Visualization Tools for Free Flight Air-Traffic Management

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The United States Federal Aviation Administration (FAA) has declared that the existing Air Traffic Control (ATC) system will shift to a new system known as Free Flight. While Free Flight has not been precisely defined in a universally accepted way, the basic concept involves reducing centralized control to allow pilots greater freedom in choosing and altering routes, leading to reduced costs and increased capacity.[1-3] In today's system, controllers command and pilots obey. Pilots wishing to change their routes must issue requests and receive clearance from controllers. The controllers maintain centralized control and responsibility for safe operation. In contrast, Free Flight will let pilots change their routes in real time, with controllers intervening only when necessary to ensure adequate separation. In some definitions of Free Flight, pilots themselves are responsible for avoiding conflicts in simple situations.

Free Flight lets pilots modify their routes in real time. It requires new conflict detection, resolution, and visualization decision support tools. We describe a testbed for building and evaluating such tools.

For Free Flight to succeed, new conflict detection, resolution, and visualization tools must be developed to support the needs of controllers, pilots, and airline managers. Controllers must mentally project the future courses of the aircraft that they monitor—a cognitively difficult task, as shown by the spatial relationship tests on examinations given to prospective controllers.[4] The restricted nature of the existing ATC system aids them in performing this projection. Aircraft usually follow established jetway paths, and an experienced controller knows their intended routes.

These restrictions may end in Free Flight, leading to a need for decision support tools that augment a controller's capabilities. Furthermore, pilots and airline operation centers (AOCs) need improved situational awareness of the traffic that affects them. Today, pilots don't get much information about their local airspace. If Free Flight demands that pilots perform conflict resolutions on their own, then pilots must have tools that clearly show the conflicts, the surrounding traffic, and appropriate options for resolving the conflicts.

This article describes a testbed we are developing for the construction and evaluation of conflict detection, resolution, and visualization tools for the Free Flight environment. The testbed runs interactively, in real time, on a realistic Free Flight scenario. We also describe lessons we've learned in experimenting with different visualizations and summarize feedback received from expert users.

Previous work

While we know of several earlier efforts in areas related to this project, we don't know of another visualization system that specifically focuses on conflict detection and resolution in the Free Flight domain. Related works include conflict probe algorithms and 3D visualizations for ATC applications.

The Center-Tracon Automation System (CTAS) from the National Air and Space Administration facility in Ames, California (NASA Ames), primarily concentrates on separating aircraft flying into an airport.[5] Mitre's User Request Evaluation Tool (URET) performs conflict probes in the en-route airspace for the existing ATC domain.[6] Neither tool focuses on visualization. Currently deployed ATC displays show 2D plan views. Several 3D visualizations have been built for ATC applications as research systems.[7,8]

The primary difference in our work is the focus on conflict detection and resolution in the Free Flight domain. Our testbed explores and evaluates both the visualizations and the conflict algorithms in a realistic Free Flight scenario. We built a previous system to explore 3D graphical and audio visualization aids for aircraft flying in the terminal area of Boston's Logan Airport.[9] Our current system differs radically from the Logan-based system, with a more realistic scenario, integrated conflict detection and resolution tools, and improved visualization modes.

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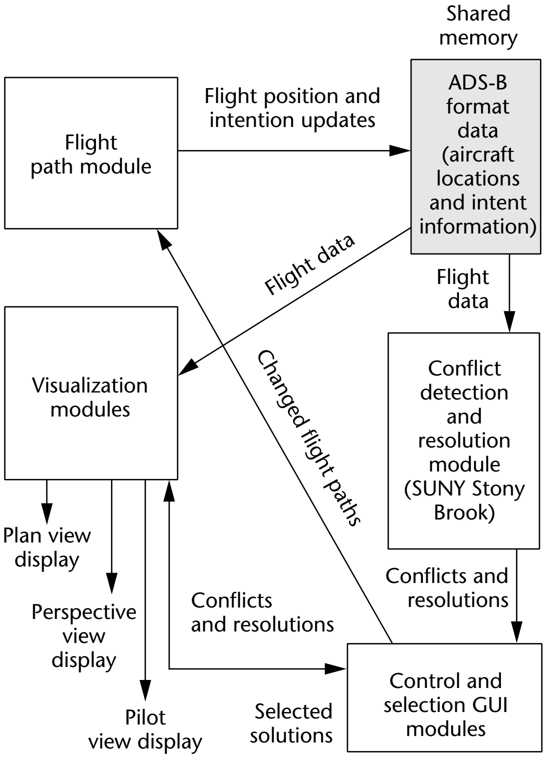
1 **Conceptual diagram of primary air traffic flows through the Coaldale sector east of San Francisco.**



2 **System dataflow.**

System overview

Since only very limited Free Flight exists today, we had to make a set of assumptions and build a full Free Flight scenario to provide the data for conflict detection, resolution, and visualization. We assume that aircraft cruise climb to their desired altitude, then maintain that altitude until they cruise descend into the destination airport. *Cruise climbing* means that an aircraft climbs at an optimal rate to the target altitude without spending time in level flight at intermediate altitudes. Aircraft fly direct routes to their destinations whenever possible, ignoring existing jetways. However, they don't fly through restricted airspace, such as zones around military bases.

We placed this scenario in an area east of San Francisco, in what's currently called the Coaldale sector, because crossing traffic occurs there naturally. Westbound traffic cruise descends into the three major airports in the Bay Area. Eastbound traffic cruise climbs away from those airports. North and southbound aircraft, which stay at their cruising altitudes, cross that area, potentially conflicting with the eastbound and westbound traffic. The diagram in Figure 1 explains this scenario; it's not an image the user sees in the visualization testbed. Aircraft must maintain a minimum five-mile horizontal or thousand-foot vertical separation from each other (the Protected Airspace Zone around each aircraft) or a conflict occurs.

The scenario consists of 87 aircraft and lasts 35 minutes. We based about 25 percent of the flights on real data recorded at the Oakland en-route Air Route Traffic Control Center (ARTCC) on 1 September 1996. These data provided good estimates of the routes and density of aircraft typically flying through Coaldale.

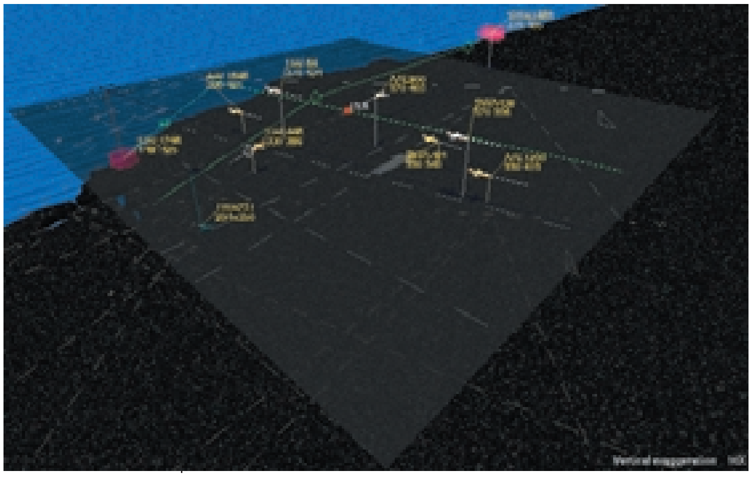
We assume Free Flight doesn't extend to aircraft at low altitudes or in Tracon regions (areas near airports); thus in our scenario aircraft below 10,000 feet aren't displayed. All aircraft are tracked with an augmented global positioning system (GPS), such as the Wide Area Augmentation System (WAAS), and broadcast their positions and intended routes to other aircraft and ground stations via a data link such as the Automated Dependent Surveillance-Broadcast (ADS-B) system. We don't currently model uncertainty in the flight paths or include weather features.

The system consists of several processes that communicate through shared memory. Figure 2 shows the processes and the communication flow.

We have run the system on an SGI O2, but it performs best on a multiprocessor system such as an SGI Onyx because of the computational burden from the conflict detection and resolution modules. The flight path module maintains the "true" paths the aircraft follow. This module places the current aircraft positions and up to 20 minutes of intended route information into a shared-memory data structure, which both the visualization and conflict detection/resolution (CD&R) modules read. The CD&R module identifies conflicts between sets of aircraft and potential alternate routes to the visualization module, which displays them and allows the user to select new routes. These new routes are sent back to the flight path module, which updates its internal database of the true flight plans for the affected aircraft. The system runs in real time. Thus, users see and resolve conflicts at the same rate that they would if these were real aircraft.

The State University of New York (SUNY) at Stony Brook provided the CD&R algorithms.[10] We have also worked with Seagull Technologies to use their CD&R algorithms.[11] The SUNY algorithms find global solutions (ones that avoid conflicts with all other aircraft in the scenario), while the Seagull algorithms work with groups of two to three aircraft but provide more sophisticated modeling of aircraft characteristics and propose resolutions based on those characteristics.

3 **Plan view display, with conflict highlighted between eastbound and southbound aircraft.**



4 **Perspective view display, showing detail view and suggested resolution of conflict.**

Visualizing conflicts and solutions

The testbed can support two simultaneous users: one in the role of a controller or an AOC manager, and the other in the role of a pilot of an aircraft in the scenario. The controller sees a 2D plan view display and a 3D perspective view display in two monitors, while the pilot sees the pilot view display in one monitor. Each view shows an aspect of the current situation. The plan view display provides an overall view, while the perspective display shows a detailed view of a particular conflict or area. The visualization modules are written in C and WorldToolKit 7. Three small control windows written in Tcl/Tk control parts of the interface. Both displays update at more than 15 Hz on an SGI Onyx with 4 R10K CPUs. The conflict detection and resolution algorithms consume much of the processing.

The plan view display (Figure 3) resembles standard existing ATC plan view displays except that ours supports the selection of conflicts and detail areas for examination in the perspective display. The dotted yellow line indicates a region that the user has selected with the mouse. The gray square region matches the area covered by the altitude plane in the perspective display, clearly marking the relationship between the overall and detail views. Aircraft icons are colored based on direction and altitude. Eastbound aircraft are orange, and westbound aircraft are blue, with lighter hues indicating higher altitudes. This allows quick visual determination of aircraft that may appear to be on a collision course in a 2D display but are actually safely separated by altitude. The data block associated with each aircraft indicates the call sign, altitude in hundreds of feet, ground speed in knots, and whether it is climbing, descending, or remaining level.

The perspective view display (Figure 4) shows the matching gray region from the plan view display, except that the user has selected a solution to the given conflict. This solution, outlined with green extension lines, reroutes the southbound Southwest Airlines aircraft to avoid the conflict location (the solid red cylinder). Numerous depth cues make the situation easier to understand. The transparent altitude plane can be moved up and down, shortening the altitude lines and providing motion cues. Shadows are projected onto the altitude plane. The Protected Airspace Zones around each conflicting aircraft are highlighted in red. An optional “rocking mode” changes the viewing angle by a varying offset controlled by a sinusoid, enabling cues from motion parallax. The user can view the perspective situation from different angles and ranges through a virtual trackball mechanism. The 2D circles, triangles, and rectangles drawn over the extension lines specify inflection points in the aircraft trajectories: locations where an aircraft changes heading or its ascent/descent rate.

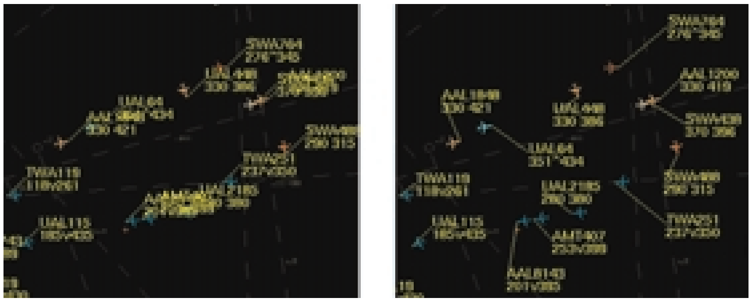
The plan and perspective displays can be switched into an AOC mode that highlights the aircraft for one particular airline, dimming the graphics and labels for all other aircraft and changing their aircraft icons to be less noticeable.

All displays use an automatic label deconfliction algorithm and draw line extensions to indicate intended routes. The data blocks linked to each aircraft can cover important features in the display or other labels, making the labels difficult to read. The label deconfliction algorithm automatically moves the labels to avoid such problems, reducing the work a controller normally performs in manually specifying the label positions. Figure 5 shows an example. In both images the aircraft are at the same locations, but the labels in the right image have been automatically repositioned. Line extensions from current aircraft locations indicate future aircraft routes; the user selects how many minutes into the future to extend the lines, allowing the interactive exploration of potential problem areas.

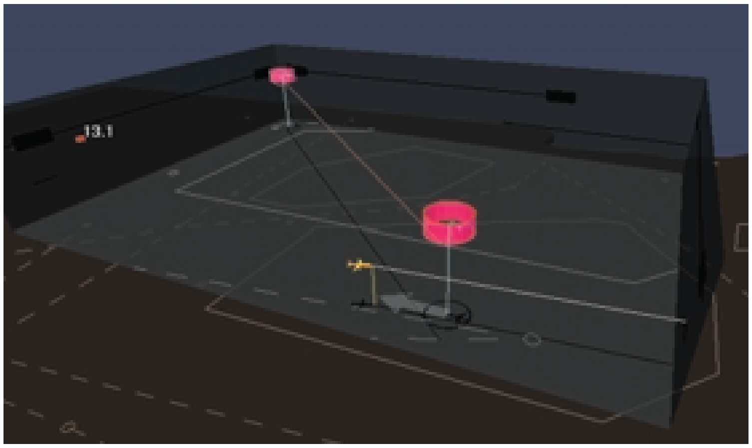
The testbed lets the controller change the path of any aircraft in the system by graphically editing its projected future path. Normally, the controller would change aircraft paths only when a conflict is projected to occur. The system proposes solutions, which the controller can accept. But the controller can also manually specify an alternate resolution or can change any other aircraft's path. The testbed will double-check the proposed new route by processing it through the CD&R algorithms. If the proposed new route generates a new conflict, the visualization modules will highlight that conflict to warn the user.

The pilot view display targets the pilot's needs. It must present the situation of interest to the pilot while minimizing extraneous information. Only one window is drawn because the cockpit won't have room for more than one display. The pilot can smoothly shift the rendering mode between a 2D plan view and a 3D perspective view.

The pilot view mode shows the pilot's aircraft in the center of the display, with automatically adjusting background "walls" that adapt to the aircraft's location and set of neighboring aircraft. Shadows projected onto the orthogonal background walls make the spatial relationships easier to understand. The testbed only draws the aircraft that come within a certain distance of the pilot's aircraft within a specified time window. This makes it obvious which aircraft have the potential to generate conflicts. To make the nature of these threats more apparent, the pilot view mode can also draw the projected paths of the other aircraft in a relative mode. This mode displays the paths of the threatening aircraft relative to the pilot's own aircraft, as if the pilot's aircraft stood still in space (Figure 6). The pilot and controller select and view proposed conflict solutions independently, so each can see a different solution simultaneously.



5 **Automatic label repositioning to improve readability.**



6 **Pilot view mode showing relative projected paths for potentially threatening aircraft.**

Lessons learned and future directions

We demonstrated versions of this testbed at the Air Traffic Controllers' Association conferences in October 1996 and November 1998. This provided evaluation and testimony from expert users: air traffic controllers, pilots, and airline operations personnel.

The scenario we built was judged realistic, and the CD&R mechanisms were effective in identifying problems 10 to 20 minutes in the future. Both pilots and controllers accepted the scenario as presented. The only complaints came from one controller who actually worked the Coaldale sector, and even those criticisms were minor. Controllers stated that they would not be able to spot these types of Free Flight conflicts 10 to 20 minutes before they occur without the information provided by the CD&R algorithms and the visualizations. This supports our belief that such decision support tools can contribute to future air traffic management systems. In complicated situations, such as the ones likely to occur in Free Flight, decision support tools can focus the attention of pilots and controllers specifically on the few areas that need attention, making the visualizations more effective.

Designing visualizations in this area is often an exercise in choosing what not to draw, rather than what to draw. Minimizing clutter and distractions is vital to controllers. We changed the perspective view to provide solely detail information because in an overall perspective view, background information often hid the vital foreground information the user wanted to see. Similarly, the pilot view only displays information of interest to that pilot.

In general, controllers were more conservative in the features they accepted than pilots or airline personnel. Controllers are familiar with plan view displays and believe they can extract all required information from them, although the cognitive load may be high. Controllers found the label deconfliction routine most useful. But pilots and other personnel who don't have extensive training to recover the 3D situation from a plan view found the detail views and CD&R visualizations useful. They stated their need for increased situational awareness in a Free Flight situation.

Our future direction is to emphasize strategic planning. This will require changing the scenario and displays to cover the continental US and support weather and uncertainty. ■

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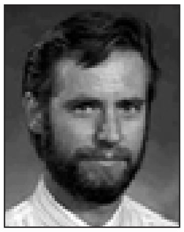

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