Design of a Multi-mode Flight Deck Decision Support System for Airborne Conflict Management

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ABSTRACT

NASA Langley has developed a multi-mode decision support system for pilots operating in a Distributed Air-Ground Traffic Management (DAG-TM) environment. An Autonomous Operations Planner (AOP) assists pilots in performing separation assurance functions, including conflict detection, prevention, and resolution. Ongoing AOP design has been based on a comprehensive human factors analysis and evaluation results from previous human-in-the-loop experiments with airline pilot test subjects. AOP considers complex flight mode interactions and provides flight guidance to pilots consistent with the current aircraft control state. Pilots communicate goals to AOP by setting system preferences and actively probing potential trajectories for conflicts. To minimize training requirements and improve operational use, AOP design leverages existing alerting philosophies, displays, and crew interfaces common on commercial aircraft. Future work will consider trajectory prediction uncertainties, integration with the TCAS collision avoidance system, and will incorporate enhancements based on an upcoming air-ground coordination experiment.

Keywords

airborne conflict management, aircraft control, alerting, decision support, displays, flight deck automation, intent, separation assurance

INTRODUCTION

Free Flight and Airborne Conflict Management

The aviation user community has identified a need for significantly increasing airspace capacity and the flexibility of aircraft operations. This need and the introduction of new surveillance concepts have led to a new operational paradigm, "free flight," in which reliance on centralized air traffic management is reduced in favor of distributed management. In 1995, RTCA Task Force 3 defined free flight as "A safe and efficient flight operating capability under Instrument Flight Rules (IFR) in which the operators have the freedom to select their path and speed in real time." [16]

In the en route domain, providing aircraft the autonomy to self-separate from traffic while optimizing their flight paths in real-time could maximize operator flexibility and airspace capacity. Researchers worldwide are engaged in developing systems and concepts of operations for this long-term, mature-state implementation of free flight. Most of these research efforts recognize the need for airborne decision support systems that assist flight crews in maintaining separation assurance [1,4,8-9]. Cooperative efforts by ATM communities in the USA and Europe have led to the definition of principles of operation for Airborne Separation Assurance Systems under FAA/Eurocontrol auspices [7], as well as the development of operational concepts for Airborne Conflict Management (ACM), coordinated by RTCA [14]. While the former provides a framework for coordination of research into enhancing the air traffic system, the latter provides concepts for ACM using Automatic Dependent Surveillance-Broadcast (ADS-B) [15].

The RTCA ACM concept includes three distinct functions: conflict detection (CD), conflict prevention (CP), and conflict resolution (CR). As envisaged by RTCA, the use of ADS-B will permit the CD function to perform long-range detection of conflicts, providing flight crews the time to develop and implement an optimal solution to the conflict. Also enabled by the use of ADS-B, the CP function will predict conflicts that could be caused by changes to current ownship target states and trajectories, allowing those maneuvers to be avoided. Finally, onboard logic and automation will enable the CR function to provide flight crews with maneuver guidance to resolve existing conflicts.

Autonomous Aircraft Operations

In 1997, the NASA Advanced Air Transportation Technologies Project (AATT) began developing and exploring the concept of Distributed Air/Ground Traffic Management (DAG-TM, [12]) as its vehicle for free flight research. DAG-TM is based on the premise that large improvements in system capacity as well as flexibility and efficiency for the airspace user will be enabled through

- Sharing information related to flight intent, traffic, and the airspace environment,
- Collaborative decision making among all involved system participants, and
- Distributing decision authority to the most appropriate decision maker.

DAG-TM Concept Element 5 (CE-5) [13] specifically defines operations in the en-route and terminal-transition

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flight domains, and it proposes the establishment of a new category of flight operations: Autonomous Flight Rules (AFR). According to the CE-5 concept, an AFR aircraft would generally operate in the same airspace as existing IFR aircraft, but the AFR flight crew would retain a distinct set of authorities and responsibilities. Trained flight crews of AFR-equipped aircraft are given the authority to dynamically plan and execute their preferred 3D trajectories without coordinating with the ground-based Air Traffic Service Provider (ATSP). With this authority comes full responsibility for traffic separation, avoidance of special use airspace, and conformance to operational constraints; the ATSP establishes these constraints in order to safeguard special-use airspace and manage traffic flows into high-demand terminal areas. The ATSP is neither required nor expected to intervene in AFR operations throughout the en-route and terminal-transition domains. However, the ATSP continues to provide traditional IFR services to non-autonomous ("managed") aircraft in all flight domains.

It is anticipated that AFR operations would provide airspace users a significant improvement in flexibility to operate cost-effectively, and would enable the airspace system to accommodate a substantial increase in traffic volume over that manageable by a ground-based IFR system. This scalability would presumably result from minimizing the interactions between autonomous aircraft operations and the ATSP, which under nominal conditions would be limited to imposing Traffic Flow Management (TFM) constraints. In the DAG-TM concept, time-based arrival metering will be the principal TFM tool. Using predictive information on arrivals and airspace status, the ATSP establishes flow metering by issuing Required Time-of-Arrival (RTA) clearances and crossing restrictions at metering fixes to AFR aircraft. Once these restrictions are received and accepted by the flight crew, the interaction between the ATSP and this autonomous aircraft is minimized until the aircraft crosses the meter fix and enters the terminal area.

Equipping the flight deck for AFR operations

In the CE-5 concept of operations, flight crews of autonomous aircraft are assisted in fulfilling their AFR responsibilities by flight deck tools and displays integrated with the onboard avionics system. Although researchers world-wide have studied the development of technologies that enable the RTCA vision of Free Flight, and much effort has been devoted to the creation of ACM tools [4,8], the ACM toolset required for AFR operations must meet several unique and challenging requirements. It must enable the crew to maintain separation from mixed AFR / IFR traffic and airspace hazards while meeting TFM constraints (such as a metering fix RTA). It must use a CP system that provides adequate feedback to ensure that flight crews do not create near-term conflicts, a requirement for AFR operations. Further, the toolset must operate under real-world constraints such as aircraft performance limitations, limited awareness of traffic path and performance, and errors in predicting winds and weather. As an airborne decision-support system, the toolset must be integrated with existing flight deck systems and procedures, and meet all pertinent human factors requirements to achieve operator acceptance.

NASA Langley Research Center is developing a research prototype of a comprehensive toolset for AFR operations, called the Autonomous Operations Planner (AOP) [2]. AOP incorporates and extends [11] several key features of the RTCA ACM concept, specifically the RTCA guidelines for the three core ACM functions (CD, CR and CP), and the use of a graded system of crew alerts when conflicts are detected.

Billings and others have established a set of human factors design principles for aviation automation [5,10,17-18,20]. Key features of the flight crew/automation interaction established by these experts include:

The flight crew must be:

- In command of the automation.
- Able to use their own expertise in evaluating and responding to the situation.
- Involved and have an active role.
- Fully informed of what the automation is doing.
- Able to interpret the consequences of following the guidance being provided.

The decision-support system should:

- Allow the crew to operate the aircraft in a style that achieves the desired result.
- Provide good feedback especially in infrequent or unusual situations.
- Be predictable to the human operator.
- Be aware of flight crew intentions.
- Be simple to train on, to learn, and to operate.
- Be comprehensible.
- Be error tolerant.
- Enhance situation awareness.

Great care has been taken in AOP development to adhere to these principles.

The flight deck of a modern airliner presents a complex and challenging environment for the installation of a new system for ACM. The next section visits the modern flight deck to establish the multiple guidance modes that the new ACM toolset must support. The subsequent section describes the design of a decision-support system and crew interfaces that support AFR operations in common aircraft guidance modes while striving to adhere to all pertinent human factors guidelines.

PROVIDING ACM SUPPORT IN COMMON GUIDANCE MODES

Modern Flight Decks and Control States

Figure 1 represents the elements of a modern glass-cockpit flight deck that are pertinent to a discussion of aircraft control strategies. These displays and interfaces are implemented in NASA Langley's Air Traffic Operations Lab and are based on Boeing 777 conventions. The primary control interfaces are the Mode Control Panel (MCP) (referred to as a Flight Control Unit on Airbus aircraft) and the Control Display Unit (CDU). The primary sources of navigation and flight status information for the crew are the Primary Flight Display (PFD), Navigation Display (ND), and the CDU. Using the MCP, the pilot can command the aircraft in a variety of guidance modes, all of which contain varying levels of information for purposes of ACM, as discussed below.

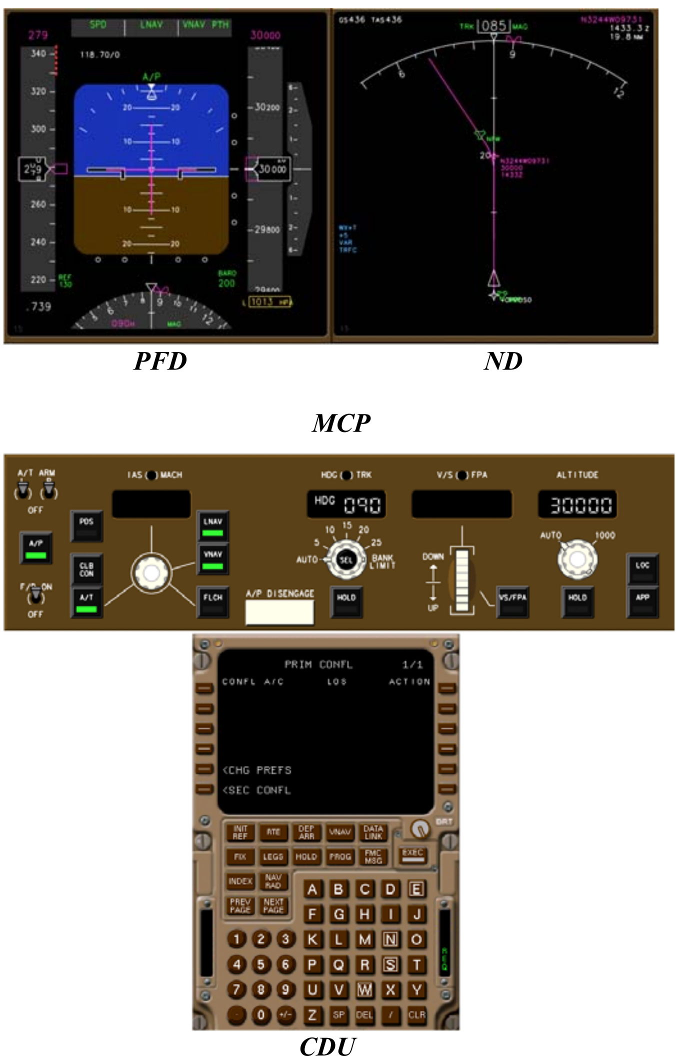

Figure 1. Flight Crew Interfaces Implemented in NASA Langley Air Traffic Operations Lab (Based on Boeing 777)

Aircraft Control States

ACM information provided to pilots depends on the aircraft control state selected by pilots of both the ownship and traffic aircraft. These control states are designed to support both tactical and strategic flying. The three primary control states, referred to here as manual (no flight director), target state, and trajectory are shown in Figure 2. With each successive outer loop, AOP is provided additional trajectory information for conflict alerting and avoidance planning.

When aircraft are flown manually without use of a flight director, only state (position and velocity) information is available. Under target state control, single commanded states are available in the horizontal and vertical planes (such as roll-out heading or level-off altitude, respectively.) In the outermost loop corresponding to trajectory control, the known aircraft trajectory consists of multiple trajectory change points and connecting flight segments. Target state and trajectory change messages sent over ADS-B provide a mechanism to supply AOP with available intent from other aircraft [3,15].

The ACM tool must adhere to a complex set of information processing and display requirements due to the multiple control state combinations that may exist between the ownship and nearby traffic aircraft. Most commercial aircraft have several flight modes corresponding to the target state and trajectory control states shown in Figure 2. Flight modes are normally selected through the MCP and include choices such as hold current heading, hold current altitude, and maintain track between Flight Management System (FMS) waypoints.

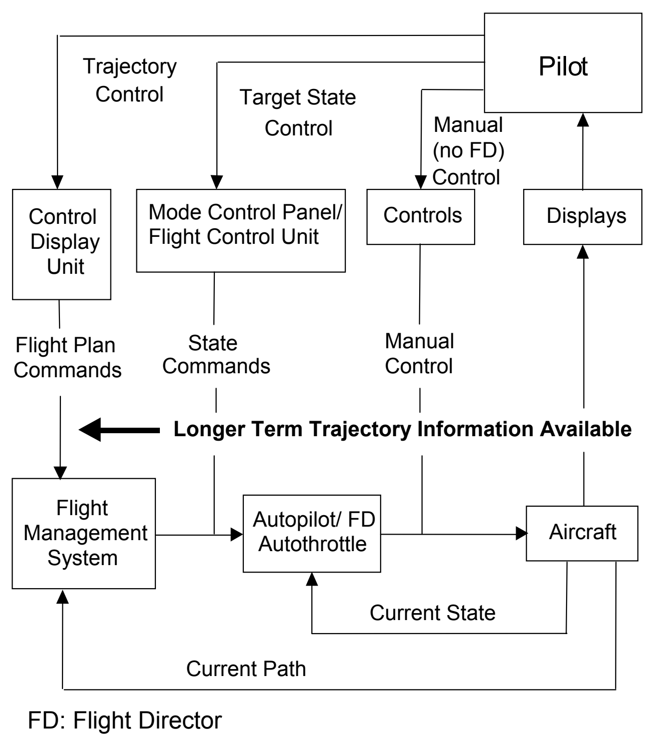

Figure 2. Aircraft Control States

The pilot can concurrently choose horizontal and vertical flight modes that correspond to different control states, leading to different intent availability in the horizontal and vertical axes.

Typical equipment sets on transport category aircraft (as shown in Figure 2) are capable of providing the associated information to AOP. Other flight hardware may also be able to generate this information. More sophisticated equipment is needed to access outer loop information and may be unavailable on older aircraft. An MCP is the primary interface between the pilot and autopilot when not operating in FMS automated modes. Pilots use the MCP tactically to select interim target states such as altitude, heading, vertical speed, and airspeed. The FMS is generally programmed before flight through the keypad-based CDU. A pilot may program an entire route complete with multiple waypoints, speed, altitude, and time restrictions, and desired speeds along different flight segments. Changes may be made to the route description at any time during the flight.

Complex paths may be created when an aircraft's trajectory is generated in both MCP and FMS flight modes. Such a situation can occur when the horizontal and vertical modes correspond to different control states, or when an autopilot target value interrupts an FMS planned trajectory. The latter case is most common when the MCP selected altitude lies between the aircraft's current altitude and the programmed FMS altitude. In this case, the aircraft will level out at the MCP selected value.

Complex interactions between modes have been shown to cause mode awareness issues for pilots [19], thereby increasing the need for a robust ACM architecture. Airline economic considerations suggest that aircraft control methods and their associated interactions will likely be in place well into the future [5,10].

Design of AOP to Perform ACM in Common Guidance Modes

As indicated in the previous section, AOP must incorporate design approaches to handle a variety of guidance mode interactions, while keeping pilots "in the loop" and providing them with effective feedback on conflict situations. The discussion that follows describes the core AOP functions of CD, CP and CR in light of these requirements, and indicates how AOP adheres to human factors guidelines in performing these functions.

Conflict Detection (CD)

The CD function provides long-range detection of conflicts between ownship trajectories and hazards, providing flight crews the time to develop and implement optimal solutions. Any conflicts are ranked and alerted to the crew through visual and aural alerts that conform to the RTCA ACM Group's guidelines on alert levels and implications [14].

In order to function in any guidance mode selected by the crew, AOP uses the concept of a *command trajectory* for conflict detection. The command trajectory refers to the path the aircraft will fly if the pilot doesn't change any automation modes or settings actively supporting aircraft guidance. This path may include multiple flight mode transitions. Changes to the command trajectory normally result from a pilot input. However, a non-programmed mode transition may also occur that affects the command trajectory, e.g. reversion to speed priority on descent if the intended vertical path results in an over-speed condition. Use of the command trajectory to represent aircraft intent was proposed by the FAA and Eurocontrol in a 2000 Technical Interchange Meeting on shared flight intent [6] and is also supported by RTCA [15].

AOP determines the command trajectory by considering flight mode logic and targets resident in all autoflight systems that support aircraft guidance. To do so, AOP continuously monitors aircraft states and the guidance mode selections made by the pilot through the MCP and CDU.

The AOP CD function uses a deterministic approach to compare the 4-D ownship command trajectory with the incoming command trajectories from other traffic and the locations of hazardous weather and special use airspace. For safety, a two minute state-based blunder protection is added to the command trajectory-based conflict alerts. Traffic information is assumed to be available through ADS-B. The current Minimum Aviation System Performance Standards (MASPS) for ADS-B [15] provide a means for aircraft to broadcast target state and trajectory information. All of these computations are transparent to the flight crew.

Conflict alerting is provided through existing flight deck displays and interfaces. Three alert levels (as recommended by the RTCA ACM group [14]) are used to alert the crew to conflicts, with proximate and more hazardous situations getting higher alert levels. Figure 3 presents an example of the alert symbology. Ownship is fully coupled to the FMS and AOP has detected a conflict with the aircraft to the left. The amber coloring of the traffic aircraft indicates conflict alert level, and the amber line overlaid on the flight plan route indicates the region where loss of separation will occur. The use of existing displays and industry standards for alert symbology and annunciation limits the need for extensive crew training and enhances comprehensibility.

The use of the currently commanded guidance mode for conflict alerting makes the display intuitive and predictable during AOP's CD function.

Conflict Prevention (CP)

AOP's CP function provides flight crews with guidance for conflict-free maneuvering in common guidance modes. This functionality has been continuously refined and enhanced following successive human-in-the-loop evaluations of AOP prototypes at NASA Langley [11,21]. As currently implemented, AOP's CP function has both passive and active elements.

The passive element provides the crew, upon pilot request, with "at-a-glance" information on flight path changes that would cause near-term conflicts. This CP information is presented to the crew by no-fly bands on the ND and PFD as

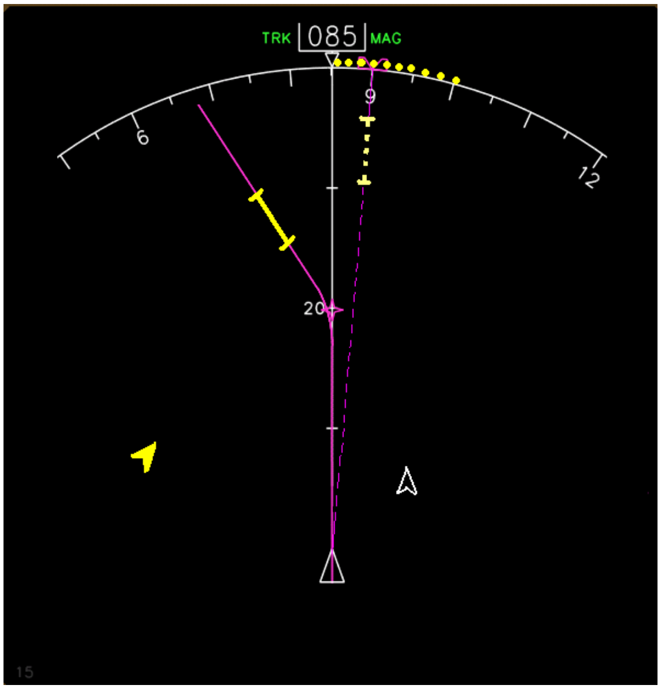

Figure 3. Display of CD and CP Information from AOP

pioneered by the NLR [8]. Based on results from previous experiments, AOP's no-fly bands have been enhanced to consider the intent-based command trajectories from both the ownship and traffic aircraft. This change ensures consistency between AOP's CD, CP, and CR functions. The by-request nature of these bands ensures that this form of CP is displayed only when the crew requires it. Figure 3 presents an example of the symbology used to depict these no-fly bands on the ND. The dotted amber band on the compass rose marks a range of headings that the pilot should not command in order to prevent a conflict with the aircraft to the right of ownship.

The active element in AOP's CP provides the crew with decision-support on proposed maneuvers, enabled by the crew communicating its intentions to AOP. Since AOP continuously monitors the MCP and CDU, it is aware of any FMS modified (MOD) routes and MCP heading/altitude selections that are yet to be executed. Therefore, when the crew creates any such form of provisional intent, AOP creates 4-D trajectories for that intent and performs CD on the provisional trajectories. Pilots are alerted to any conflicts detected on these trajectories through the ND, so that they can evaluate the trajectory and make an informed decision on implementing the intended route or target-state changes. The alerts used for these provisional maneuvers are simple modifications of the CD alerts provided on the command trajectory.

In Figure 3, the pilot has provisionally selected a heading slightly to the right of current heading, as indicated by the dashed magenta line. This heading, if commanded, would put ownship in conflict with the traffic to the right, and AOP conveys this information to the crew by displaying a dashed amber line overlaying the selected heading. The pilot is not allowed to implement this heading once AOP has indicated this provisional conflict. This CP function is aligned with a feature of the operational concept that requires AFR flight crews to verify that intent changes are conflict-free (for a prescribed look-ahead period) before they are implemented, in order to limit conflict proliferation.

Conflict Resolution (CR)

AOP's CR function provides crews with resolutions in several common aircraft guidance modes. They are presented to the crew through existing displays (PFD and ND) and crew interfaces such as the CDU. AOP supports two types of resolutions, referred to as strategic (trajectory-based) and tactical (target state-based).

Strategic resolutions are computed using a genetic algorithm [2] and are displayed one at a time as modified FMS routes on the ND. They provide crews with (a) a solution to the current conflict, (b) a return to the FMS route, (c) protection from creating future conflicts, and (d) conformance to active TFM constraints to the extent possible within ownship performance limitations. The crew is always in full control of the aircraft and its systems, and these resolution advisories are not created or implemented without crew input through the CDU.

Tactical resolutions are presented to the crew as simple "go-to" headings, vertical speeds, and altitudes that can be implemented by the flight crew either manually or through the MCP. They are annunciated as simple "bugs" on the ND and PFD. Time-to-conflict considerations determine the extent to which these resolutions protect the ownship from future conflicts. Again, the crew is in full control of the aircraft, and these resolutions can only be implemented by crew input through the MCP.

AOP computes and provides resolutions that complement the currently engaged guidance mode. If the pilot is commanding trajectory control (in both the horizontal and vertical planes), AOP provides strategic resolutions. When not operating under full trajectory control or when the time to conflict is short, AOP gives tactical resolutions. These features ensure that AOP is responsive to the crew's preferences in controlling the airplane [20], and that AOP's resolutions are appropriate for the situation.

CONCLUSIONS

The ongoing AOP design process has considered human factors principles and incorporated lessons learned from previous human-in-the-loop experiments [11,21]. The AOP provides an interactive tool suite that enables flight crews to specify resolution preferences and probe intended flight paths for potential conflicts. Resolution status and results are presented on the appropriate crew interface, based on the current aircraft control state. Graded alerts and resolution strategies, based on time to conflict, are based on existing alerting conventions and provide a convenient platform for crew training. Error tolerance is supported through a robust interface that allows re-consideration of previous maneuver choices.

A June 2004 pilot and controller-in-the-loop experiment on air-ground coordination, conducted jointly with NASA Ames Research Center, has been the first study to use the latest AOP design. Major enhancements (described above) include upgrading CP and tactical CR to consider intent-based command trajectories. In this experiment, pilots used the AOP to resolve traffic conflicts during en route and descent flight in airspace modeled after the Dallas Ft. Worth area. Simultaneous AFR and IFR operations were conducted in the same airspace and overflight traffic levels were varied up to twice the current day capacity. For arriving aircraft, controllers assigned speed, altitude, and time constraints at a terminal area meter fix. Preliminary results indicate overall acceptance of the AOP and also illustrate several complex trajectory prediction issues associated with merging traffic at the meter fix. Follow-on work will need to re-consider the appropriate blending of state-based blunder protection with command trajectory-based conflict alerts. The alerting trade-off of false alerts and missed detections is more difficult in areas where dynamic flight and close aircraft separation are common. Experimental results indicating how pilots used the AOP under these conditions should give insight into addressing this trade-off.

To this point, AOP development has concentrated mainly on medium to long-term CD, CP and CR. Future AOP versions will need to develop an interface between existing separation assurance functions and a collision avoidance system. This interface should consider data fusion issues associated with ADS-B and Traffic Alert and Collision Avoidance System (TCAS) antennas, as well as ensuring that pilots are presented with consistent alerting and resolution guidance information. AOP designers will continue to use a process of applying core human factors principles and using results obtained through experiments with expert users to address these challenges.

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