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Performance Evaluation of a Computational Model of en Route Air Traffic Control

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PERFORMANCE EVALUATION OF A COMPUTATIONAL MODEL OF EN ROUTE AIR TRAFFIC CONTROL

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This paper describes a model of en route air traffic control and presents the results of a performance evaluation of computational air traffic controller agents based on the model. The purpose is to better understand the representations, heuristics, and processes that expert air traffic controllers use and develop agents useful for air traffic management concept development and safety/risk analysis. The results show the agents control low-to-medium traffic levels effectively. The research was supported by the NASA Aviation System Capacity Program and the FAA/NASA Aviation Safety Program.

Introduction

Today's air traffic management (ATM) system is highly safe and robust, but it cannot sustain current capacity limits, inefficiencies, and adverse environmental impacts over the long term. Researchers are therefore investigating new ATM concepts to address these problems. The complexity of the ATM system makes developing new concepts challenging. Researchers must address a broad range of issues—automation functionality and operator interaction, operational scenarios, and training. Simulations with computational agents offer an attractive complement to development through iterative human-in-the-loop simulations.

Several recent research efforts address air traffic controller models. For example, Niessen, Eyferth, and Bierwagen (1999) studied how experienced controllers assess traffic situations. Niessen and Eyferth (2001) then used a computational cognitive model based on the ACT-R framework to study how controllers construct a 'picture' of the traffic situation. Other research has investigated control strategies (Nunes and Mogford, 2003) and conflict detection and resolution rules (Mondoloni, 1998). Models have been developed to assess control techniques (Krozel, Peters, Bilimoria, Lee, and Mitchell, 2001), produce predictive performance measures (Leiden, 2000), and enable decision support (Hexmoor and Heng, 2000).

ATM safety and efficiency studies have also been conducted with computational cognitive models. For example, AirMIDAS has been used to analyze the safety of new alerting systems (Pritchett, Lee, Abkin, Gilgur, Bea, Corker, Verma, Jadhav, Reynolds, Vigeant-Langlois, and Gosling, 2002) and the effects of proposed changes to practitioner roles and responsibilities (Corker, Gore, Fleming, and Lane, 1999). Cognitive agent models of conflict resolution in distributed ATM have also been developed (Harper, Guarino, White, Hanson, Bilimoria, and Mulfinger, 2002).

This paper describes a model and its implementation as a computational agent that functions as a radar (R-side) controller controlling traffic in a single sector. The model approximates controller behavior using heuristic methods rather than optimization methods. The research aims to better understand the representations and processes air traffic controllers use and refine agents useful in advanced ATM concept development and safety/risk analysis. After describing the model and its implementation in en route controller agents, the paper describes a performance evaluation with three agents controlling arrival traffic in adjoining sectors. Additional detail is provided in Callantine (2002b).

Model and Computational Architecture

Figure 1 shows the information flows within an agent and its interactions with other agents and a traffic simulation via a 'simulation hub.' Agents issue clearances to simulated aircraft, initiate handoffs to other agents, and accept handoffs from other agents using messages passed through the simulation hub. Figure 2 shows a screen snapshot of an agent controlling traffic. The following sections describe the model components and processing.

Activity Model

A Crew Activity Tracking System (CATS) activity model serves as the basis for the air traffic controller agents (Callantine, 2001). The model represents the high-level structure of the air traffic control task. Each air traffic controller agent uses the CATS activity model shown in Figure 3. The model represents activities hierarchically, down to the action level, and includes conditions that specify when each activity should preferably be performed.

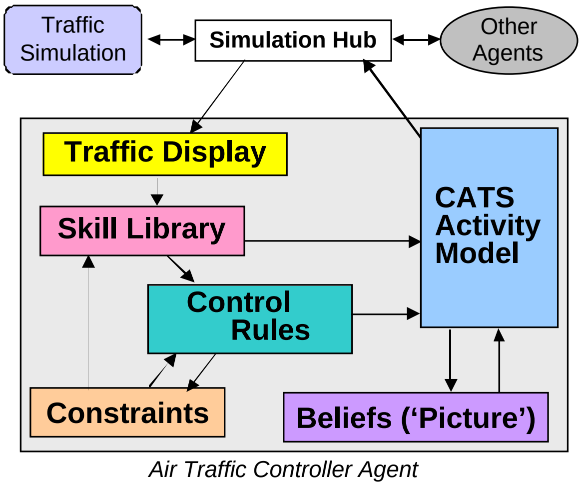

Figure 1: *Information flows within and between air traffic controller agents.*

The model in Figure 3 can be thought of in three parts. The first is the Maintain situation awareness activity, and its children, Monitor traffic display and Scan aircraft. These activities are devoted to gathering information from displayed traffic information. The second is the Determine aircraft to work activity, which represents selecting a traffic control problem to address from those currently identified. The third portion is a collection of Manage *X* activities that are performed based on the outcome of the Determine aircraft to work activity. Thus, the model is similar to conceptual air traffic controller models with situation assessment, planning, and execution modules (e.g. Davison and Hansman, 2003).

Agents exhibit a ‘flow of activity’ that hinges on the Determine aircraft to work activity. Executing this activity identifies the next aircraft (or ‘cluster’ of aircraft) that the agent should address according to a static set of priorities. In plans with multiple steps (e.g., vector an aircraft off its route, then to a route-intercept heading, then back on its flight plan route), later steps depend on earlier steps for their success. The highest priority is therefore to implement plans whose execution conditions are currently satisfied. Planning to solve conflicts is second, planning to solve spacing problems third, and issuing descent clearances fourth. Handoff acceptance and handoff initiation are the lowest priority. The priority

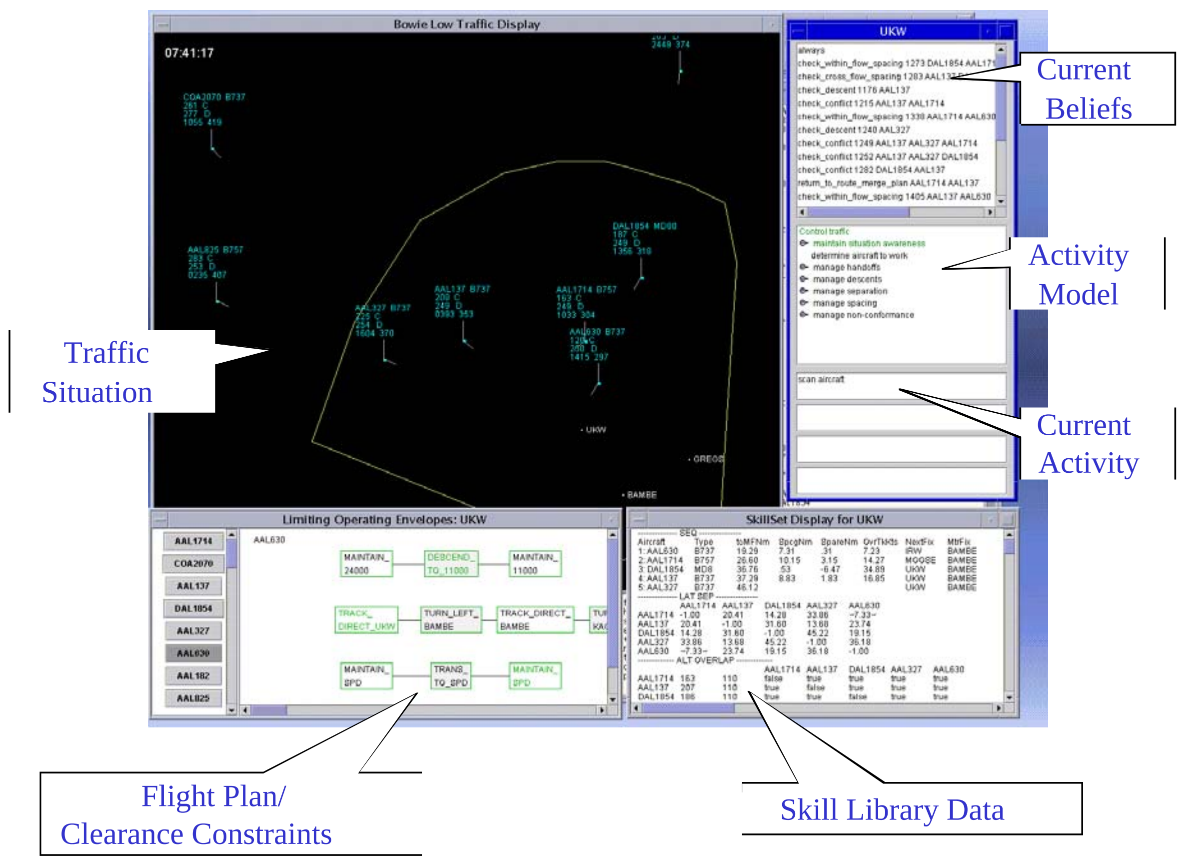

Figure 2: *Screen snapshot.*

- Maintain situation awareness
  - Monitor traffic display
  - Scan aircraft
- Determine aircraft to work
- Manage handoffs
  - Accept aircraft
    - Accept handoff
    - Roger check-in
  - Initiate handoff
    - Inform other controller
    - Issue frequency change
- Manage descents
  - Issue descent clearance
- Manage separation
  - Evaluate separation clearance options
  - Issue separation clearance
- Manage spacing
  - Evaluate spacing clearance options
  - Issue spacing clearance
- Manage nonconformance
  - Re-issue clearance

Figure 3: *CATS activity model.*

structure enables agents to reasonably approximate 'chunking' of air traffic controller behavior. As an example, controllers are sometimes observed to issue several clearances to separate a cluster of aircraft, then accept several handoffs in succession.

Beliefs

The agents maintain beliefs about the current task context and current traffic situation. Agents transform their belief set by performing activities, in accordance with the theory that all salient operator activities in complex human-machine systems involve transforming or communicating contextual information. For example, performing a perceptual activity entails transforming information found in a representation of the appropriate visual or auditory 'display' into a set of beliefs about the information. Performing a cognitive activity entails modifying the agent's belief set to produce beliefs at different levels of abstraction, or beliefs that encapsulate the results of a decision making process.

Task context beliefs on the left side of Figure 4 appear in the conditions for performing activities in the CATS activity model. Depending on various traffic assessments, the agents add or remove different beliefs from their belief set. The last several beliefs ('know which…' and '…identified') correspond to the type of control problem identified in Determine aircraft to work. For example, if the Determine aircraft to work activity finds a conflict is the highest priority problem, an agent adds 'factors identified' to its task context belief set, which causes the agent to execute Evaluate separation clearance options on the next processing cycle. Executing this activity references the 'control rules' heuristics and results in a 'know which aircraft to clear' belief, which then triggers the Issue separation clearance activity.

The right side of Figure 4 lists beliefs about the current control situation, including memory for when problems were last addressed, and prospective memory for plans. By planning to issue a clearance to solve the conflict, rather than issuing the clearance right away, the agent has the option to adapt the plan or abandon it altogether if its execution conditions happen not to materialize. Retrospective memory about when problems were last addressed is also important because it takes time for traffic to reflect the effects of clearances. The 'check…' beliefs tell the agent to move on to lower priority problems until after the indicated time (Figure 4). Situation beliefs

Task context

Always
Display needs scanning
Looked at traffic display
Have aircraft to work
Know which aircraft to accept
Know which aircraft to hand off
Know which aircraft to descend
Factors identified (refers to conflict aircraft)
Spacing aircraft identified
Know which aircraft to clear (separate)
Know which aircraft to space
Know which aircraft is not conforming

Situation context

- *beliefs about current situation*
- *memory for 'problem status'*
- *prospective memory for plans*

Check_cross_flow_spacing [time] [aircraft]
Check_within_flow_spacing [time] [aircraft]
Check_conflict [time] [aircraft]
Check_descent [time] [aircraft]
Cross_flow_spacing [aircraft clusters]
Within_flow_spacing [aircraft clusters]
Conflicts [aircraft clusters]
Sector_aircraft [aircraft]
Plan_exec [aircraft]

Figure 4: *Task and situation beliefs.*

refer to individual aircraft or clusters of aircraft, according to the level of structural abstraction required (Davison and Hansman, 2003).

Agents also maintain other important information via encoded Java™ objects and variables. The most important of these are 'role bindings' for aircraft, which provide a general way to specify a frame of reference for the application of heuristics. When agents execute the 'monitor traffic display' activity, they apply encoded skills to 'bind' aircraft to roles (e.g., front, frontSequence, etc.). For each bound role, the agents also access skills that assign a bit-vector of fuzzy-valued attributes (e.g., tooClose, atSameAltitude, etc.).

Control Rules and Plans

A collection of heuristics determines the control techniques to use to achieve proper spacing or separation (Figure 5). Spacing heuristics relate to establishing a desired in-trail distance, while separation heuristics resolve conflicts. In this research, spacing problems can by definition be solved using speed clearances, while separation problems by definition require heading vectors. Separation heuristics are differentiated according to whether aircraft are merging or not. The control rules use role bindings to reference other aircraft.

Planning is crucial for solving separation and spacing problems. The heuristics address the aircraft currently bound to roles; however, other aircraft may also be in conflict. Allowing the agents to develop plans for all conflicting aircraft before issuing any clearances means agents first execute plans whose execution conditions are met first. Figure 6 shows plan steps in each dimension (grayed-out plan steps were replaced with immediate clearances in the evaluation study). Figure 6 also shows examples of plan-adaptation conditions for lateral plans. Each plan contains roles (e.g., front, etc.) bound to the plan and a 'planned time' for executing the plan. Plans may simply be

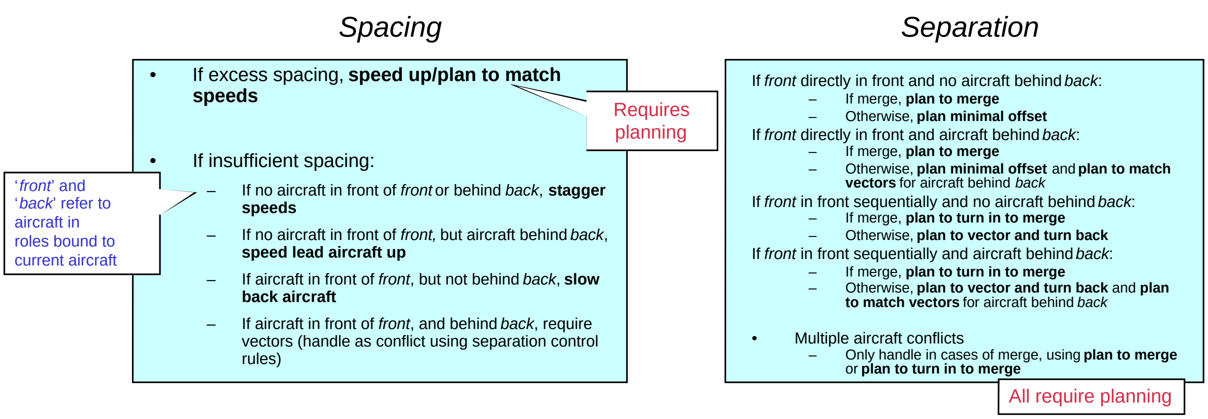

Figure 5: *Spacing and separation control rules.*

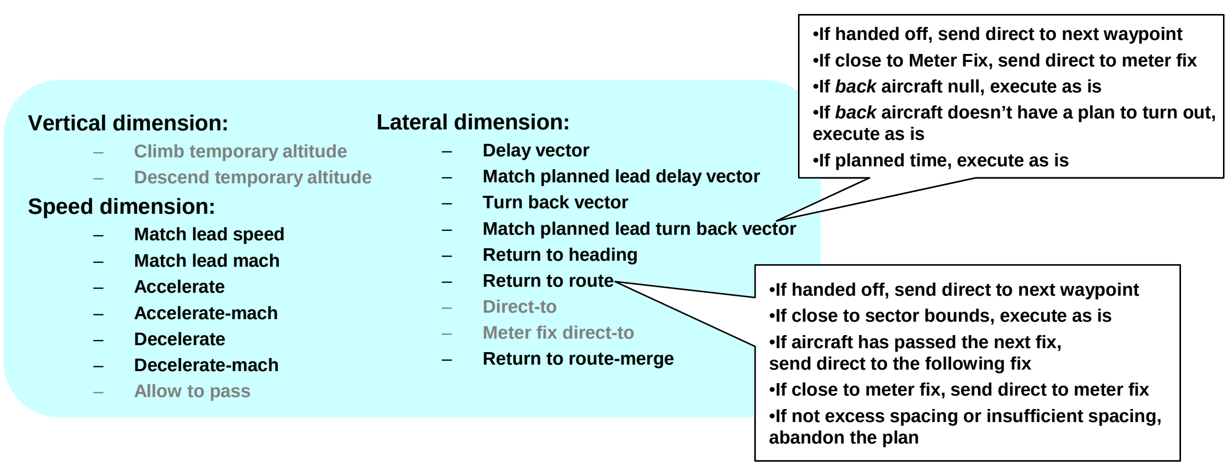

Figure 6: *Plan steps and examples of adaptation/execution conditions.*

executed at their planned time if no adaptation conditions are met.

Skill Library

The ‘skill library’ is collection of encoded methods that enable agents to perform low-level pattern recognition and display-based decision-making. Examples include determining the lead aircraft for an aircraft of interest, determining the precise heading to issue when a heading clearance is called for, or assessing the distance between two aircraft. Skills figure prominently in determining which aircraft to work, applying control rules, and monitoring plan adaptation/execution conditions.

Constraints

Each agent maintains a representation of operational constraints on each aircraft (see Figure 2) in its ‘area of regard’. Constraints derive from the aircraft’s flight plan and amendments to it specified by clearances (Callantine, 2002a). The constraint representation enables agents to monitor conformance with clearances and predict future behavior (e.g., time remaining until an aircraft should maneuver).

Traffic Display

The traffic display is a representation of the information available on a controller’s scope (see Figure 2). Skills operate on the traffic display information to assess the traffic (see Figure 1).

Method

A performance evaluation was conducted with three agents controlling simulated arrival traffic in en route airspace in real time. The evaluation compared number of loss-of-separation events (less than 5 nm of lateral separation and less than 1000 ft vertical separation) with and without full agent control.

Airspace

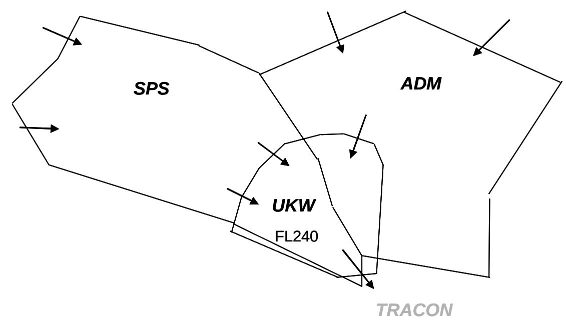

Figure 7: *Airspace and arrival traffic flows.*

Two agents simultaneously controlled traffic in high altitude sectors SPS and ADM; another agent was responsible for merging the arrival flows in the low altitude sector UKW (Figure 7).

Traffic Scenarios

Nine scenarios were adapted from scenarios that were being used in other NASA ATM research. The scenarios represented a range of traffic conditions. Each of the nine scenarios was run first in a ‘no control’ condition with agents only issuing descent clearances, so that aircraft simply arrived on their nominal flight plan arrival trajectory. Each scenario was then run again with the agents issuing clearances.

Results

Figure 8 summarizes the performance evaluation results. The agents handle spacing problems in the high altitude sectors (SPS and ADM) well. The agents are less adept at handling merge problems in UKW. More loss-of-separation events occurred in dense-traffic scenarios with poorly conditioned arrival flows (scenarios 7-9). In no case did the agents produce more loss-of-separation events than the uncontrolled (descent clearance only) condition.

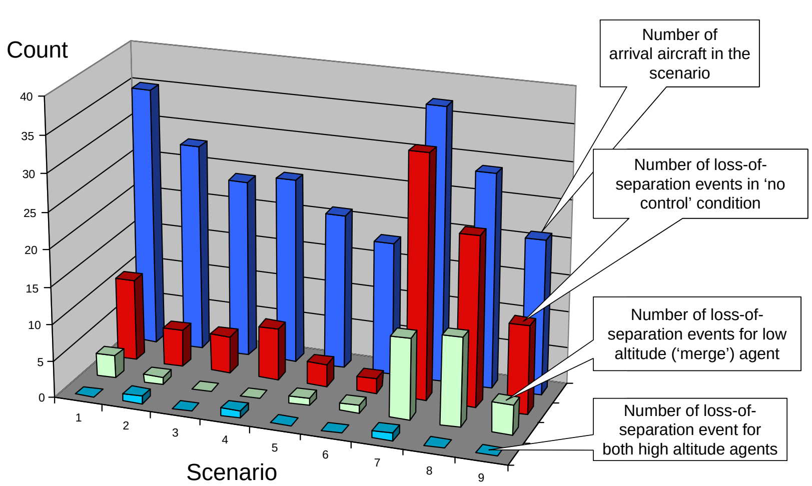

Figure 8. *Scenario traffic counts and loss-of-separation events.*

Conclusion

The agents performed reasonably well considering the difficulty of the air traffic control task. The knowledge representations and processing scheme embodied in the agents are elicited from observations and anecdotal evidence about how human controllers operate. The control rules, plans, adaptation/ execution conditions, and prioritization of control problems therefore may not be appropriate in every situation. Because the study did not include professional human air traffic controllers, suitable validation measures are not available. In addition to validated control knowledge, the results suggest that better predictions and intentional focus would improve the 'picture,' and in turn, overall agent performance.

Current research is addressing enhancements to the air traffic controller model and computational architecture. The enhanced agents are designed to control traffic in terminal radar approach control rather than en route airspace. Human controller performance data is available for the same traffic scenarios to be used for agent testing, which will enable detailed validation studies.

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