

REAL-TIME THREE-DIMENSIONAL GRAPHICS DISPLAY FOR ANTI-AIR WARFARE COMMAND AND CONTROL

Control of air defense operations—anti-air warfare—requires commanders to interpret and act on computer-generated graphical representations of aircraft traffic throughout a defended area. A watch officer's ability to interpret this virtual environment rapidly and correctly determines operational success. As part of a continuing effort to improve coordination of anti-air warfare, the Applied Physics Laboratory is building a prototype system having as one of its functions a three-dimensional perspective display that can improve the commander's effectiveness in assessing a tactical situation. A distributed, object-oriented computer program has been developed to provide the performance and adaptability required for this approach to graphical display.

INTRODUCTION

The control of air defense operations is a complex and demanding task that becomes substantially more difficult as Navy operations move into the littoral area. Anti-air warfare (AAW) involves the use of aircraft and ship missile systems to defend ships, aircraft, or land-based troops. Success depends in large part on the commander's ability to understand the tactical situation clearly using area surveillance sensors and graphic displays of detected aircraft.

APL is developing a prototype system that gives battle group commanders a virtual environment for control of AAW operations. The prototype, the Force Threat Evaluation and Weapon Assignment (FTEWA) system, supports control of all phases of anti-air warfare.

A primary system element is a realistic, three-dimensional (3D) perspective display of the defended air space. The display provides AAW watch officers with a virtual environment they can readily understand; it requires minimal interpretive effort and creates minimal distraction from the tactical situation. All information needed to assess real-time air threats is integrated into the tactical display, which significantly reduces the effort required to integrate multiple information sources and interpret the tactical display, and thus improves AAW officers' effectiveness in controlling air defense operations.

Creating a 3D display to support tactical control requires much system implementation effort, particularly with the program that generates the display. System responsiveness to user actions must be essentially immediate, regardless of how quickly tactical control actions are taken. Therefore, the system must support the ability to preempt generation of a complex display when the user needs immediate access to other functions or information, and the latency must be very low between the issuance of a command and its execution by the computer. The difficulty of achieving this requirement is compounded since the methods usually employed to accelerate two-dimensional (2D) tactical displays do not apply to 3D presentations.

The prototype system is being developed within the Force AAW Coordination Technology (FACT) program, which is sponsored by the Program Executive Office for Theater Air Defense. The advanced AAW control techniques and display approach used in the FTEWA system depend on the availability of a coherent air track database, which has been provided by previous FACT projects that are now installed on ships as production systems and prototypes.

THE ANTI-AIR WARFARE PROBLEM

Anti-air warfare employs aircraft, missiles, or other systems to defend Navy ships and other points from air attack. Anti-air warfare operations involve planning air defense in a given tactical situation, monitoring the tactical situation, assessing potential threats, and responding to the perceived threat. Responses can be to direct aircraft to investigate suspicious sensor contacts, increase the level of preparedness, take various warning actions, or engage the threat.

These activities have become particularly challenging in recent years. The Navy must now operate in more complex environments, and, concurrently, comply with the imperative to prevent loss of U.S. forces while inflicting no damage to noncombatants. An especially difficult situation arises if operations are conducted close to the shores of both friendly and hostile countries when there are no overt hostilities. During these periods, extensive commercial traffic will be intermixed with U.S. forces and, potentially, with surreptitious threats. Nevertheless, the reaction to threats must be fast enough to defend against antiship missiles detected only a few seconds before impact.

Navy air defense operations include ships with surface-to-air missiles; aircraft for intercepting threats, called combat air patrol; and other aircraft for airborne surveillance and refueling. The AAW commander typically manages the use of many aircraft and ships during peacetime deployments. Surveillance often extends

beyond 300 nmi, and may detect more than 100 aircraft at any one time.

To evaluate the tactical situation and determine an appropriate response, the watch officer must fully comprehend this environment, which changes constantly as the situation evolves. The officer must assess aircraft behavior to determine the presence, magnitude, and possible intentions of a perceived threat and must know the disposition and readiness of available defensive assets. The officer uses these assessments to act and then must monitor and evaluate the effectiveness of the action, being prepared to continue or escalate defensive actions.

Characteristics that must be considered in assessing threats include range, heading, altitude, speed, attitude (climbing or descending), and location on Earth (e.g., an aircraft flying over a hostile country). Each parameter is measured by sensors on AAW participating units. Individual measurements are correlated over time by each unit to form “tracks” indicating the presence of aircraft or missiles. Tracks detected by each unit are exchanged so that all units have a comprehensive picture of the overall area of operation.

In assessing the situation, the commander must also evaluate the capability and readiness of each AAW unit, considering factors that can limit available options. Equipment malfunction or damage can severely degrade performance, by reducing radar detection ranges, for example. Available fuel constrains aircraft intercept capabilities. Atmospheric conditions and terrain affect basic

capabilities for detection and intercepts. Furthermore, all of these evaluations and resultant actions are time critical, and the situation must be interpreted and alternative actions evaluated within a broad context of political constraints and command directives. Finally, each problem must be resolved in a high-stress environment where errors are potentially catastrophic.

VIRTUAL ENVIRONMENT ASPECTS OF CURRENT ANTI-AIR COMBAT SYSTEMS

The combat systems of modern U.S. Navy ships create a virtual environment in which an AAW commander perceives and acts on threat aircraft. Aircraft near defended ships are detected by radar and other sensors and are represented to the user within a graphical display. The watch officer interacts with this representation of the environment by initiating defensive measures. Figure 1 shows how the process works.

Periodically, various sensor systems are used to detect aircraft at long range. Recurring detections are correlated to form a track indicating the presence of an aircraft at a particular location with a determined altitude, speed, and heading. These parameters and other information are used to identify the track.

Current combat systems present this information in a two-dimensional “plan view” showing the bearing and range of tracks within the area around the defended units. All aircraft are depicted by symbols indicating location, speed, heading, and identity. The symbols are annotated

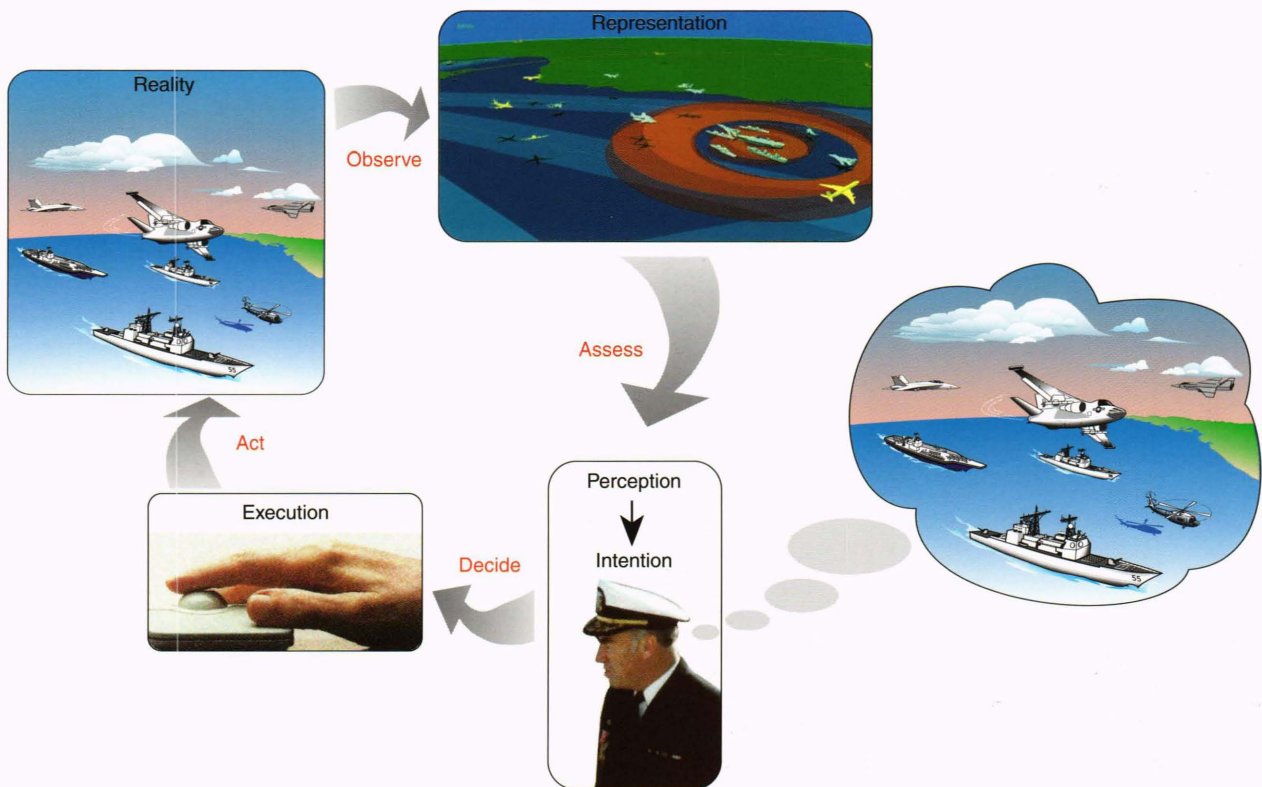


Figure 1. Modern combat systems create virtual environments—computer-generated representations of the operational theater—with which decision makers interact to assess and control the tactical situation.

to indicate track status. The display generally shows a coastline map, operationally significant areas, and, possibly, commercial airways to provide a context for the track display. All display elements are rendered as monochrome line drawings. Figure 2 is an example of such a display in use during a Navy operation. Several recent combat system prototypes and production systems have markedly improved the clarity of these displays by using color and filled areas, although they retain the two-dimensional, symbolic representation of tracks.

To access the additional information needed for monitoring own forces and assessing threats, the user must "hook" each track: that is, select the track individually with a trackball pointing device and then press a button to request an amplifying textual display. Among much other data, these displays contain readouts of altitude and further identification of the track. The interaction sequence to access amplifying track data is repeated frequently, since altitude is critical to tactical assessment.

To determine another critical threat assessment parameter, aircraft attitude, the watch officer must monitor track altitude readouts over time and observe changes. This task is difficult in high-density track environments, particularly when the officer is under stress.

To fully understand a threat, the user must integrate the various graphical displays, the symbology, and information from several sequential textual readouts into a complete threat characterization. The effort to manually select tracks of interest and to interpret the abbreviated textual readouts and symbols creates a significant burden, distracting the user from the critical decision-making process.

The AAW commander acts on this virtual representation to initiate real-world actions, redirecting friendly interceptors or even launching missiles against a threat. To initiate such actions, the user selects the subject tracks

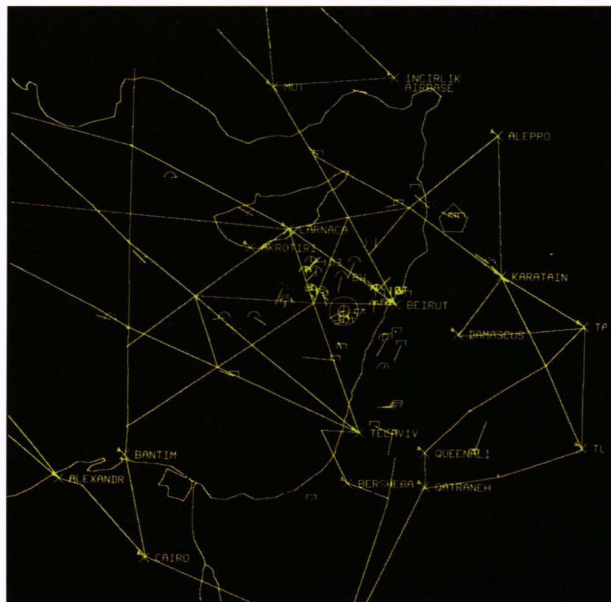


Figure 2. A two-dimensional "plan view" from a current combat system display of the area around defended units during typical operations.

within the automated system, again using a trackball pointer, and directs engagements with subsequent button entries. Of course, even though the effectiveness of automated support is critical to AAW operations, the extensive interaction among numerous watch officers is essential to success. Personnel on every ship and aircraft in the force support the AAW commander.

THE FORCE THREAT EVALUATION AND WEAPON ASSIGNMENT SYSTEM

The FTEWA system features a 3D tactical display, a prototype AAW command support system being developed within the FACT program. The FACT program's mission is to improve the Navy's ability to coordinate AAW operations among battle group units. The program addresses detection, command and control, and engagement. The control of AAW coordination requires a coherent track database across all participating units. Several previous FACT systems that address detection have substantially improved the capability to establish such a coherent track picture.

System Overview

The FTEWA system provides comprehensive support of AAW operations. It addresses planning, situation assessment, and battle management, all at the force level. The 3D display supports the interaction needed to manage all operational phases, not just basic tactical situation assessment.

Planning support principally addresses prediction of AAW system performance. The system models the capability of each unit to detect and intercept threats to the area defended by the force. It can represent the force-level effectiveness of all units combined, which supports decisions about where units should be stationed and helps in evaluating the impact of equipment failures. Because the composite performance predictions are extremely complex, particularly in the terrain of littoral operations, automated stationing is also available to help the commander optimize utilization of forces.

Situation assessment, addressing the identification and evaluation of threats and the force's ability to counter them, is supported in several ways. The readiness of each AAW unit is monitored. Equipment failures, changes in system modes, and unit locations can be evaluated using the performance prediction capability. In addition, track behaviors are continually assessed, providing alerts under user-specified conditions and events. The system ranks all tracks by the level of threat they present to the force, and this ranking is used to cue track assessment.

Engagement control is supported by the system's capacity to evaluate the ability of individual units to intercept specific threats. Also, the commander can use force-level engagement scheduling to help with engagement decisions (for instance, to estimate the amount of time left before a unit's effectiveness is reduced) or to optimize engagement of designated threats.

The FTEWA display supports each of these system capabilities; moreover, the increased situational awareness fostered by the 3D perspective presentation markedly improves AAW control.

The Three-Dimensional Tactical Display

The FTEWA tactical display offers an interactive 3D perspective representation of sensor data and other objects used in AAW operations. Though not nearly photo-realistic, the representation closely resembles the external reality of aircraft and land masses near the battle group (see Fig. 3). The user can navigate by directly manipulating the view port to examine the representation from any point above the Earth's surface. As the user moves about, the representation rapidly updates, or animates, enhancing the sense of realism.

Instead of a traditional flat map projection, the Earth is shown as a sphere with oceans and land masses. The land masses include detailed coastlines and national boundaries derived from Defense Mapping Agency (DMA) databases. Terrain data from the DMA ETOPOS database (elevation topography of 5-mi² resolution) are rendered as mountains and valleys on the Earth's surface. Commercial airways are depicted as transparent strips overlaid on the Earth's surface; these commercial airline paths are valuable in judging whether or not an air contact is a commercial airliner.

Air and surface contacts detected by force units are displayed with realistic 3D symbols that reflect the position and heading of the contacts in 3D space (see Fig. 4). The shape and color of each symbol denote tactical identification, such as airliners, fighters, and tankers. Track symbols are drawn with a pitch to indicate whether an air contact is ascending, descending, or flying at a steady altitude. Each symbol has a corresponding shadow drawn with the appropriate shape and orientation. Rather than showing where a shadow from the sun would fall, however, the shadow's placement indicates the track's "ground truth": that is, the position on the Earth's surface

over which the track is flying. Protruding from each shadow is a vector, called a velocity leader, which supports coarse judgments and comparisons of track speeds and headings. The distance between a track symbol and its shadow is one indicator of the track's altitude. The user can enable an additional altitude indicator, a ruled vertical line running perpendicular from the Earth's surface to the aircraft symbol. The altitude line facilitates more precise altitude perception but increases display clutter. In most tactical situations, the shadow alone will probably depict altitude adequately.

By providing additional heading cues, the shadow can also help resolve a notorious source of ambiguity associated with head-on symbols in perspective displays: the difficulty of determining if the aircraft is moving toward or away from the viewer (see Fig. 5). The absolute size of track symbols is uniform unless uniformity would be counterintuitive (e.g., since an aircraft carrier is larger than a destroyer, its symbol is larger). In the perspective scene, tracks closer to the viewer appear larger, a visual cue for distance that adds to the distance cue of the shadow's position on the Earth. Track symbols can change in appearance to indicate such things as user selection, engagement status, or status as a threat.

The FTEWA system also displays position of intended movement (PIM), station plans, battle group performance contours, battle group engagement schedules, and threat envelopes. The PIM is the path along the Earth's surface over which the battle group is planning to travel. It is displayed as a series of connected line segments projected on the surface. Station plans are postulated arrangements of battle group units along the PIM. The user can step through the station plans or choose to have them animated along the PIM. Performance contours reflect the predicted

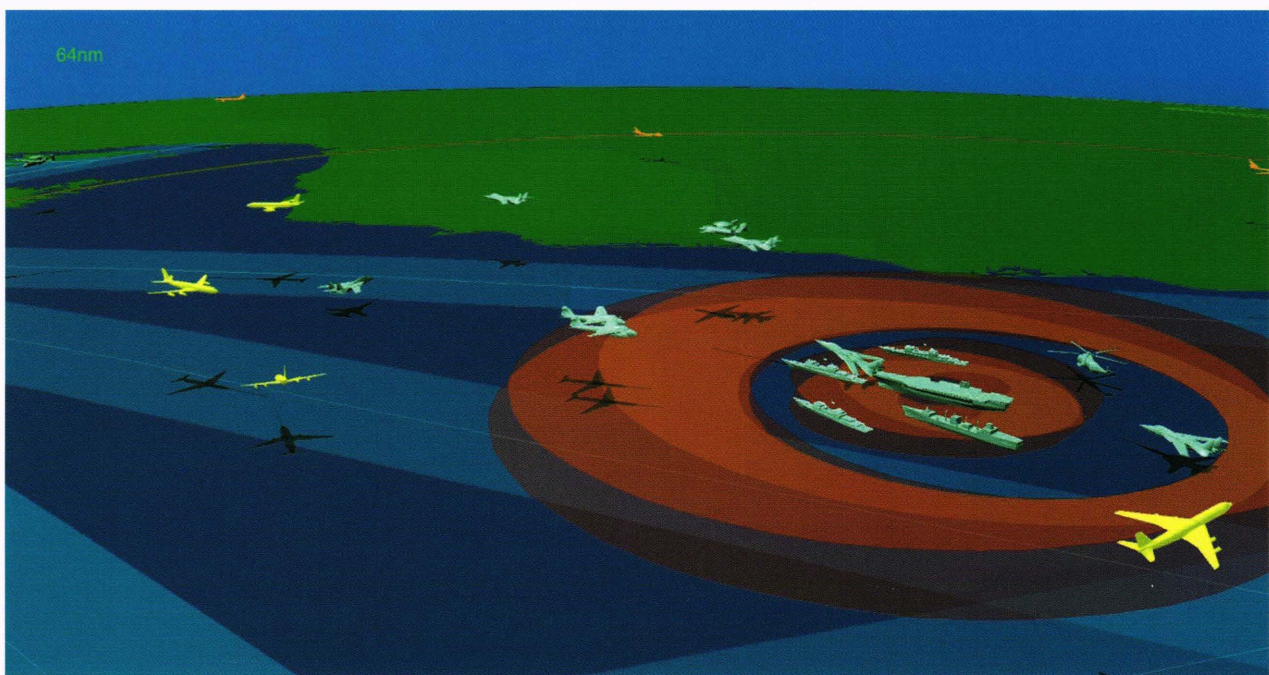
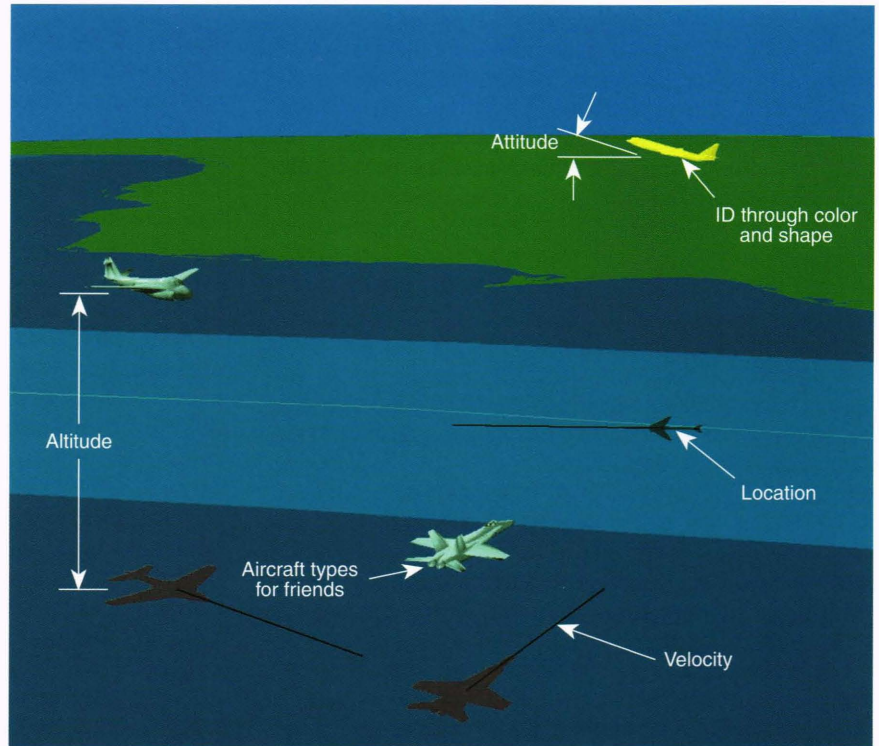


Figure 3. The Force Threat Evaluation and Weapon Assignment system's three-dimensional perspective display of the tactical situation.

Figure 4. The Force Threat Evaluation and Weapon Assignment system's three-dimensional aircraft symbols (ID = identification).



effectiveness of battle group radar and missile systems. For example, a contour can show where the battle group can detect a target or where a unit can engage a target with a given probability. These contours are shown as two-dimensional transparent slices projected onto the Earth's surface. An engagement schedule consists of all ongoing, planned, and hypothetical battle group weapon assignments. Each engagement is graphically displayed to indicate the threat's positions at launch and at interception, as well as the firing unit and the salvo size.

Threat envelopes specify regions in range of known or supposed enemy missile sites. Both effective and maximum ranges are displayed.

Benefits of the Three-Dimensional Display

The FTEWA 3D display integrates nearly all tactically significant data to improve the effectiveness of the human-computer interface. The main goal of the FTEWA interface is to give users the primary data needed for engagement decisions in a manner they can easily perceive within the 3D tactical display. This approach enables the user to perceive the interrelationships among tactical data and to focus on the AAW situation rather than on the problems of obtaining and unifying information from the computer. In particular, the track presentation directly integrates altitude and attitude, relieving the user of the burdensome, error-prone task of associating numerical data with a graphical representation.

Representations lacking integrated altitude and attitude information complicate situation assessment in two ways. Data that are difficult to acquire are more difficult to use in making a decision. Also, without immediately evident altitude information, a decision maker may substitute arbitrary or situation-biased altitudes that may be difficult to supplant even when the actual data are presented. In a study of how display format affects avoidance of air traffic collisions, Ellis et al.¹ showed that airline pilots have twice as much difficulty using altitude information presented textually with a plan view than presented in an integrated perspective view. Although this result cannot be directly extrapolated to the FTEWA system because the perspective displays differ, it clearly indicates that 3D presentation of altitude information can be superior to use of a plan view with textual information.

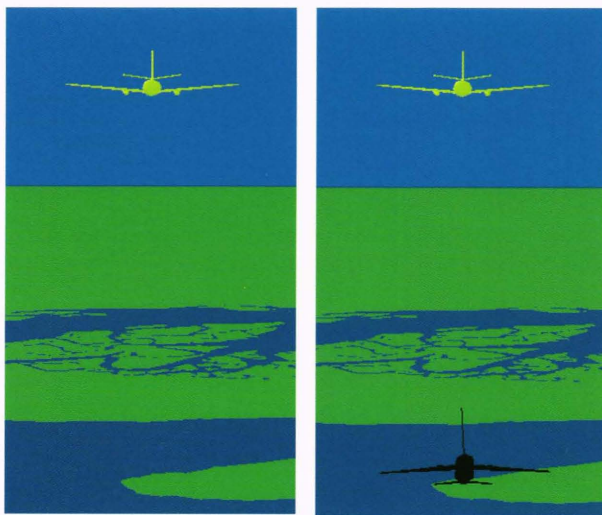


Figure 5. A shadow added to the aircraft symbol helps resolve ambiguity associated with symbols viewed head-on in perspective displays. Is the aircraft on the left moving toward or away from the viewer? Adding a shadow to the image clarifies that the aircraft is moving away from the viewer.

With the FTEWA virtual environment, a user's perception is rapid and accurate because the high-quality 3D images resemble external reality and are thus easy to comprehend. The images are based more on what the user already knows about the world and less on system-specific knowledge such as symbol encodings for detected air contacts. Interfaces that incorporate this quality require less training and result in better performance.² Certainly, the human mind is most experienced with 3D information and representation: it constantly operates on the unified, consistent representations it generates from the 3D input of visual, aural, and tactile sensory systems.³ With the 3D display, the computer is made to conform to the way people think and work most effectively instead of users being required to conform to the computer through extensive training.

The 3D display also facilitates the decision maker's recognition of battle group assets. The system presents a wide range of tactically significant "friend" symbols, such as fighters, strike support aircraft, tankers, electronic surveillance aircraft, and helicopters. Each friend type has a particular role in AAW operations, and awareness of these assets' positions is key to AAW control. The combination of friend identifications with altitude information allows tacticians to rapidly pinpoint key assets, thus facilitating such decisions as which unit should respond to an urgent situation.⁴ These enhanced capabilities eliminate the current taxing process of locating battle group units, which involves hooking a track, reading and interpreting a numeric code, integrating the unit type with the track symbol, and remembering the association.

Another aspect of the FTEWA 3D virtual environment that improves the human-computer interface is flexible perspective. Ellis et al.¹ suggested that allowing the user to control the view can be an effective strategy for reducing clutter and resolving ambiguities. In the FTEWA system, the user completely controls the perspective from which the tactical situation is viewed. The tactical situation can be viewed from any distance, from any location, and looking down from any angle. This flexibility allows the user to visualize tactical data more freely and to observe characteristics that might go unseen in fixed, top-down views. The flexibility also permits a higher degree of interactivity. The real-time animation responds directly to changes in the user's viewpoint. Changes are incremental and reversible, and the effects are immediately evident, resulting in a much more natural interface than indirect offset and range controls can provide.⁵

Equipment Used for the Display

The equipment suite that generates the FTEWA tactical display was selected on the basis of physical characteristics that foster comprehension. A large, high-definition television (HDTV) display monitor is driven by a high-performance, 3D graphics workstation. Together, these systems provide a large viewing area, high resolution for image detail, broad-dynamic-range color space, and very rapid update rates.

The use of HDTV confers two benefits: an aspect ratio consistent with the innate characteristics of 3D perspective views, and very high resolution. In a perspective view

(see Fig. 6) the depth is foreshortened, requiring fewer pixels and screen space to display data. In contrast, the width is expanded, requiring more screen space, to prevent objects on the periphery from being clipped. A square aspect, typically employed for tactical plan view displays, is best for top-down views. A wide aspect is better for perspective views; less vertical screen space is wasted showing the sky, and more horizontal screen space is available for objects in the periphery. The HDTV display resolution is 1900 by 1024 pixels. (Workstations currently used in Navy shipboard systems are typically 1160 by 900 or 1280 by 1024 pixels.) The high resolution permits clear enough detail in the presentation that track types can be recognized rapidly.

A 38-in.-diagonal HDTV monitor was selected over smaller formats for several reasons. Viewing the large-format tactical console from up close, as the user will, enhances both the perception of depth and the comprehension of the tactical picture. The increased depth perception in the 3D display results from the minimal perception of the display frame, which is visually distant from the area of focus. The observer is less aware of the flat display surface and can more easily integrate the displayed depth cues into the perceived picture. The large display surface also contributes significantly to the level of observer engagement.⁶ Enhanced observer engagement can reasonably be expected to increase the user's attention level and, consequently, comprehension of the display.

Another benefit of the 38-in., high-definition monitor is that detailed information is accessible within the context of the larger tactical display. The commander can both survey the overall tactical situation and study particular detailed aspects in depth without disjointed, disruptive viewing changes. The detailed circumstance is viewed within the larger context, which should provide greater continuity than with smaller displays that require narrowing the field of view to discern detail.

Finally, the large display surface allows track representations to be larger and easier to see. The larger symbols can be used without being overlaid or appearing cluttered. When necessary, the screen can be interpreted more easily from a distance.

The FTEWA system uses a Silicon Graphics, Inc., Onyx computer and a Sony high-definition television to achieve the required performance. The Onyx, with its Reality Engine graphics subsystem, provides the highest performing advanced-feature graphics available on a general-purpose development platform. The Onyx features very fast polygon fill rates and millions of colors, and it implements most graphics capabilities directly in hardware for improved performance. These capabilities include anti-aliasing, hidden surface removal, texture mapping (the application of a scanned-image bit map to a surface to enhance realism), clipping, lighting, and shading. The 3D view is manipulated by a six-degree-of-freedom input device called a Spaceball.

Display Implementation

The requirement to generate 3D perspective views that are fast and responsive enough for tactical use is

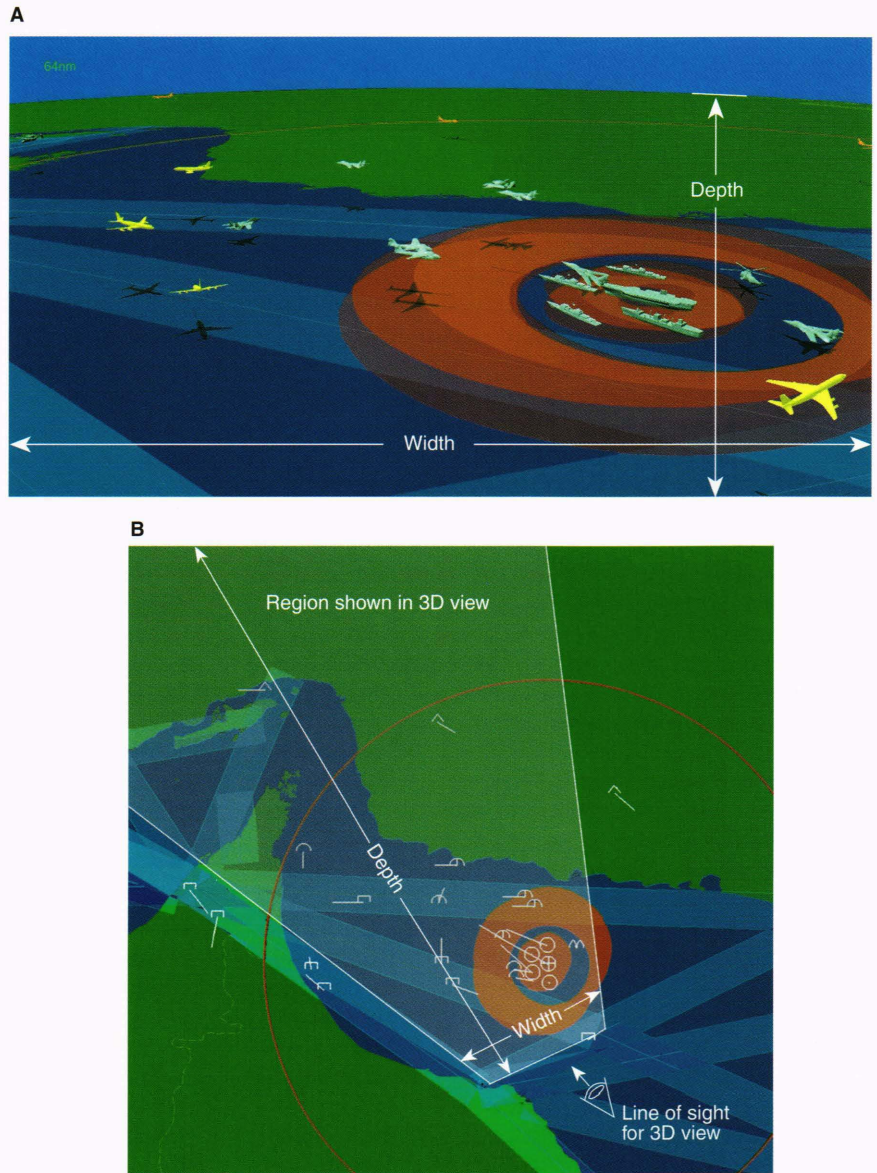


Figure 6. Two views of the same tactical situation. **A.** Three-dimensional perspective view. **B.** Two-dimensional plan view. In the three-dimensional view, the depth is foreshortened, requiring less screen space than the two-dimensional view requires, and the width is expanded, requiring more screen space to display data.

technically challenging, especially when the tactical picture must contain all information pertinent to initial engagement decisions. State-of-the-art 3D graphics generation hardware simply is not fast enough to render the scene without concern for performance issues. Therefore, the FTEWA team developed a graphics display software architecture specifically designed to maximize responsiveness, speed, and flexibility, so that the system is suited to tactical operations.

The primary concern in tactical operations is responsiveness; slow response would impede command actions. Particularly troublesome is the general design of commercial workstations, which queue, or “stack,” multiple user entries, processing each in turn. Because numerous interactive events can be queued during intense operations, responses can slow down so much that the situation depicted no longer reflects the current situation. Worst-case response times of no more than 0.1 s are essential to overcome such limitations,⁷ but currently available

raster graphics computer systems are not capable of such fast update rates, even in 2D displays. Because of these hardware restrictions, the FTEWA display generation design supports fine-grained preemption of drawing to ensure adequate response. Fine-grained preemption lets the user interrupt the system while a scene is being drawn to allow immediate response to new commands.

System responsiveness is also a measure of how quickly the system generates a scene in response to user inputs. Both experience and Military Standard criteria⁸ indicate that scenes must be generated within 0.5 s to realize the fast update rates. The FTEWA system addresses this requirement in several ways. First, it adapts the resolution of rendered objects on the basis of their distance in the scene. Distant objects are drawn much more simply than objects in the near field, since any detail is lost anyway because of the distant object’s small size. Also, some elements of the view, such as annotation, are drawn in a 2D overlay format and separated from the full 3D view,

thus obviating the need to completely re-render the view whenever annotation is updated.

The high-level system architecture of the FTEWA graphics display software aids in high-speed rendering. A multiprocessing computer system is used, and the software elements are partitioned to allow simultaneous rendering, display object generation, and event handling. The rendering processes can begin before all display objects are fully defined. Display items that require relatively long delays for generation (more than 0.25 s) are drawn as they become available. Thus, event processing and rendering are not delayed during the wait for these items.

Animation of view changes also requires very fast rendering to support effective view control. If drawing times exceed 0.1 s, the scene appears to jump so much between successive views that interactive view control is difficult because incremental, reversible control is lost. Animation smooth enough to look like live motion requires rendering rates of 0.03 s per frame, but such rates are not necessary for effective view control. Animation rates of no less than 10 frames per second have been specified for the FTEWA system. To achieve this rate, the rendering system has been designed to eliminate time-consuming display features, such as hardware lighting, during viewing animation. The enhanced fidelity these operations provide in the steady-state picture thus can be traded for increased responsiveness in animation. Also

for animation, all objects can be rendered at reduced resolution. Once motion ceases, objects can be redrawn at full resolution with all display features. The trade-off of picture quality for high-speed rendering can be tailored to the graphics hardware capabilities. Faster hardware requires fewer concessions to achieve the required update rates.

The FTEWA graphics generation software must also be flexible, since the system is a prototype that will evolve and grow with operational experience. The software architecture must allow easy modification of display content and characteristics and must accommodate multiple, distributed hardware suites.

The display software architecture is designed to fulfill these system requirements. Figure 7 illustrates the top-level software design. The architecture supports several rendering processes, each rendering scenes in separate graphics windows. A description of each scene is held in shared memory, accessible to all processes. Graphic objects to be rendered, as defined in this scene description, are produced by data generation processes that place data into a second shared memory area called the graphical entity data cache. Data generation processes categorize objects and describe their geometry using a high-level data description language that abstracts the data generation process from the rendering details.⁹ The rendering process handles presentation issues and display generation. As part of the rendering process, the color

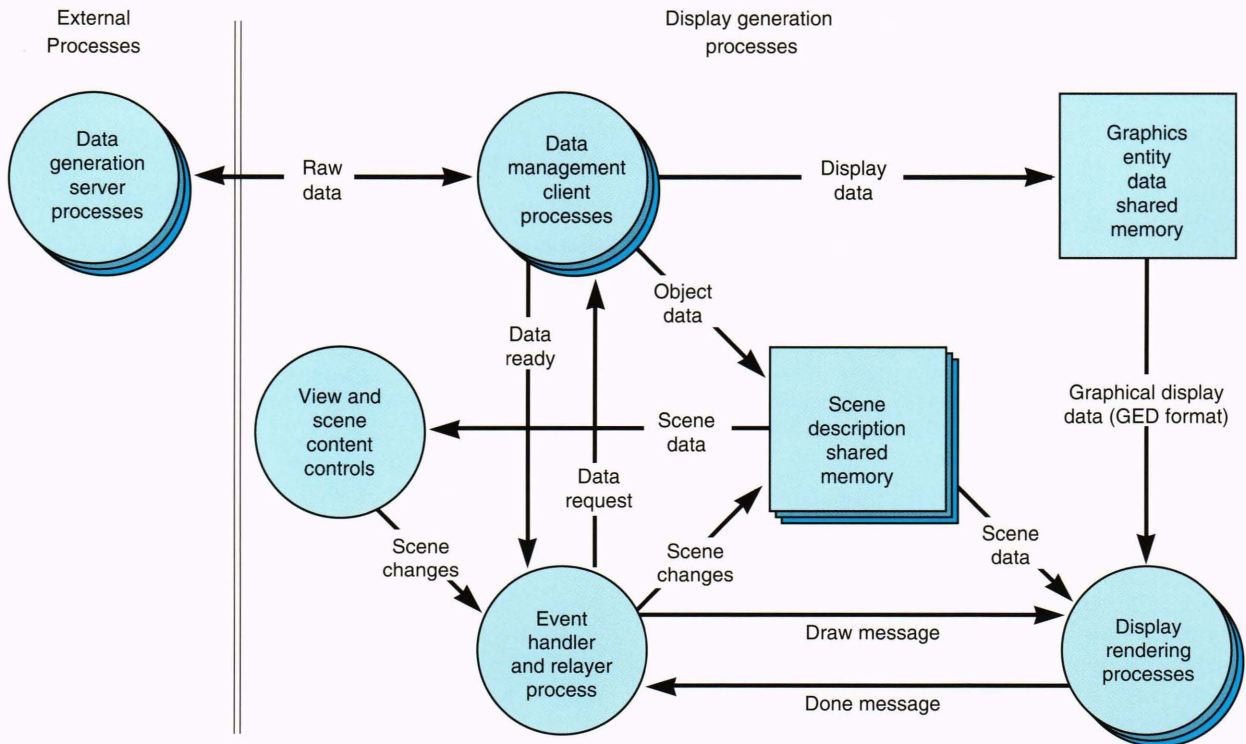


Figure 7. A top-level view of the software architecture of the Force Threat Evaluation and Weapon Assignment system's three-dimensional perspective display (GED = graphic entity data).

display control system¹⁰ uses the object categorization to assign color, line style, and texture. Event processing and coordination of scene generation and rendering are performed by the separate event handler and relayer process.

This distributed system architecture appears to be well suited for rapidly updating complex 3D perspective displays. The design speeds up the drawing of the individual scenes for the following reasons:

1. Communication paths from the data generation processes to the rendering process have been eliminated, which eliminates message interrupts and processing within the rendering process.

2. The rendering process can begin drawing data as soon as the first display object is available. Prior system designs required the data generation applications to create all display objects before the rendering process could begin displaying the data.

3. The removal of event handling from the rendering process allows rendering to occur without processing extraneous events. The event handling and rendering processes can run concurrently on a multiprocessor workstation.

4. The design allows data generation applications to begin setting the scene description data while the renderer performs several procedures required before drawing the first object. The rendering process clears the frame buffer and z buffer and sets up the viewing matrix before requiring any data from the data generation applications.

The distributed rendering architecture works very well in a networked environment and benefits from multiprocessor computer architecture. Data generation and rendering tasks are split into multiple processes, allowing system processor loads to be utilized more effectively.

CONCLUSION

The ability of the commander to rapidly and accurately comprehend and interpret the aircraft detected in a defended area largely determines the success of anti-air warfare operations. For rapid and accurate interpretations, the commander must have effective computer-generated graphical representations of detected aircraft. The advent of littoral operations has substantially increased the difficulty of AAW control, thus demanding more effectiveness from these representations. With advances in computer processing and graphics capabilities, display hardware technology, and interaction devices, new options for graphical representations can be developed to improve effectiveness. APL has used these technological advances to develop a 3D perspective tactical display capability as part of the FTEWA system.

The FTEWA real-time, 3D virtual environment presents all tactically significant information from a defended area in a single integrated display. Because they resemble the external reality of aircraft near defended ships, the high-fidelity 3D images rendered on the display require less effort to comprehend than currently used 2D displays. Integrating altitude and attitude information directly into the track presentation speeds the characterization and

assessment of threats. Unlike 2D symbols, the FTEWA system's realistic track symbols are based on knowledge of aircraft commonly held by Navy commanders. The virtual environment can improve AAW control by eliminating the burden of integrating and interpreting multiple representations, abstract symbols, and textual readouts. The wide range of easily recognizable 3D friend track symbols allows tacticians to pinpoint the positions of key assets rapidly, facilitating both recognition of urgent situations and formulation of appropriate responses.

The computer programs that generate the 3D images are fast enough and responsive enough for AAW control. The distributed graphics display software architecture maximizes responsiveness, speed, and flexibility. Because even state-of-the-art 3D graphics hardware cannot render scenes fast enough to keep up with rapid, user-interactive events, the system supports preemption of the rendering process to allow immediate response to user actions. Distributing software elements speeds the drawing of a scene in a multiprocessing environment by allowing the rendering to occur while display objects are being defined. Animation of view changes to support effective view control has been achieved at a rate of ten frames per second. Finally, to support future evolution and growth, the FTEWA display system has been designed in an object-oriented manner to facilitate modification and adaptability to multiple distributed hardware suites.

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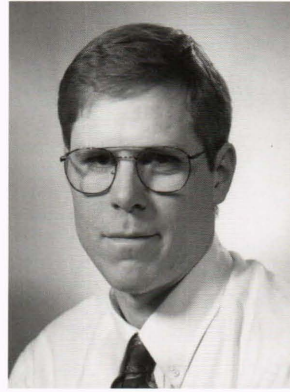
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