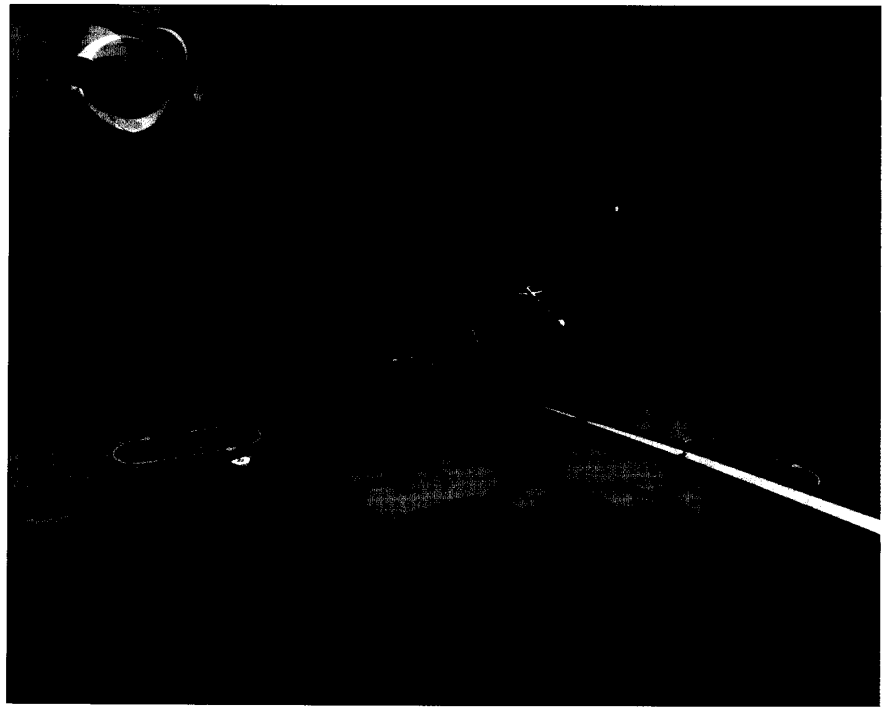
Exploring 3D Computer Graphics in Cockpit Avionics

Peter W. Pruyn and Donald P. Greenberg
Cornell University



Three-dimensional symbolic representations visualize and integrate flight information for tasks such as navigation, collision avoidance, and the instrument approach.

Over the last decade, many of the round-faced, analog instruments used in commercial airliner cockpits have been replaced by color CRT displays. These displays go a long way toward integrating information previously displayed by many instruments. However, frequently these electronic displays simply mimic the older analog instruments that they replace. Furthermore, the computer graphics technology in these displays is more than 10 years old, and flight information is represented two-dimensionally.

Figure 1 shows a Honeywell flight director from a Gulfstream IV. The upper portion is a top-view, moving-map display showing the way points along the aircraft's route. At the bottom is what Honeywell calls the vertical profile mode, which shows way points in a side view.

Figure 2 is a state-of-the-art real-time computer graphics image from an Evans and Sutherland ESIG 4000 flight simulator image generator. It may be unfair in 1993 to compare this kind of image with the Honeywell flight director display. The cost of the calligraphic computer graphics in the Honeywell display is measured in hundreds of dollars, while the cost of the hardware that produces the rasterized, full-color, photo-textured Evans and Sutherland image is currently measured in hundreds of thousands of dollars. But as computer processing power increases, the day will soon come when it will be economical to put photorealistic computer graphics displays in the cockpit. And when that day comes, the question will be, "Exactly what pictures would be useful to a pilot?"

To provide a preliminary answer to that question, we have explored ways of using 3D computer graphics to integrate and visualize flight information. By encoding navigational information into the objects of a 3D scene, we can integrate flight information into a single display. Global illumination rendering techniques let us visualize this information by exploiting a variety of visual cues.

As an example, in the images that follow, we use a computer model of the primary navigational features around the Binghamton (New York) Regional Airport.

Geographic features

We included basic geographic features around Binghamton and borrowed symbols from aeronautical charts to create a computer-generated view of the area from the southeast, shown in Figure 3. The city itself appears in yellow, and you can see the

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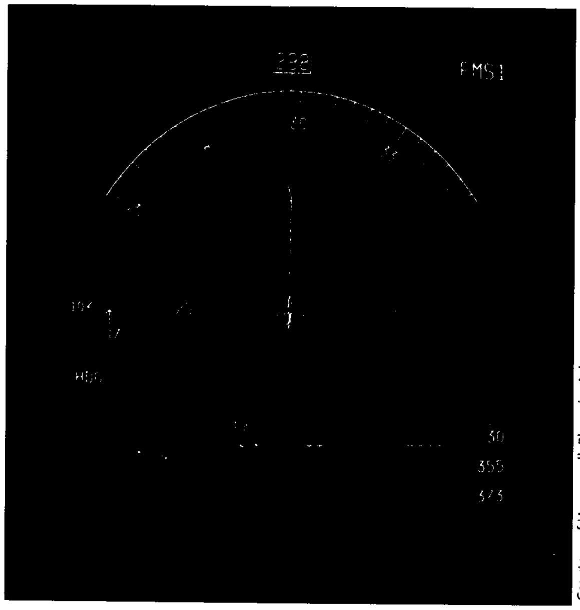

Courtesy of Honeywell, Phoenix, Ariz.

Figure 1. Honeywell flight director for a Gulfstream IV.

Figure 2. An image from an Evans and Sutherland ESIG 4000 flight simulator image generator.

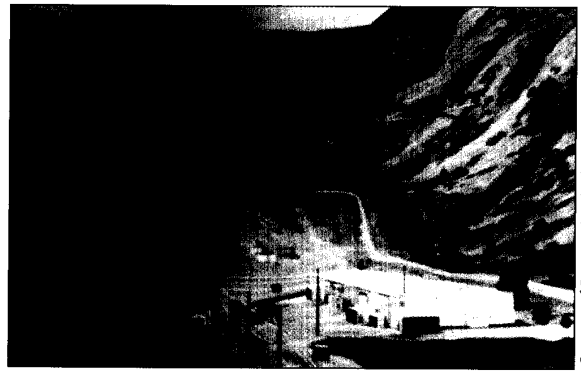

Courtesy of Evans and Sutherland, Salt Lake City

Figure 3. A computer-generated image of the primary geographic features around Binghamton.

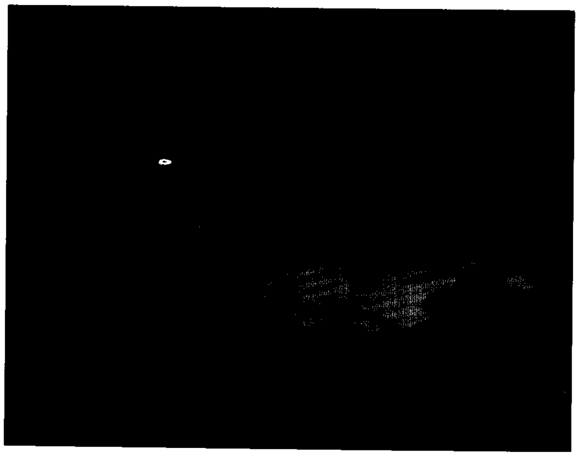


Figure 4. Text labels incorporated into the navigational display.

Susquehanna River, Whitney Point Reservoir, Tri-Cities Airport, Link Field, and a cluster of radio antennas just to the left of the final approach to Runway 34.

In addition to the representations of geographic features, we can include textual information to identify objects and provide additional navigational information (Figure 4). This kind of labeling dates from the early part of this century, using a slightly different medium: white paint on roof shingles (Figure 5).[1] No doubt the town name painted on top of an airport hangar spared many lost aviators the embarrassment of landing to ask where they were.

Figure 5. History repeats itself. Aerial view of the Twin City Airport, Minneapolis-St. Paul, Minn., circa 1920.

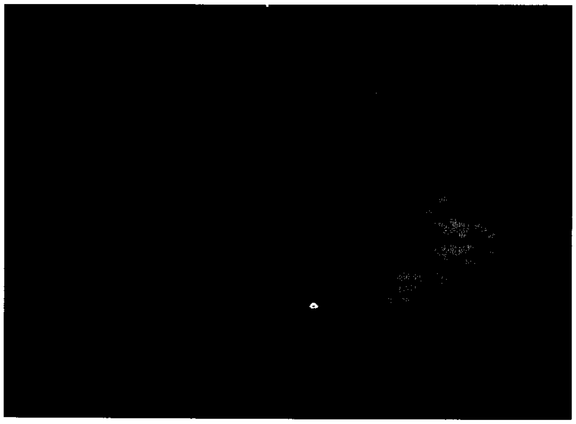


Figure 6. Victor airways over Binghamton.

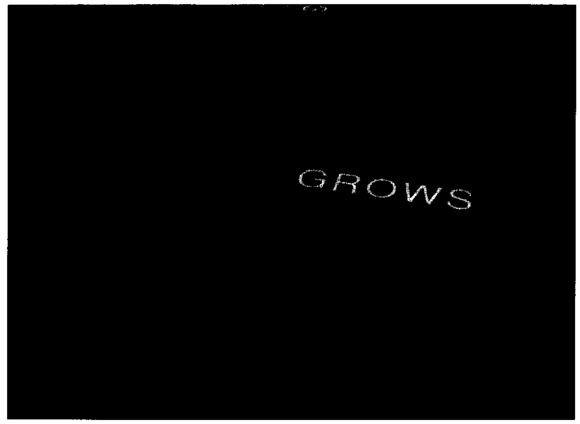


Figure 7. The Grows intersection shown as a gray tetrahedron.

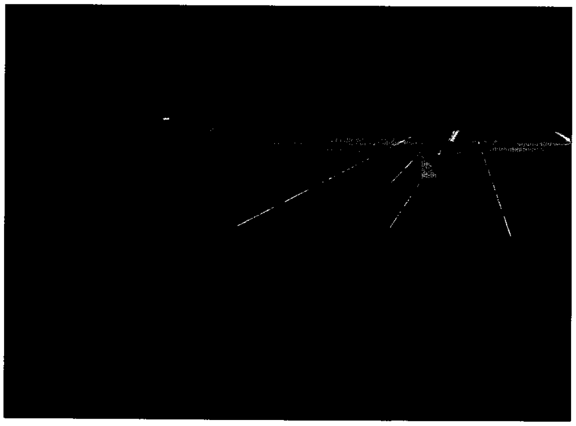


Figure 8. The Latty intersection on the approach path for Binghamton's Runway 34.

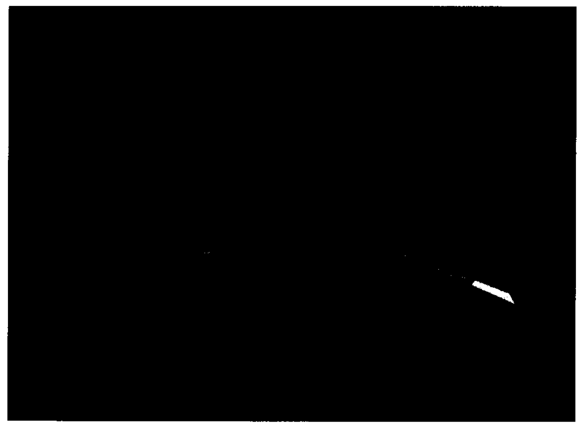
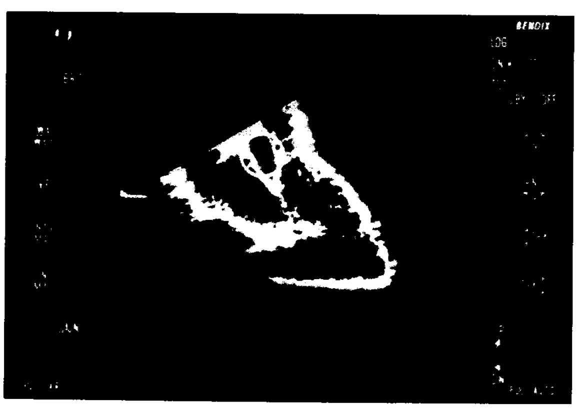


Figure 9. Binghamton's terminal radar service area airspace represented as a transparent volume.

We can also show air routes and label them (Figure 6). Once we have representations of air routes, we can show air intersections as 3D objects (see the Grows intersection in Figure 7). As pilots get close to the Latty intersection on the Runway 34 approach, they would know it easily—it just floats realistically by on the screen (Figure 8).

Figure 10. Bendix vertical profile color weather radar.



Special-use airspace is traditionally represented in a plan view on aeronautical charts with upper and lower altitude limits shown in hundreds of feet. With computer graphics we can represent such regions of airspace as 3D transparent volumes (Figure 9). The color of these volumes could also change over time to communicate meaning. For example, many military operations areas are restricted only at certain times. During those times, the regions could be represented as opaque.

Weather information

Pilots consult a variety of information sources for weather. One source is National Weather Service weather maps. As in-cockpit, weather-map fax machines become a reality, pilots will have access to weather map information in real time.

Another source of weather information is cockpit radar. Figure 10 shows a color weather radar made by Bendix.[2] The manufacturer refers to this model as vertical profile radar because it not only displays precipitation density in the traditional top view, but also in a side view. In other words, although today's technology can collect precipitation information in three dimensions, it still displays it only in two.

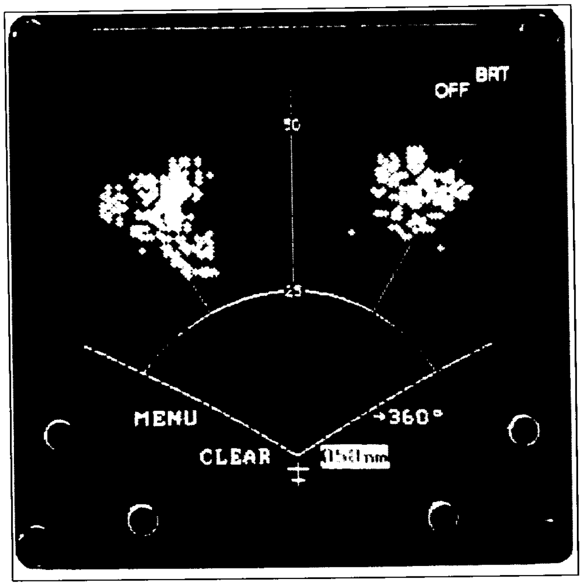


Figure 11. 3M Stormscope lightning-strike detector display.

Figure 12. 3D presentation of weather radar, lightning strikes, and weather map information.

A third source of weather information is the lightning-strike detector. 3M's Stormscope, whose display is shown in Figure 11, is one such device.[3] Unlike conventional weather radar, lightning-strike detectors can detect certain severe weather conditions, such as thunderstorms, even when precipitation may not be present.

We might integrate all three weather information sources into a perspective display like the one in Figure 12. Lightning-strike data is represented as small lightning bolts. The color weather radar has been rendered three dimensionally as concentric, transparent isosurfaces. The black, occluded-front weather symbol suggests how weather map information could likewise be integrated into the same display. While the line representing the occluded front is somewhat unrealistic at such a small scale, there is no reason we cannot integrate traditional weather map symbology for frontal systems and precipitation with perspective views of other weather and navigational information.

Figure 13. Honeywell TCAS display recommending execution of a 1,500- to 2,000-feet-per-minute climb to avoid a target 600 feet below and climbing.

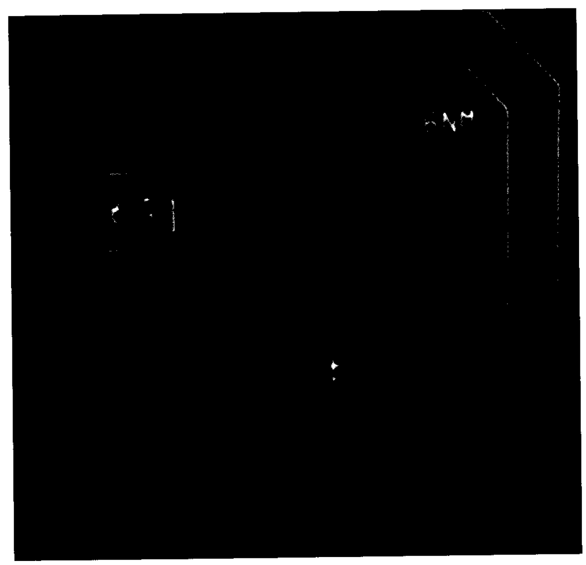
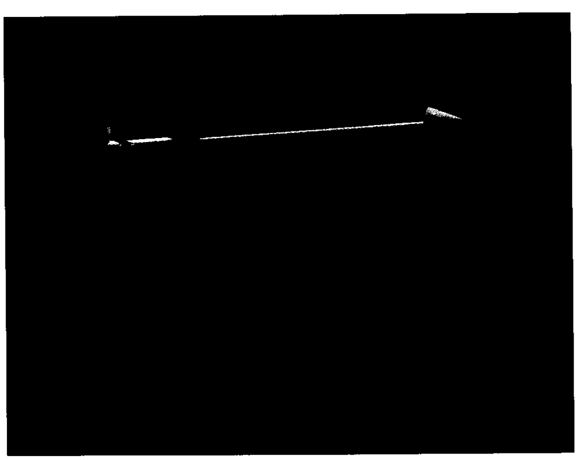


Figure 14. 3D air-traffic icon.



Air traffic

The display of a traffic alert and collision avoidance system (TCAS) manufactured by Honeywell appears in Figure 13.[4] On the left is a rate-of-climb scale. The center is a plan view of the other air traffic that the system is currently aware of. As shown, the current display recommends that the pilot execute a 1,500- to 2,000-feet-per-minute climb, as indicated by the green region on the rate-of-climb scale, to avoid a target 600 feet below and climbing. As soon as we have a perspective view of flight information in the cockpit, there is no reason why we cannot include the 3D positions of other aircraft as physical objects. Figure 14

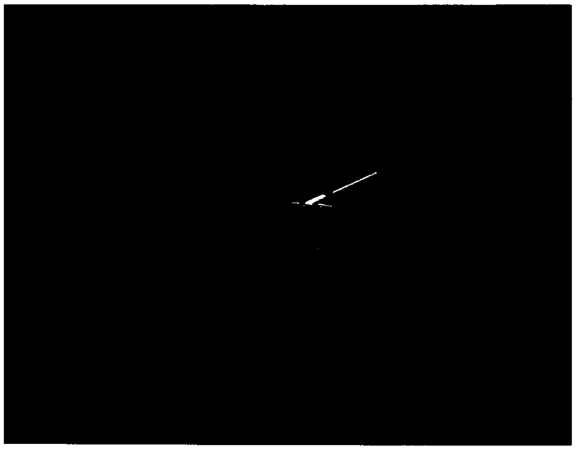


Figure 15. Wake turbulence icons.

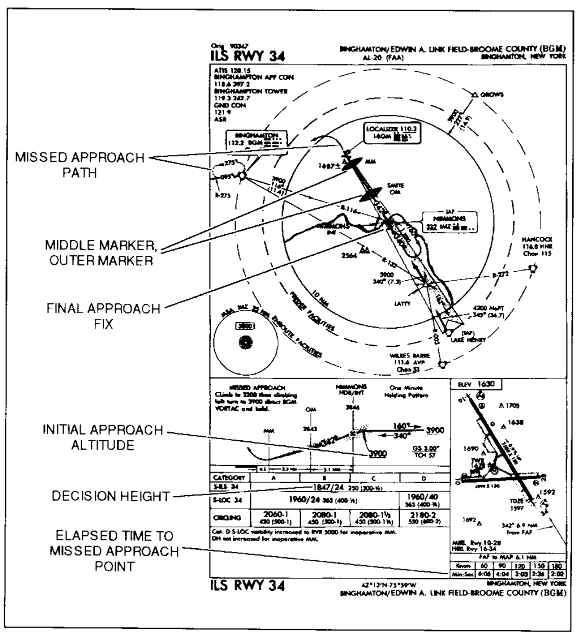
shows the air-traffic icon as one mile long, making it easier to see from far away. In front of the air-traffic icon, a trend vector predicts where the aircraft will be in 30 seconds. Thus we can encode the position of other aircraft for interpretation in terms of the 3D world in which we have always navigated.

Once we have 3D representations of air traffic, we can also include representations of wake turbulence (Figure 15). The goal here is not to compute a precise air-flow simulation of the wingtip vortices, but rather simply to provide the pilot with a general region to avoid.

One design goal of our work has been to represent visually information that has previously been represented numerically. For example, a pilot typically gets airport wind information numerically over the radio as a direction and a magnitude. When flying into an uncontrolled airfield in a light plane, a pilot frequently gets no answer on the radio and is left to figure out the wind conditions on the runway by looking at a 10-foot-long piece of orange cloth thousands of feet below. But everybody knows what a wind sock is and can interpret it intuitively. If we can receive wind information on the flight deck, we can encode direction and magnitude into the geometric description of a 3D object— say, a wind sock two miles high and one mile long (Figure 16). Pilots can "see" this miles from the airport. We admit to some intentional humor here, but the design principle is valid. Familiar real-world objects can be scaled, in size but also perhaps in time, to more effectively communicate information.

Figure 16. Wind direction and magnitude represented as a wind sock two miles high and one mile long.

Figure 17. Instrument approach plate for Binghamton's ILS Runway 34.



Instrument approach

A large portion of our work focuses on instrument approach technology. The following examples show how the Runway 34 approach at Binghamton might look to a pilot on a 3D display of the instrument landing system (ILS) information shown in Figure 17.[5]

When the pilot is far from the airport, the approach path stands out from the rest of the scene to facilitate flying toward it. In Figure 18, the final approach to Runway 34 is represented as the traditional yellow-and-blue ILS spike over the southeast portion of the city of Binghamton.

Once we descend closer to the approach course, it is no longer as important to know our position over the approach path as it is to understand our position within it. The representation changes. When flying an instrument approach, a ground-based radio signal called the localizer provides left/right information, and a similar signal called the glide slope gives high/low information. The localizer and the glide slope are represented here as four dashed white lines. Figure 19 shows how such a display might look just before we arrive at the final approach fix. We

Figure 18. The Runway 34 final approach course as represented by the traditional yellow and blue spike over the southeast portion of Binghamton. This view is from the southwest at approximately 30,000 feet.

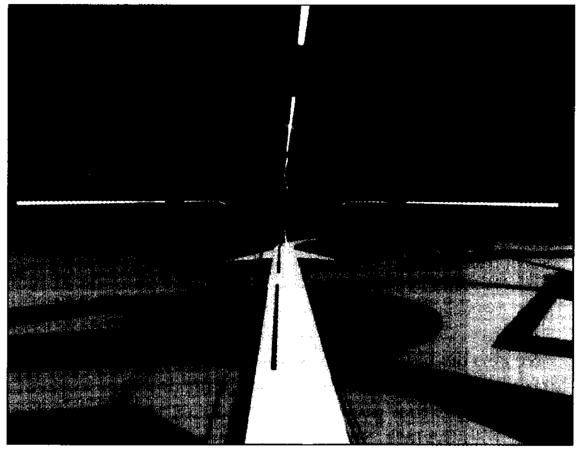


Figure 19. Perspective display just before final approach fix passage. Aircraft altitude: 3,900 feet. Distance to airport: 7.5 nautical miles.

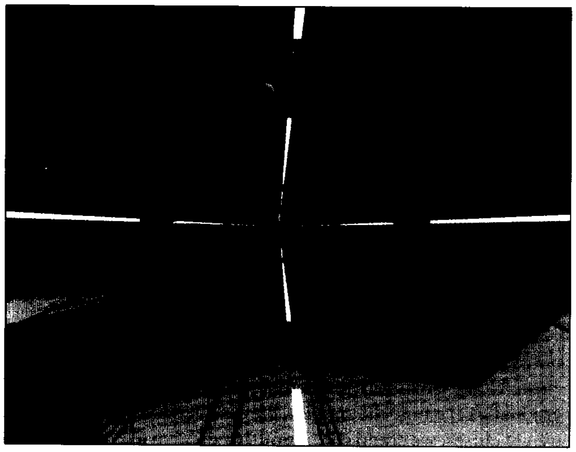


Figure 20. Perspective display before the outer marker. Aircraft altitude: 3,300 feet. Distance to airport: 5.4 nautical miles.

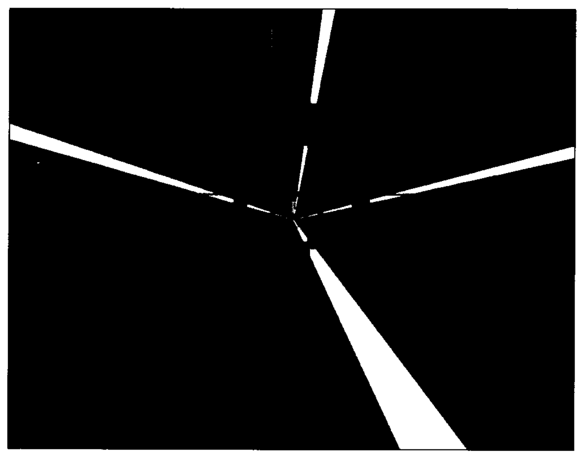


Figure 21. Perspective display when low and to the left of the glide path before the middle marker. Aircraft altitude: 2,500 feet. Distance to airport: 2.8 nautical miles.

can now judge our position within the ideal approach path by our position relative to these dashed lines. The glide slope lines bend downward after the final approach fix to provide a visual cue showing when to commence our final descent. The horizontal green lines each represent a given level of altitude. The black Maltese cross signals the final approach fix. The circular, dark magenta disk on the ground represents the radio beacon that identifies the final approach fix. A portion of a gray "racetrack" symbol leads us directly into the center of the image and then bends off to the right. This large oval represents a holding pattern over the final approach fix.

After we pass the final approach fix and begin our final descent (Figure 20), the horizontal green lines provide a visual cue of altitude change. A transparent, blue "V" represents the approach outer marker.

Figure 21 shows the display view if we had then drifted too low and to the left of the approach path. The glide slope lines angle upward above us, and the localizer lines angle off to the right. The amber V up ahead is the approach middle marker.

As we pass the middle marker, we can see the runway ahead (Figure 22). At the far end of the runway, gray arrows represent the missed approach procedure. Figure 23 shows touchdown.

This still sequence loses most of the dynamic nature of the information. A VHS-format videotape of this entire approach that accurately shows the dynamic sequence has been submitted to the Cornell University Libraries with Pruyn's thesis on this subject.

Design issues

A number of design notions have come out of this work. We observed that pilots really don't like to fly into things, even if the objects are transparent, computer-generated icons. As a result, we changed many symbols into less confrontational forms. For example, we changed the approach marker beacons, originally represented by the traditional transparent cone, to the open V.

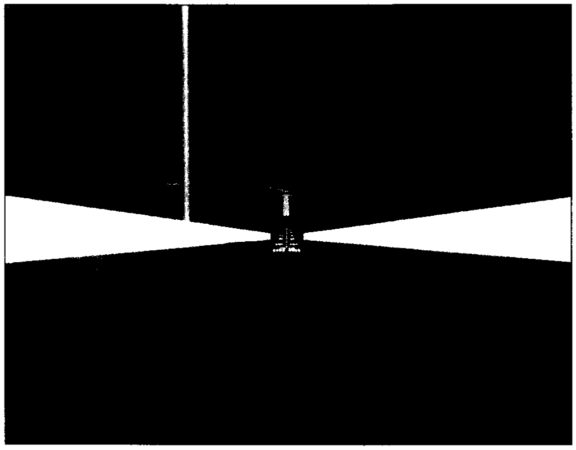


Figure 22. Perspective display at the middle marker. Aircraft altitude: 400 feet. Distance to airport: 0.6 nautical miles.

Figure 23. Touchdown.

We also developed the concept of "symbol evolution." Different information is useful for completing different stages of a task. Symbols that provide task feedback should therefore evolve with the task. Such was the changing representation of the ILS final approach path from the yellow-and-blue spike to four dashed white guides.

Changing the appearance of symbols over time is not an ordinary design option. But computer graphics provides virtually limitless parameters to manage the visual evolution of symbols. We can change not only shape and size, but also hue, color saturation, texture, and transparency. Icon rendering parameters can evolve to communicate meaning. However, because symbol evolution does not normally occur, more research must be done in choosing these dynamic object changes to ensure that their meaning can be grasped quickly and intuitively.

For example, the air traffic icons we used are one mile long so pilots can identify them well before evasive action becomes necessary. However, just before landing, when pilots frequently are flying within a few miles of other aircraft, it would be appropriate to render these air traffic icons smaller. But exactly how should this change in size occur? If the icons simply decrease in size as we get closer, how does this affect the perception of our distance from them? If an object gets smaller as we approach, we may perceive that our distance remains constant.

We can construct air traffic icons life size, with an opaque outer shell of the same shape but much larger. As we come closer to the icon, the transparency of the shell would increase, gradually revealing the smaller, life-size version within. Also, as we get closer, we could continuously perceive the outer and inner icons until the outer one fades away entirely. Figures 24 through 27 show this transition.

Figure 24. Large outer air-traffic icon shown just beginning to fade as we approach it. The inner life-size icon is just barely visible directly in the center of the image.

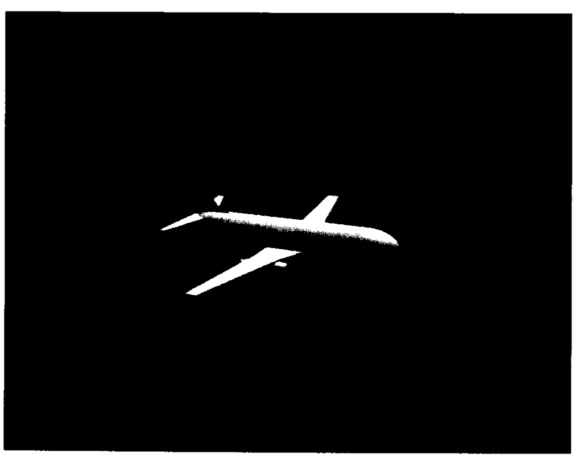
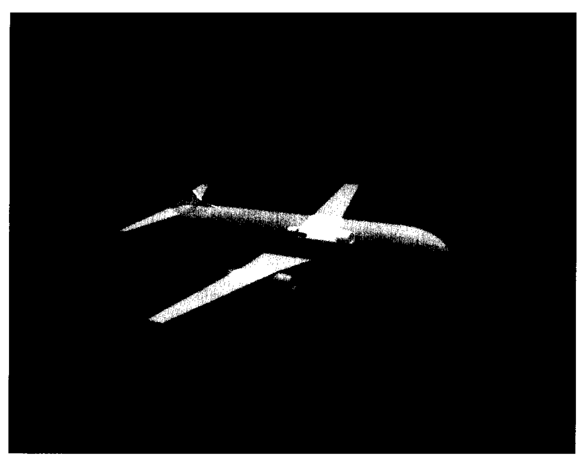


Figure 25. The large outer air-traffic icon fading away.



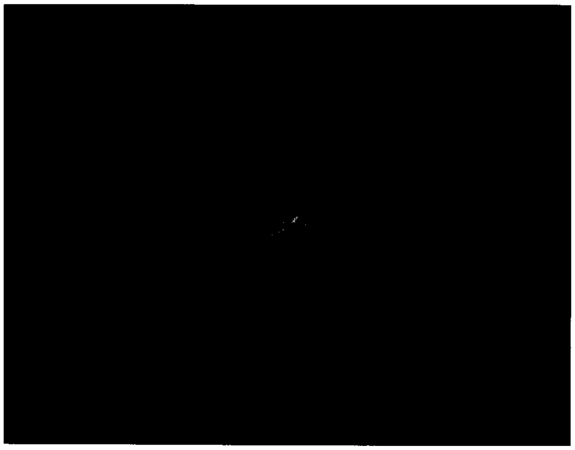


Figure 26. Outer air-traffic icon almost faded away, revealing the smaller icon within.

Figure 27. The inner life-size icon is now unobscured.

Conclusion

The primary design goal of any cockpit display should be to help minimize the use of the most valuable resource on the flight deck: human attention. A display should be as intuitive as possible. We have explored some possible uses of dynamic 3D color images to help achieve these goals.

Computer graphics can integrate flight information, clustering information for related tasks in a single display. Such a display is effective if it minimizes the mental transformations a pilot must apply to the feedback symbols to create useful information. The symbols should mimic the pilot's mental model of the task as closely as possible.[6] Therefore, they should represent task components pictorially rather than numerically. Computer graphics can help achieve these goals by visualizing data using representations of objects that are already a part of a pilot's experience. We end with an anecdote from the personal experience of one of the authors (Peter Pruyn):

I began this project in May 1991. By August, I had built most of the 3D computer model of the primary navigational aids and geographic features around Binghamton. After manipulating this model over a number of weeks, I had the experience of flying over Binghamton for the first time. I felt a profound sense of *déjà vu* while over the *real* Binghamton. I saw the airport first, and then looked to the west to spot the small white building that houses the radio transmitter for the Binghamton VOR (VHF omni-directional range). And there it was. To the south were the Susquehanna River and the city of Binghamton, just as I had pictured them. Even though I'd never really been there before, I'd been there before. This very subjective experience shows the powerful sense of situational awareness this technology can provide. ❑

Acknowledgments

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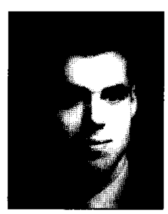

Peter W. Pruyn currently teaches computer science in the Seychelles for the Peace Corps. He is also a private pilot. He received a BA in computer science from Cornell University in 1990 and an MS in computer graphics from Cornell's Program of Computer Graphics in 1992.

Donald P. Greenberg is the Jacob Gould Shurman Professor of Computer Graphics at Cornell University, Director of Cornell's Program of Computer Graphics, and Director of the National Science and Technology Center for Computer Graphics and Scientific Visualization. He is a member of ACM, IEEE, Siggraph, and Eurographics.

The authors can be reached at Program of Computer Graphics, Cornell University, 580 Engineering and Theory Center Bldg., Ithaca, NY 14853. Pruyn's address is U.S. Peace Corps—Seychelles, Box 564, Victoria, Mahe, Seychelles, Indian Ocean.