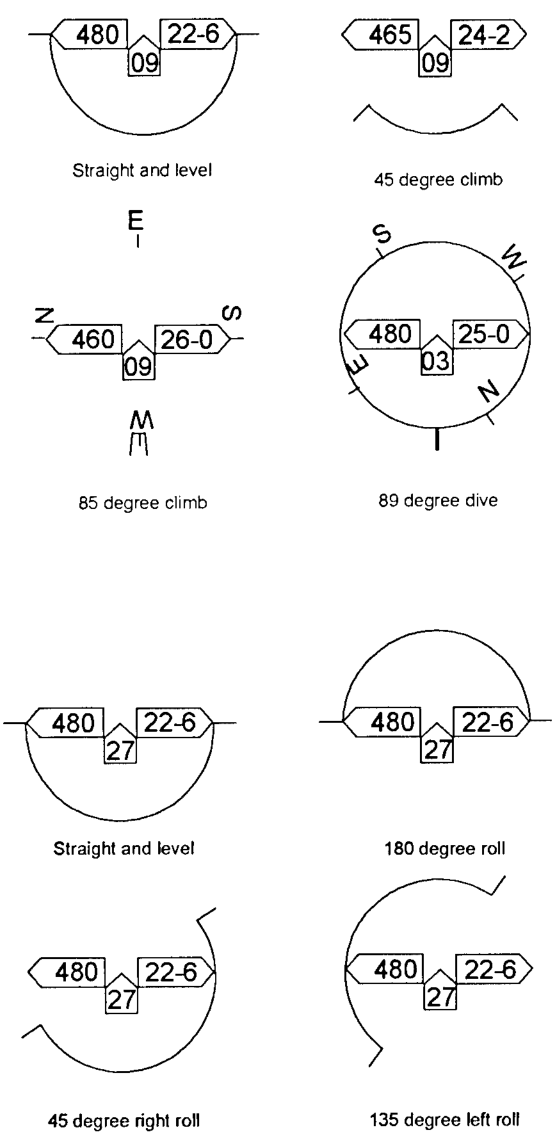

Figure 6.4. Non-Distributed Flight Reference Candidate Symbol Set with modified ASAR Attitude Symbology during various Climb and Dive Angles and Roll Maneuvering [18].

the reference frame used to present attitude information to the pilot ("pilot perspective") needs to be determined. Two major display concepts are commonly referred to as inside-out or "pilot's view" versus outside-in or "God's view." Typically, inside-out displays are viewed more appropriate for precise flight control and outside-in displays more appropriate for navigation and landing tasks. However, some research has demonstrated that an outside-in format is superior for unusual-attitude recovery [19]. In fact, pilots have noted that traditional aircraft-referenced inside-out attitude displays are more difficult to interpret when the head is moved off-axis.

Multiple coordinate reference frames can also be used. For example, one complex format envisioned for a HMD has a large instantaneous field-of-view and multiple cueing symbols. One aiming symbol would be in the upper portion of the HMD for designating aiming points outside the aircraft and another aiming symbol would be in the lower portion of the display to designate space stabilized electronic cockpit switches and functions [2]. The position of the cockpit switches imaged on the HMD stays fixed with respect to the cockpit, while the lower reticle moves with changing head position. When the lower reticle is placed over the electronic cockpit switch, it's visual form changes to indicate it is active and is being designated by head position. The pilot must then give a consent response by activating a single standard switch located on one of the primary manual controllers (e.g., joystick) or by issuing a standardized verbal command. Meanwhile, the upper aiming reticle remains active for designating outside world targets through other electronic control loops. Although it appears that this envisioned format would provide pilots with enormous display and control capabilities, there are numerous ergonomics issues that need to be examined before these anticipated advantages can be realized.

6.3.1.4 Pictorial Portrayal of Information in HMD/T Systems

Symbols and alphanumerics presented in display formats depicting status of aircraft systems can be viewed as individual chunks of information that must be perceived and cognitively integrated by the pilot. Humans are limited as to the number of information chunks that can be managed at a time. Advances in the generation of display graphics enable pictorial portrayal of information that groups individual pieces of information into fewer chunks. Theoretically, this reduces the pilot's workload because the processing required to chunk the information has already been accomplished [20]. The pilot can more rapidly acquire the message (assuming the pictorial is easy to interpret) and then devote time executing a response.

For HMD formats, the most popular pictorial presentation entertained is a three-dimensional perspective path to assist the pilot in flight control (see below). Pictorial formats occupy more display area than conventional formats. Given the limited field-of-view of the HMD and a desire to minimize the extent to which symbology interferes with the pilot's outside view, the added value of pictorial formats for HMDs needs to be verified.

6.3.1.5 Stereopsis Cues in HMD/T Systems

The introduction of true depth cues via stereopsis techniques in HMDs offers a means of further enhancing pictorial displays, particularly in improving the perception of pictorial layouts. For example, in one format a range marker element (waterline symbol) provides a non-stereo cue in that when the lead aircraft is at the desired range, the wingspan of the aircraft symbol is the same width as the ownship symbol (the desired range marker). Inclusion of stereo depth cues with this symbology was found to improve performance by 18% in a simulation evaluation [21].

Probably the most entertained cockpit application of this technology, is to provide the pilot with a three-dimensional "pathway-in-the-sky" which integrates all relevant information into a single display and the pilot's task is reduced to simply following the path (Figure 6.5). With the current accuracy afforded by

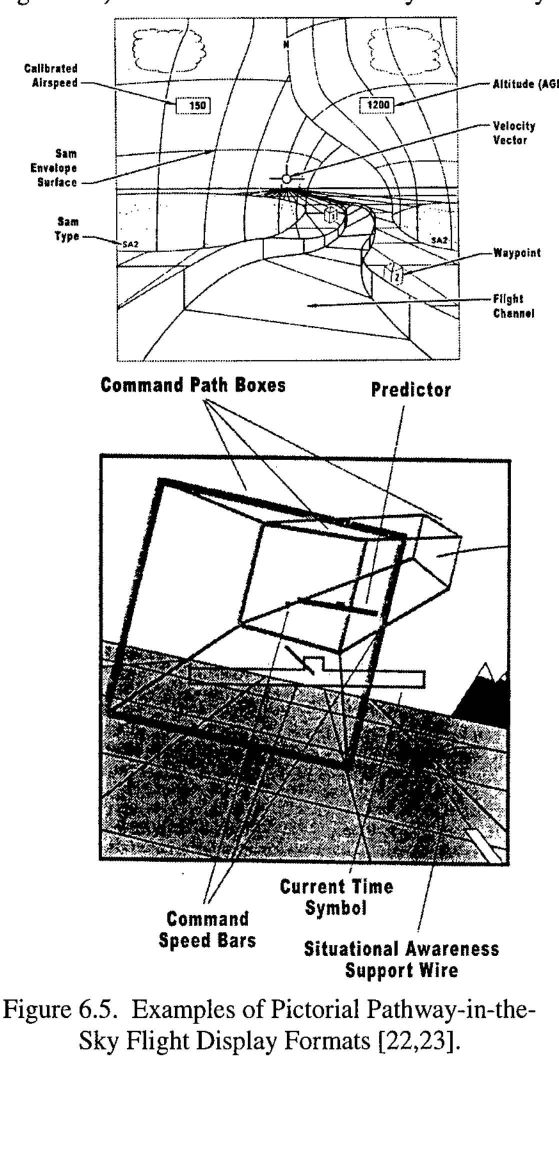

Figure 6.5. Examples of Pictorial Pathway-in-the-Sky Flight Display Formats [22,23].

Global Positioning and vast digital terrain data bases, the pathway-in-the-sky visualization concept is even more obtainable. In the example flight path display formats depicted in Figure 6.5, the pilot's task requires guiding the aircraft through the center of the channel to accurately stay on course. Each of the channels extends into the distance so the upcoming changes in the path can be anticipated. In the channel depicted at the bottom of Figure 6.5, the aircraft is a stationary symbol and the channel moves about it with changes in lateral and vertical direction. This channel configuration depicts the aircraft to be slightly to the right of command path, but flying the command altitude.

Of course during combat, the dynamics of the maneuvers make using a path-type format as a command display less appropriate. However, such a display could be very useful for: 1) providing predictive information to the pilot – illustrating the endpoint if the aircraft continues in its current flight path, and 2) providing short term command information to execute a pilot-selected stereotypical maneuver (e.g., scissors maneuver). In considering these channel displays for agile aircraft, there is a body of relevant research. Researchers have found that three-dimensional tunnels where the viewpoint of the display corresponds to the position of the pilot (i.e., fully egocentric) are superior for flight path control, particularly for flying curved paths [13, 23]. Subjects found the channel display intuitive and to provide quick and simple orientation. Integrating information pertaining to the aircraft's vertical situation, horizontal situation and profile situation also relieves the pilot from scanning multiple displays to acquire the same information. However, such a display reduces situational awareness due to its narrow field-of-view, making it difficult for the pilot to be aware of hazards in the surrounding airspace. If the field-of-view is increased, however, valuable display real estate is consumed or a distortion occurs as real space is compressed. This, in turn, also disrupts situational awareness, increasing the ambiguity of where things are in space. The resolution of predictor information in the display is already less, since the perspective presentation means a reduction of size for objects far away. Moreover, it is difficult to get sufficient quantitative information, unless additional scaled reference markers and readouts are added. These items, though, lessen the natural impression of flying through the channel [13]. In an experiment evaluating a three-dimensional perspective flight display compared to multiple two-dimensional planar displays, measures for flight performance and situational awareness were worse for the perspective display. The subjects commented that the key problem was the ambiguity in depth judgement along the line-of-sight that the perspective display caused when the aircraft was approaching landmarks [24].

A more near term application of stereopsis cueing for agile aircraft is to present different categories or classes of information at different levels in depth [25]. With this application, only a few levels in depth are needed and there is no requirement that they accurately represent a certain dimension in depth. Use of three-dimensional presentations on HMDs helps declutter information and enables the pilot to more efficiently switch attention between different information classes. For instance, the altitude, heading and airspeed indicators could appear on a different plane from the aircraft symbol [25]. As one pilot interviewed by the Working Group commented, if information can be positioned at different depth levels, much more information can be presented on the HMD. Of course, research would be required to determine the optimal assignment of information to depth levels – whether by information class (flight, weapon status, threat status, etc.), priority, flight segment, or some other combination. Another possibility is to have the coding pilot selectable.

6.3.1.6 Use of Color in HMD/T Systems

Assuming that the image source for a HMD is such to make colors visible under high ambient illumination conditions, use of color in display formats with discrete elements can make information uptake easier and faster. A likely near term application of color is in the pitch ladder symbology. Monochrome coding has already been applied in conventional formats to help reduce ambiguity between the positive and negative pitch bars and facilitate recovery from unusual attitudes. This has included using different shape coding for negative (bendy) and positive (tapered) bars. Color coding the pitch ladder (positive bars blue, negative bars brown) has been found to be beneficial in simulations, especially when used in conjunction with shape coding [26].

Application of color (red and green) to help code target location, tracking, and weapons deployment was examined in a simulation of off-boresight weapon aiming [27]. Overall, the pilots preferred the color-coded symbology to the monochrome baseline. Furthermore, a "red means shoot" color-coding strategy (involving a progression from green to red as an indication of shoot-criteria satisfaction) was preferred over a "green means go" strategy (progression from red to green). In a subsequent study, the "red means shoot" coding was systematically compared to a monochrome baseline HMD symbology in an air-to-air simulated weapon delivery scenario. Results showed the "red means shoot" symbology produced significantly faster shots without degrading the probability of kill [28].

Any application of color in agile aircraft should be aware of the results of an initial evaluation showing sequential changes in color perception during relaxed, gradual onset of Gz acceleration [29]. The effects occurred at 4 Gz and the first hue shift was a disappearance of light blue into white, indicating that use of light blue on a light background may be problematic during a high Gz turn. The second shift was green to yellow. Thus, use of green and yellow to code classes of threats on a display may be confusing. Such findings support formats that employ redundant (e.g., color and shape) coding.

6.3.2. EYE-BASED CONTROL

The next plausible extension of the capabilities of HMD/T systems is the integration of eye tracking to enable control of crew station functions using the pilot's eye line-of-sight [30]. In that the visual system is the primary channel for acquiring information and eye muscles are extremely fast and respond very quickly, it is advantageous to have the direction of eye gaze serve as a control input. In other words, if the pilot is looking at a target, it is more efficient to use the pilot's gaze to aim a weapon, rather than align the head or manually slew a displayed cursor over the target. In this manner, eye-based control can increase the envelope and speed of target acquisition with a HMD/T system. Line-of-sight cueing between pilots can also be facilitated by eye designation of points of interests. The pilots briefing the Working Group were very positive as to the increased capability that could be realized with eye-based control. Moreover, eye motion is more feasible under high acceleration conditions, compared to head or hand movement.

For eye-based control to be useful, however, it is important that the pilot's eye movements remain natural and not involve unusual blinking or lengthy fixations. Eye-based control is similar to operating a computer mouse in the sense that gaze position indicates the position or response option on a display, and some method analogous to a mouse button press is used to trigger the response. Without the additional consent response, a "Midas touch" problem could occur, with commands activating wherever the pilot looks. Different types of consent responses have been evaluated [31] and it is recommended that a dedicated, conveniently located button (e.g., on the joystick) be employed as a universal consent response. If the pilot's gaze is only being utilized to call up additional data for eye designated icons, then perhaps only a short fixation is sufficient, without a consent response. In this manner, the pilot's sequential review of a series of targets can be made more rapidly, with detailed information popping up, as the gaze briefly pauses on each target.

Although current eye tracking systems are not flight worthy for agile aircraft applications, numerous efforts are underway to explore how eye tracking optics might be integrated into HMD systems and how best to track the eye under varying illumination conditions. It is anticipated that eye-based control will eventually be feasible for agile aircraft and be used to designate display areas subtending approximately 1 degree of visual angle (by fixating 50-100 milliseconds) [32]. Designation of very small targets may be problematic; however, there are several techniques the designer can employ to aid in the gaze-based selection of densely packed targets [33]. Improvement in eye tracking technology will also be required to enable eye-based control at more extreme "look angles" (e.g., +40 degrees azimuth and elevation).

6.3.3. ELECTROMYOGRAPHIC (EMG)-BASED CONTROL

It is feasible to modify the hardware or helmet housing a HMD/T system, or the pilot's oxygen mask, to position electrodes on the surface of the skin which detect the asynchronous firing of hundreds of groups of muscle fibers. These electrical signals that accompany muscle contractions, rather than the movement produced by these contractions, can be used to provide EMG-based control. Most commonly, these electrical signals are compared to some threshold value to derive a binary control input – above threshold initiates one control action, below threshold initiates another [34]. Development is still required to optimize the signals employed, assess the stability of electrode contact over time, and minimize the effect of operator movement and external electrical activity on signal recordings. However, EMG-based control is a far-term candidate head up controller that enables the pilot to make discrete responses without using the hands. To implement EMG-based control, it is important to choose a body movement that does not interfere with the pilot's normal functions, is not likely to be made during normal activity or in response to acceleration loading, and can be implemented such that the system can discriminate a purposeful EMG input from an inadvertent one. To date, subtle/slight eyebrow lifts and jaw clenches have been successfully used in concept demonstrations as enter and tab functions on a computer task. However, these simulations targeted ground-based tasks and the results may not be applicable to agile aircraft controls.

6.3.4. ELECTROENCEPHALOGRAPHIC (EEG)-BASED CONTROL

Electrodes integrated into the pilot's headgear positioned over specific areas of the scalp can provide the necessary signals to implement EEG-based control [35]. This type of control translates the electrical activity of the brain into a control signal. In one approach, EEG patterns are brought under conscious voluntary control with training and biofeedback. A more applicable approach harnesses naturally occurring brain responses to modulated stimuli. These brain responses include components that modulate at the same frequency as the evoking stimuli. Selectable items of a display are modulated at different frequencies. The pilot's choice (gaze point) between selectable items can be identified by detecting which frequency pattern is dominant in the visual evoked brain activity. In effect, the advantages of eye gaze-based control can be realized with less expensive and obtrusive components with this mechanization.

Optimization of this head up control requires minimizing the time required for signal processing, developing easily donned electrodes, and minimizing the distraction produced by modulating (flashing) display items. Research is underway to investigate whether the brain responses produced by high-frequency modulated stimuli (that the pilot does not perceive as flashing) are adequate for implementing EEG-based control [36].

6.3.5. SPEECH-BASED CONTROL

Speech recognition technology allows the pilot's speech signals to be used to carry out preset activities (e.g., allocate missiles to targets, change navigation route and radio frequency, alter displays, control radar, etc.). Unless a high recognition reliability can be achieved (e.g., 95% correct recognition under 4 G), voice entries may need an additional validation step for many agile aircraft control functions. Design factors that influence the utility of speech recognizers include: acoustic similarity of commands, length of words, microphone placement, consistency of the speaker's speech, vocabulary size, and the extent to which the order of commands is restricted [1]. A key challenge to the application of speech-based control for agile aircraft is efficient dialogue design. The vocabulary and syntax must be manageable, without imposing a great memory load or interfering with communications. If the pilot has to look down into the cockpit to read command names off a menu, then the head up control advantage of speech-based control is compromised. Use of speech input also has the potential of rapidly accessing functions several levels down the hierarchical structure of a multifunction control. On the other hand, selection of a dedicated, frequently selected switch (e.g., HOTAS concept) may be more rapid than the mental processing involved in issuing a verbal command and the time required by the voice recognizer to process the signal.

There are several environmental factors, which can impact the performance of speech systems: high ambient noise, vibration, stress level of the pilot, and acceleration (although, "intelligible speech" can be produced up to 9 G). To compensate for these shifts in speech due to changes in the environment, adaptation algorithms are required in the speech processing, as well as noise canceling hardware [37].

6.3.6. GESTURE-BASED CONTROL

Besides using the electrical activity produced by slight facial gestures, other small sensors mounted in the oxygen mask can be used to track fine movements of the pilot's face or lips. Optical and ultrasonic sensing technologies, for instance, have been used to monitor an operator's mouth movement. In one implementation, a headset boom located in front of the speaker's lips contains an ultrasonic signal transmitter and receiver. A piezoelectric material and a 40 KHz oscillator are used to create a continuous wave ultrasonic signal [38]. The transmitted signal is reflected off the speaker's mouth, creating a standing wave that changes with movements in the speaker's lips. The magnitude of the received signal is processed to produce a low frequency output signal that can be analyzed to produce lip motion templates.

There are two candidate applications of lip motion measurement. In one, the pilot's lip movements are processed during speech inputs to provide "lip reading." An experiment using an ultrasonic lip motion detector in a speaker dependent, isolated word recognition task demonstrated that the combination of ultrasonic and acoustic recognizers enhances speech recognition in noisy environments [38]. Alternatively, symbolic lip gestures can be translated into communication tokens that are used as control inputs.

6.3.7. DISPLAYS IN THE PERIPHERAL VISUAL FIELD

Given the increased likelihood of spatial disorientation in agile aircraft, the "Malcolm Horizon" attitude display was reviewed [39]. This concept involves projecting an artificial bar of light across the instrument panel and having it move in a manner corresponding to the horizon outside the aircraft. Such a display enables supplemental attitude information to be acquired in the pilot's periphery. Although pilot response to demonstrations of this concept was generally positive, problems with upright-inverted ambiguity were noted.

The display of information in the pilot's periphery also takes advantage of the human's increased ability to detect movement in the periphery, compared to central vision. Thus changes in attitude may be more readily detected with a peripheral display. On the other hand, this phenomenon may make the frequent detections of attitude changes a source of distraction. Or the peripheral display may not be perceived at all, if the pilot is attending to the central field. To date, efforts to develop large-scale peripheral attitude displays have met with only mixed success and their value for agile aircraft can only be determined with additional evaluation. These evaluations should consider a more textured format that provides a "flow field" in the periphery and the likely utility of HMD/T systems. Other modalities (tactile and auditory) may also be useful for increasing attitude awareness.

6.3.8. TACTILE DISPLAYS

Tactile displays are another candidate device for agile aircraft applications. ("Tactile displays", herein, refer to devices that convey distributed sensations, rather than devices that provide vector force haptic feedback.) Tactile displays located on the human trunk have the potential of providing information without interfering with motor or any other sensory function. Also, they are "head up" displays since the perception does not require the pilot to glance into the cockpit. The human skin responds to several distributed physical quantities: vibrations, small-scale shape or pressure distributions, and thermal properties. Vibration based displays use frequencies ranging from a few Hertz (Hz) to a few hundred Hz. For aircraft applications, the distribution of skin stimulation is mapped to the state of some aircraft parameter or system. For instance, one university group [40] is examining microelectronic mechanical systems which, when integrated with a fabric suit, can provide a thumping or gentle pressure on a certain part of the pilot's abdomen to notify the pilot when the aircraft is listing to one side.

One tactile display has already been demonstrated for a helicopter application. The Tactile Situation Awareness System (TASS) is designed to provide an indication of velocity direction and velocity vector magnitude [41]. Specifically, 22 pneumatically driven tactors (1.25 in diameter) were integrated into an F-22 cooling vest worn on pilot's torso (Figure 6.6). By activating (vibrating the membrane at +/-2 PSI amplitude at 50 Hz) different tactor locations on the torso, the direction of helicopter drift (in 45 degree increments) was indicated and the tactor activation pulse pattern (rate of turning tactor on and off) was used to indicate the magnitude of drift. The preliminary results from four pilots completing hover maneuvers suggest that such a tactile display may improve pilot awareness of helicopter movement and reduce workload, especially under reduced visibility conditions. As one pilot commented: "I could feel the tactors before I could detect visual cues of movement." This promising technology may also

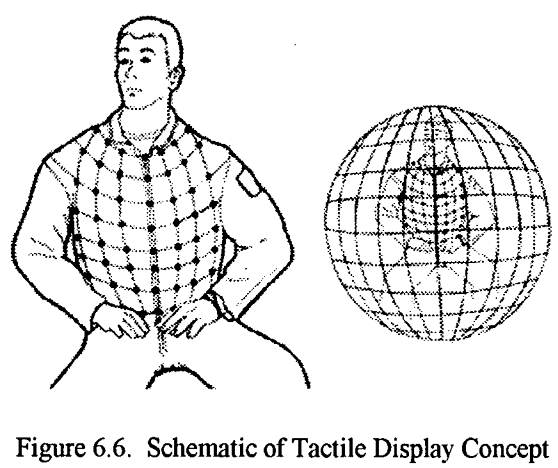

Figure 6.6. Schematic of Tactile Display Concept

have additional applications for altitude awareness (e.g., using a tactile display on the arm), position maintenance around a reference point, directional indication of threats, and non-verbal communication. The utility of tactile displays is determined in part by their limited resolution (discrete number of tactors), the limitations in the rate at which pilots' can effectively use incoming tactile data, and their utility under acceleration. In particular, evaluation is required to determine how pilots resolve any conflicts between visual and tactile information.

6.3.9. AUDITORY DISPLAYS

Auditory displays are also a "head up" source of information for pilots. Although auditory signals have been used in crew station design for some time, to date they have been limited to single frequencies or voice communications, primarily presented monaurally. In one application, navigation deviations were indicated with a Morse code type auditory signal: a Morse code "A" for one direction and an "N" for the other. The two frequencies fused into a steady tone of 1,020 Hz when the aircraft was on course. Changes in both frequency and pulse rate of an auditory signal have been used to indicate key points in AOA (30, 40, and 70 degrees). Another approach "aurally" presents several flight parameters with an acoustic orientation instrument. The instrument displays airspeed as a sound frequency (repetition rate), vertical velocity by amplitude modulation rate (increase shown by increased pitch), and bank angle by right/left lateralization (louder signal in side that is same as direction of bank). This display was presented to pilots over earphones, after processing the auditory signal to map with the actual aircraft flight data. The results showed that acoustic signals can be useful indicators of the orientation of an aircraft, and interaural intensity differences, representing bank angle, are particularly effective in this regard [42].

Additional improvement in the acoustic orientation instrument might be realized by using three-dimensional localized signals, rather than lateralized signals. This is now possible due to recent advancements that have enabled the faithful reproduction of omnidirectional, complex auditory signals. This includes duplicating the interaural intensity difference, interaural time difference and the direction dependent spectral information that occurs when incoming sounds impinge the head and outer ear (pinnae). The latter are especially important to externalize the sound to appear "outside of the head." To reproduce the dynamic cue changes that occur with the pilot's head movement, some type of head tracker needs to be integrated with the audio display. Head tracking enables the headphone presented stimuli to be corrected in real-time so that they are perceived by the pilot to be at fixed positions in physical space.

For agile aircraft operation, the combination of three-dimensional auditory displays with a HMD/T may be especially useful. The auditory cues could improve situational awareness by informing the pilot that critical visual information lies outside of the current visual field. The spatial auditory cues may even indicate exactly where the information is located relative to the current position of the pilot's head (see Figure 6.7). In a study which compared different methods of directing attention to peripheral targets, target acquisition time with three-dimensional tones was less than other auditory signals (coded aural tone, speech cue, and three-dimensional speech cue) [43]. In another study, use of spatial information from the auditory channel reduced search latencies on the order of 100-200 milliseconds. This advantage increased as the eccentricity of the target increased beyond the limits of the central visual field [44]. The results of an evaluation on the effects of using localized auditory information to perform a target detection task using a HMD in a simulation study were similar. Subjects were able to detect targets with less overall head motion and reduced head velocity [45]. Under high acceleration environments, this may help reduce the risk of neck and shoulder fatigue and injury. In actual Harrier flight tests, a three-dimensional audio system was particularly effective for azimuth cueings. Aviators were able to discern targets separated by 12-20 degrees [46]. Three-dimensional elevation cues, however, did not provide similar precision, but were adequate in discriminating two spatial levels (low versus high).

Speech intelligibility and discrimination can also be improved by localizing speech inputs. Small angular separation of messages (45 degrees) has been found to greatly improve speech intelligibility. At 90 degrees of separation, the speech intelligibility levels were maximized [46]. A three-dimensional communication separation system also worked well in Harrier flight tests, aiding the copy of dual message traffic [46].

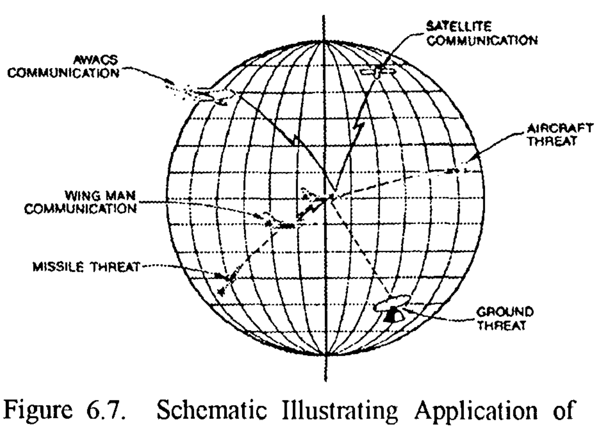

Figure 6.7. Schematic Illustrating Application of Three-dimensional Auditory Display for Three-dimensional Awareness of Threats and Communications.

Information from spatialized auditory cues can also help code system status information. For example, to aid the pilot in understanding a critical situation and add redundancy to the message, a left engine auditory fire alert message could be displayed such that it appears to emanate from the left. The auditory space can also be used to indicate the level of urgency of an auditory warning. The most urgent warnings would be presented so they are perceived inside the head, while less urgent warning are perceived to the sides [47].

In sum, three-dimensional auditory signals have the potential of being detected more quickly than visual signals, and, at the very least, relieving the pilot's already over burdened visual workload. Some candidate agile aircraft applications of three-dimensional auditory displays include: 1) alert pilots of ground or aerial threat location and facilitate target acquisition, 2) enhance situational awareness during air-to-air combat by localizing voice communications, 3) segregate multiple channels of communication so as to improve intelligibility, discrimination, and selective attention among audio sources, and 4) provide an additional cue for location or urgency of an aircraft system malfunction. Before these candidate applications can be implemented, further research is required to determine how best to exploit the capability to present spatial auditory signals and the best format for the information to be presented.

Given the flight envelope for agile aircraft, auditory localization accuracy under varying levels of sustained +Gz acceleration is of interest. The results from one centrifuge evaluation [48] showed that localization error did not significantly increase between 1 and 5.6 +Gz. Error did significantly increase at the 7.0 +Gz level, although, this performance decline can also be related to the difficulty making the manual response required in the experimental task. Localization performance in agile aircraft will more likely be influenced by factors already known to have an effect in ground-based simulations. First, auditory cues will need to be presented over headphones, as opposed to free-field localization, the latter providing more accurate localization. This is not foreseen as an insurmountable problem, since localization errors using headphone presentation has been reported as low as 4.4 to 5.9 degrees, depending on the type of stimulus [46]. Also, given the large field-of-view, a general indication of a target's position will greatly benefit the pilot. Second, errors in elevation are larger than for azimuth [46]. Once again, the pilot will benefit from any veridical directional information, whether it be solely azimuth or also include a coarse indication of elevation (e.g., high versus low). Third, and most important, it is likely that auditory localization will be accomplished with minimal movement of the head, since the pilot will most likely be attending to the forward field-of-view. This impacts performance because movement of the head helps disambiguate front/back reversals by tracking changes in the magnitude of the interaural cues over time influenced by the apparent source position. The most common type of reversals is when sounds simulated in the front hemisphere are heard at the mirror image position in the rear. The percentage of front/back reversals can be as high as 50% of the classifications. Until this confusion is controlled, application of three-dimensional auditory displays might best be limited to serving as a redundant cue. Also, further research is required to evaluate dynamic auditory resolution.

6.4. HEAD DOWN CONTROLS/DISPLAYS

In order for the agile aircraft pilot to keep the head up and out of the cockpit as much as possible, head down information needs to be easily acquired and head down control operations need to be quick to complete. This presents a difficult challenge to designers – *maximizing* the information conveyed or inputted by head down devices while *minimizing* the time required for head down viewing. The following addresses these implications and presents some candidate head down controls and displays.

6.4.1. HEAD DOWN CONTROL ISSUES

Head down controls need to be easily located, grasped, and manipulated. All the information and control devices needed for a particular set of activities should be in close proximity and available with less than two key presses. Proper and consistent formats, abbreviations, symbol meaning, control assignments, procedures and rapid (< 0.2 seconds) feedback need to be employed so the action required and status of control operation is intuitive to the pilot [9]. In addition to dedicated control devices, many control functions are activated by selecting a switch associated with a function presented on a display. The functions associated with each switch change depending on the flight segment or task to be performed. Human-engineered design of the required interactive sequences is key to the utility of these multifunction controls [49]. Function selection using touch activated displays (press display surface over appropriate label) has proven to be useful in ground-based applications, but operators must be more attentive to visual and audio feedback due to the lack of kinesthetic feedback [50]. Selection of small targets or closely spaced functions is also difficult, especially with flight gloves (one pilot described as "Fist on Glass").

6.4.2. HEAD DOWN DISPLAY ISSUES

The primary function of head down displays is to increase the pilot's situational awareness and provide additional systems information. If this information continues to be presented on numerous dials, indicators, and multiple small displays, it will be very difficult for pilots to rapidly fuse the information together to access the situation. One solution is to present this information on a single large (e.g., flat panel) display [3]. Merely moving all the information onto one surface will not facilitate pilot performance. Rather careful format design is required to identify an integrated format that makes it easy for the pilots to determine what actions are possible at any moment and evaluate the current state of aircraft systems. In other words, the right information in a useful format needs to be presented at the right time. Moreover the information needs to be presented in the right location – any critical information should appear at the same location all the time.

With programmable displays, there is virtually no limit as to how information can be presented. This is a mixed blessing because there is a natural tendency to provide the pilot with several options, not knowing the optimal approach in advance. This is counter-productive, adding to the pilot's visual workload and cognitive demands to filter out the required information. Display formats for head down displays (as well as head up displays) represents a research topic requiring significant attention. Specific design guidelines and useful metrics for managing the presentation of information in multipage displays are available in [51].

For map displays, the scale and frame of reference (track up or north up) should be pilot selectable. As a default, a track up view in which the map display rotates to match the momentary heading of the aircraft is better in that it eliminates the need for the pilot to do mental rotation [23]. A three-dimensional presentation may help provide information about the relative distances of objects from the ownship. To date, though, there has not been a consistent advantage with a three-dimensional approach [23]. Color-coding has been found useful for distinguishing boundaries and differentiating symbology sets. Rather than present sensor data on different formats, an attempt should be made to fuse the information into a single format or integrate and code the information so that the pilot knows the source of each datum.

Information presented on head down displays is the primarily source of weapon and aircraft systems status. The information needs to be limited to what is meaningful or more easily used by the pilot. Examples include fuel in available range format and threats as potential killers or not [1]. For some systems, a pictorial presentation of the information may be more intuitive and more quickly assimilated. Figure 6.8 shows examples that were generated in a study to examine use of pictorial formats for military cockpits [22]. Pictorial symbols can be used to describe the status of subsystems as well. For example, a pictorial representation of the four mechanical fuzing options (nose, tail, both, or none)

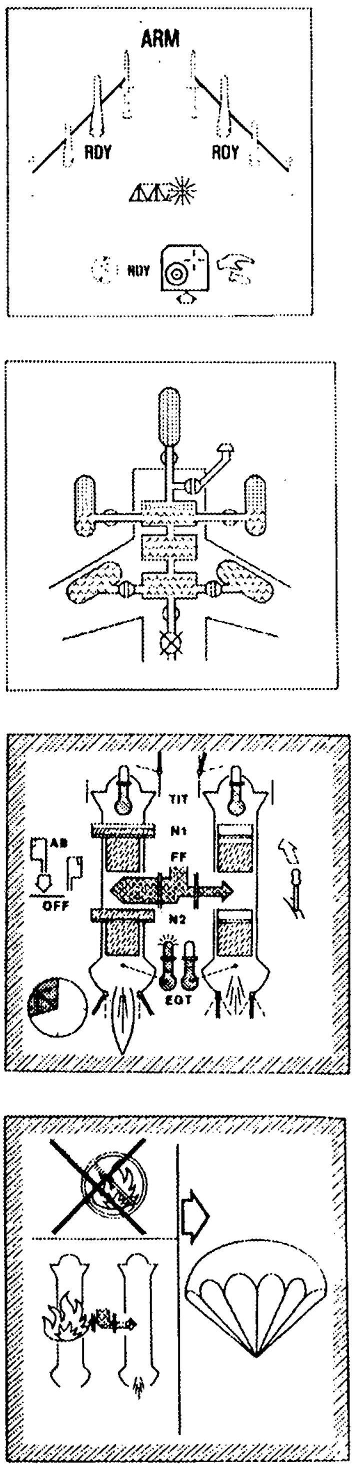

Figure 6.8. Example Pictorial Display Formats Showing Systems Status [22]. First two show weapons and fuel status. Last two are engine formats.

provides a more realistic impression of what is actually happing with the fuzing, compared to an alphanumerical readout. Color-coding can also be very useful to note operating ranges of a system parameter. Evaluations are required to determine whether additional costs to provide pictorial and color formats are merited in terms of aircrews' performance and preference. The results may differ depending on the particular display format [52].

The flight control stick can also convey information to the pilot. In the past, stall warning systems employed stick shakers or stick pushers to warn pilots of impending stall conditions. The pilot's attention can be easily acquired by altering the control stick's force gradient. More recently, the utility of the pilot's sense of touch was examined in a landing experiment that fed information concerning lateral deviations from a runway centerline into a force reflecting control stick. The results indicated a consistent advantage in performance and perceived workload for the force feedback system, particularly for landings conducted under heavy turbulence [53].

6.5. MULTI-MODAL CONTROLS/DISPLAYS

A *combination* of modalities can facilitate the information exchange between the agile aircraft cockpit and pilot. However, there is also a danger in imposing an additional load on the pilot to remember the steps used to employ different controllers or burdening the pilot with superfluous stimulation with multi-modal displays. It is only through research that the optimal control and display configurations can be identified for specific tasks/applications.

6.5.1. MULTI-MODAL CONTROL ISSUES

Just as operators with desktop computers can navigate with a variety of controls, it is possible to implement aircraft system such that several control modalities can be used for a single control action. This mapping approach provides the pilot with increased flexibility: a) the pilot may have individual preferences for specific controls, b) a temporary task or environmental condition may deem one controller more efficient than another (e.g., eye-based control when manual selection is difficult under high acceleration or positive pressure breathing interferes with speech-based commands), and d) should one control device malfunction, the pilot can use a different control.

A multi-modal approach is also useful when two or more controls are integrated such that they are used together to perform a task. In one integration approach, a control technology that cannot perform a particular function alone can be used to improve the performance of another control. For instance, eye line-of-sight data might be used to enhance speech processing by restricting the vocabulary search to the most probable verbal commands associated with the current gaze point. In another type of integration, two or more control devices operate in parallel to increase the accuracy or reliability of a control action (lip movement data when used together with acoustic signals can improve speech recognition compared to either one alone). In a third integration type, controls are mapped to different subcomponents of a task. For example, the pilot can use eye gaze to designate a waypoint on a map display and a voice command for a consent response, commanding the navigation system to update the mission plan. The use of both control devices capitalizes on the ability of eye gaze to rapidly designate a position on two-dimensional surfaces and voice commands to quickly initiate an action. In fact, eye and voice systems can replace or augment conventional controls for many interactions with aviation displays (e.g. configure displays, tailor displayed information, retrieve information, and input information) [54].

6.5.2. MULTI-MODAL DISPLAY ISSUES

Multi-modal displays may be more effective in warning the pilot of an aircraft system malfunction or an impending threat. In one experiment, visual icons and verbal warning messages were used singly and in combination and the results showed a significant decrease in response latencies when correlated bimodal information was provided, as compared to either unimodal alert [55]. In another experiment, both a three-dimensional tactical (visual) radar display and a three-dimensional auditory display were presented to provide the pilot with information about the target aircraft. The radar display showed the target's relative speed and whether it was above or below ownship. The auditory display showed the direction of the target to ownship. The displays also differed with respect to frame of reference. The radar display was outside-in, indicating the relative position of the target as seen from above and the auditory display was inside-out, indicating position relative to the subject's head. The results showed that both displays, when used individually, reduced search time [56]. However, when the two modalities, visual and auditory, were used simultaneously, search time was reduced more.

Multi-modal displays can also help overcome the inherent limitations of display technologies when used individually. For instance, target detection performance has been found to be poorer with a HMD compared to a full field-of-view visual condition [57]. The results of follow-on research suggest that a three-dimensional auditory display can be effective in mitigating the negative effects associated with performing a visual target detection task with a HMD [45]. Another example where two modalities could complement each other is three-dimensional auditory displays and tactile displays.

6.6. INTELLIGENT INTERFACES

6.6.1. ADAPTIVE INTERFACES

The use of computer-driven controls and displays in agile aircraft cockpits offers the opportunity to include intelligent interfaces which help the pilot acquire information and execute decisions. This would provide more time for the pilot to control the aircraft and think about decisions that must be made. To meet this objective, the displays must be configured to provide information salient to the specific situation being addressed by the pilot and the controls must facilitate the pilot's response. The use of tailoring has already been introduced – only information previously determined appropriate for the current flight phase is presented. This tailoring is a result of an explicit control input by the pilot (e.g., selection of a flight mode switch). However, it is likely that the pilot would benefit from variations in the control/display configuration for specific tasks within a single flight segment. Rather than have the pilot continually commanding the system to make such changes (and in cases where the pilot is over loaded or incapacitated), it is desirable to have dynamically adaptive interfaces that change the display and/or control characteristics in real time [58] (see Figure 6.9). These changes are initiated by predetermined triggers:

- external (changes in mission, tactical constraints, threats, and aircraft systems (hydraulic failure)),
- internal (physiological) indices (measurable aspects of the neurophysiology that index changes in the pilot's physical and cognitive states), and
- behavioral indices (overt behaviors executed by the pilot (eye gaze point, control activity, etc.).

Besides choosing and validating the triggers and decision rules that initiate the adaptations, the specific modifications to be made to displays and controls in each instance must be identified. Implementation of adaptive interfaces is also a challenge due to the real-time timing constraints and the need to analyze continuous parallel input streams from numerous sources. To ensure that the candidate adaptive interfaces are indeed a benefit to the pilot, evaluations are required. The goal is to provide the agile aircraft pilot with the right information, at the right time, and in the right location for optimal performance and mission success. On the other hand, there are potential problems with impeding the pilot's cognitive momentum and causing confusion by changing information. The lack of consistency could also interfere with the pilot's skilled-based behavior. However, the results of one simulation suggest that dynamic changes in displays or controls will not interfere with the development or execution of skilled behavior [59]. This experiment utilized three interface conditions: conventional, advanced (flight director display and force reflecting stick), and adaptive (which switched between the conventional and advanced, depending on pilot performance on a navigation task). The need for further evaluation was indicated, though, that utilizes a more demanding task environment and more complex mechanisms to trigger adaptive changes.

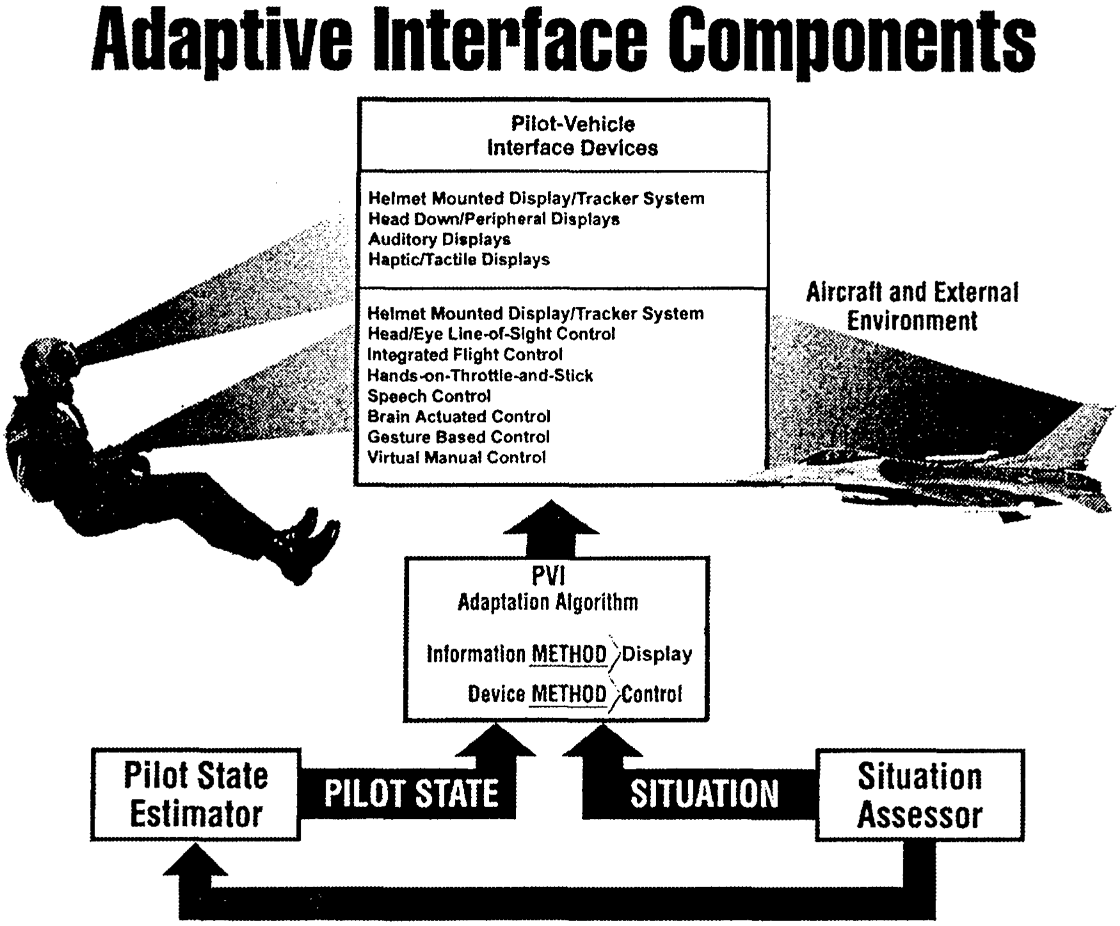

Figure 6.9. Illustration of Adaptive Interface Components in Crew Station Design.

Adaptive interfaces can also capitalize on the human's capability for parallel processing across sensory modalities. If a workload assessor determines that the pilot's visual channel is saturated, then a high-urgency display element that would nominally be presented on a visual display (e.g., approach of a G-limit) could be presented via the auditory system or via force feedback in the control stick. If it is determined that the pilot is heavily engaged in some activity (evading an enemy) and does not have the resources to attend to another task (activate electronic counter measures), intelligent systems could automatically perform the task and inform the pilot of its completion. In this case, the intelligent system is not only changing the interfaces but also accomplishing a task for the pilot. This role of automation in crew system design raises additional issues, which are discussed below.

6.6.2. AUTOMATION

Automation of some crew station tasks can certainly help reduce the workload facing the agile aircraft pilot. However, problems with automation can arise due to "clumsy" use of this technology. If the entire pilot/system operation is not considered, there is a likelihood of automation being activated at a time when it is least needed and hindering performance in situations where it is greatly needed. Even more common is the failure to provide the pilot with adequate feedback on the status and behavior of the automated system or task, which affects the pilot's ability to maintain situational awareness. The pilot needs to be able to maintain a mental model of both the monitored process and the status of the intelligent system, especially when multiple dynamic systems are in operation as is the case in aviation. Special attention should be given to the level of feedback. The complexity of modern systems makes it impossible and undesirable to display every data item, but a minimum level of information is desirable to keep the pilot on line, so that decisions can be made when needed. Also, the level of information provided to the pilot may be context-dependent. Lastly, there are instances where automating a task is not in the best interests of the pilot. For example, having the pilot a passive occupant during automatic guns aiming or automated missile avoidance can increase the pilot's disorientation and sickness during abrupt maneuver changes.

Some of these problems arise because the environment and workload characteristics of the cockpit are so complex and dynamic. What may be an optimal automation scheme for one flight segment/task may be totally inappropriate for another. Therefore, automation also needs to be dynamic or adaptive, with the goal of maintaining an optimal division of labor between the pilot and the aircraft [60]. In other words, the automation needs to be flexible and responsive to pilot and task demands and the same triggers used in adaptive interfaces are also useful for adaptive automation. With this pilot centered approach, there should be fewer difficulties with automation induced difficulties in monitoring and maintaining situational awareness because the pilot is kept more involved. Tasks requiring judgement, multi-sensory information gathering, hypothetical reasoning, and contingency reaction are best suited with the pilot in the loop. There are, however, some ongoing "housekeeping" tasks that can be automated; tasks that require accurate responses, fastidious and repetitive actions, and exhaustive calculations are good candidates for automation. The following are example candidate applications of automation:

- if an engine failure is detected, perform correction and concurrently notify the pilot
- manage fuel and hydraulic systems, but give high level information to pilot (range, malfunctions, etc.)
- perform appropriate actions for battle damages and inform pilot if operational capabilities or flight performance affected
- manage navigation systems, but store data for call up by the pilot
- assess situation, manage sensors and attach confidence indicators to fused and correlated outputs
- analyze target to provide identification, performance capabilities and optimum engagement parameters
- deploy aircraft defensive measures when pilot is busy accomplishing a popup weapon delivery sequence [61].

Besides adapting automation to the pilot and task demands, a human centered approach calls for obtaining the consent of the pilot (or requiring a command from the pilot) before initiating an automated action. This pilot preferred approach is referred to as "management by consent" – automation cannot take action unless and until explicit pilot consent has been received [62]. Since there are numerous instances where automation could play a role, requiring a consent response for every automated action is also unreasonable. It is recommended that the pilot input a nominal set of rules to be used by the automation system for the majority of tasks. For each task, the pilot should indicate preferences on whether the automation system should: always perform the task, sometimes perform the task, perform the task and notify the pilot, or ask for permission to perform the task. Having the pilot tailor the automation system before the mission helps minimize the chance of interfering with workload on other simultaneous tasks.

The term "management by exception" refers to instances where the system takes over *sometimes.* For instance, automation systems can perform less critical tasks on their own when it is detected that the pilot is suffering from demanding time pressures and workload. Of course, the pilot maintains an option to override this automation. There are also instance where pilot consent may not be practical (e.g., pilot injured) and function changes may need to be implemented directly by the adaptive system.

Given the number of aircraft systems and corresponding procedures and tasks involved, research is needed to decide how tasks should be shared between the pilot and aircraft, how much autonomy and authority should be given to each, and how agreements and commitments to actions can be negotiated between the two. Certainly, the degree to which automation is successful in agile aircraft is a function of the degree to which there is coordination between the pilot and the automation system [61].

6.7. SUMMARY

The issues raised in this lecture pertaining to controls, displays, and intelligent interfaces illustrate opportunities for enhancing the cooperative interaction between the pilot and the aircraft, with the ultimate goal of achieving pilot-cockpit symbiosis. Moreover, the importance of the pilot-cockpit interface to the successful exploitation of agile airframes, agile weapons, and agile systems has been demonstrated. It is clear that considering ergonomics in crew station design is key to the success of agile aircraft.

6.7.1. THE GOOD NEWS

The results of the pilot interviews and the reviews of this Working Group show that *drastic changes in the crew station design <u>hardware</u> are <u>not</u> needed for agile aircraft.* For the most part, near term control and display suites (Figure 6.10), current systems along with the advances that are nearing transition (e.g, HMD/T), are adequate. Even though modifications in formatting and configuration are required to address specific agile aircraft issues (e.g., presenting flight path information when at a high AOA), most are easy to implement since so much of the hardware is computer driven. A recent simulated air combat study demonstrated: 1) the feasibility of implementing many of these advanced concepts, and 2) these advanced concepts can result in statistically significant advantages, despite the fact that the subjects (pilots from three NATO countries) were more experienced with conventional crew stations [63]. This evaluation assessed both a conventional cockpit (F-16/F-15 type cockpit displays) and a virtually augmented cockpit (HMD/T, pictorial formats, color coding, three-dimensional audio

NEAR TERM
Head Mounted Tracker/Display System
Integrated Flight Control System
Hands-on-Throttle-and-Stick
Voice Control for secondary tasks
Improved Display Formats:
color, pictorial, and sensor fusion

FAR TERM
Visual Peripheral & 3-D Displays
Tactile Displays
Auditory 3-D Displays
Eye Control
Gesture Control
Bio-potential Control
Multi-modal Displays/Controls
Adaptive Displays/Controls

Figure 6.10. Candidate Near and Far Term Displays and Controls for Agile Aircraft.

cueing for the radar warning receiver, and a ground collision avoidance system) using objective and subjective measures. The findings indicated that the new design not only resulted in superior mission performance, but also did so with less workload and enhanced situational awareness. In general, those aspects of the mission that relied on target identification and maintenance of tactical position relative to the target appeared to be the most positively affected by the advanced crew station design.

Therefore, there is good news that significant investments in control and display hardware development are not required to meet the pilot-vehicle interface requirements of agile aircraft. Far term developments (Figure 6.10) that provide the pilot with *new* capabilities are, though, certainly welcomed candidates for agile aircraft application.

6.7.2. THE BAD NEWS

The results of this effort showed that the mental workload involved with information management in crew station operation is a limiting factor for agile aircraft operation. In order to achieve full operational performance in agile aircraft, the pilot must be able to perform several simultaneous functions: fly the aircraft, maintain situational awareness of the total air battle scenario, communicate with friendly forces, plan attacks, fly complex attack maneuvers, control aiming and release of multiple weapons, manage onboard systems, organize self defense against arriving threats, and perform high acceleration escape maneuver for threat avoidance. Given the increasing number of systems involved in completing these tasks and the myriad of control options available, it is not difficult to understand how the pilot can be overwhelmed. Rather than helping the pilot with these added capabilities, the design may in fact be hindering the pilot's ability to execute and survive the mission.

The bad news is that the *current approaches for pilot-vehicle interfaces do not support fast assimilation of information and control actuation.* Simply, the right information is not being provided at the right time in the right location. It is this inadequate information flow between the pilot and the aircraft that is the limiting factor in the performance of agile aircraft. Therefore, a significant investment is needed to conduct the human factors engineering, task analysis, design iteration, and evaluation needed to identify how the pilot-vehicle interface needs to be improved to support pilot/airframe/weapons/systems information exchange [9]. Compared to past aviation ergonomic studies, this needed research will be much more difficult to conduct. As the complexity and dynamics of the systems increase, so do the ergonomic challenges to consider new styles of interaction. New requirements are levied on user interface software and user communication dialogue in order to handle and describe complex and substantial input/output processing, simultaneous parallel inputs, continuous inputs and outputs, imprecise inputs, and timing constraints. Thus, designers are faced with both a great challenge and opportunity to realize crew station designs that will truly enhance the operation of agile aircraft. Hopefully, the concepts and technologies described in this lecture will assist in this creation of a pilot-cockpit symbiosis for agile aircraft applications.

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