Computational Modeling of Trajectory-Oriented Air Traffic Management

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Summary

Computational modeling of modern aircraft Flight Management System trajectories is useful for understanding trajectory-oriented air traffic management. This paper describes a tool called TCSim (Trajectory-Centered Simulator) that models and simulates aircraft flying FMS arrival procedures, air traffic controller agents, and air traffic control automation. The research is supported by the NASA Vehicle Systems Program Quiet Aircraft Technology project and the Advanced Air Transportation Technology project of NASA's Airspace Systems Program.

Introduction

Current Air Traffic Management (ATM) systems are highly robust and safe, but can at times be unpredictable and inefficient due to their complexity and susceptibility to environmental disturbances. Advances in aircraft automation, air traffic control (ATC) automation, and communications, navigation, and surveillance (CNS) systems hold promise for future ATM systems with reduced delays, noise, and fuel usage, and increased safety and security.

This paper addresses how computational modeling complements human factors research in developing future ATM concepts. The modeling is centered on a specific aspect of modern commercial aircraft: the Flight Management System (FMS) trajectory. An FMS trajectory is the trajectory an aircraft flies as it attempts to follow the FMS-computed lateral/vertical/speed profile. Modern FMSs compute 4D trajectories to meet precise required-times-of-arrival (RTAs) at specified points.

The precision of FMS trajectories provides a potential solution to inefficiencies, but recognized human factors problems persist, including difficulties with modifying the FMS trajectory and with predicting how the aircraft will fly it under various environmental conditions. While pilots have become accustomed to the FMS, its potential is unrealized because ATC operations are still, to a large extent, tactical. For example, air traffic controllers continue to use 'heading vectors' to create and maintain the required spacing between aircraft. More strategic ATM operations therefore include the development of control techniques for managing aircraft on FMS trajectories. For example, air traffic controllers might use speed control instead, enabling them to control aircraft while the aircraft fly the lateral portion of an FMS procedure 'as is.'

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This paper describes how the Java™-based tool TCSim (Trajectory-Centered Simulator) helps understand prospective ATM improvements by modeling and simulating FMS procedures[1]. It draws examples from two ongoing NASA ATM research projects. The first entails determining how air traffic controllers can manage FMS arrivals that merge in the terminal-area (TRACON) airspace to land on the same runway. This 'TRACON merge problem' is a sub-problem of NASA Distributed Air/Ground Traffic Management Research (DAG-TM)[2] concerned with how air traffic controllers should manage aircraft unequipped for spacing themselves relative to another aircraft. The second project addresses how a platoon of arrival aircraft might be set up to fly so-called continuous-descent approaches (CDAs) so as to keep the required ATC-aircraft interaction as simple as possible. This problem relates to the conduct of CDA flight tests as part of NASA Quiet Aircraft Technology (QAT) research[3] in which the initial focus is on FMS performance and noise reduction benefits.

FMS Trajectory Modeling in TCSim

Central to TCSim is an algorithm for computing FMS trajectories and 'in-flight' modifications to them. Real aircraft FMS computations are proprietary; TCSim therefore computes 'idealized' FMS trajectories. The primary assumptions are that decelerations must take place on profile segments where the flight path angle is two degrees or less, and that they occur at a 'standard rate' of one third of a knot per second. The algorithm first computes bounds on the speed and altitude at each ground-referenced waypoint in order to observe any speed and/or altitude restrictions, including one-sided (e.g., at-or-above) restrictions. It then computes estimates of the speed and altitude of the aircraft at each waypoint. Using these estimates, it computes the lateral turn radii. Finally, the algorithm works backwards from the end of the trajectory to compute flight path angles or descent rates along each segment as required for achieving the specified speeds and altitudes. For each trajectory segment, TCSim computes how the corresponding aircraft flies using difference equations to integrate through the specified wind field (which can be constant, altitude-varying, or altitude-and-location varying). TCSim collects performance metrics for each aircraft, including state information, inter-aircraft spacing along the FMS arrival/approach path, and waypoint crossing times.

Figure 1 depicts an arrival trajectory (a CDA, because it contains no level segments) modeled in TCSim. The figure illustrates a smoother trajectory than one containing real-world variations. This aids comparisons of different FMS procedures and control strategies. Figure 2 shows the effects of winds on flight times along a CDA. An interesting outcome is that two of the wind conditions selected for the purpose of creating rather different conditions for study yield very similar overall flight times. An extension of this analysis compared flight times for CDA aircraft with different cruise altitudes and altitudes at the TRACON boundary under four altitude-varying wind conditions. The results show the range of possible flight times for different CDAs, and confirm that greater throughput is possible when aircraft stay higher longer.

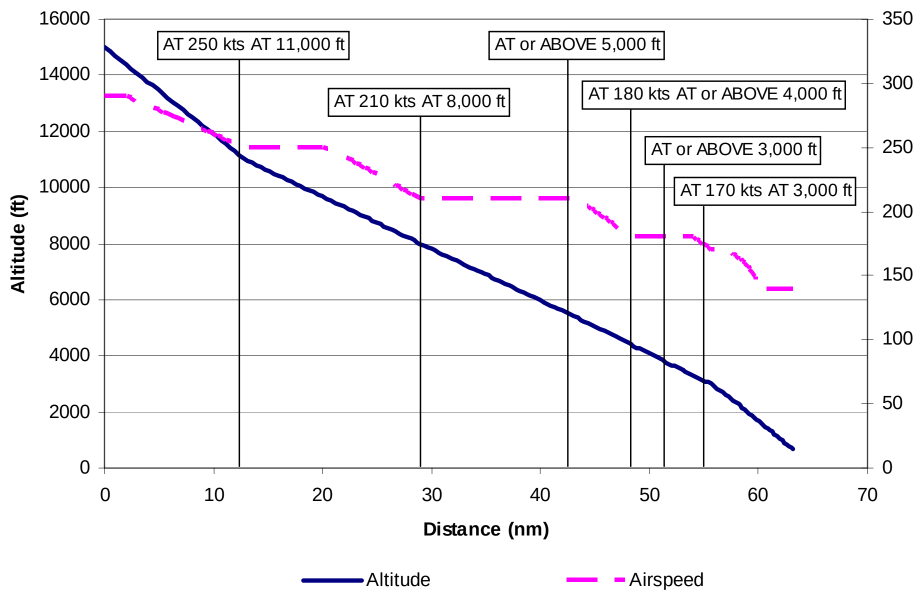

Figure 1. TCSim FMS altitude and speed profile honoring specified restrictions.

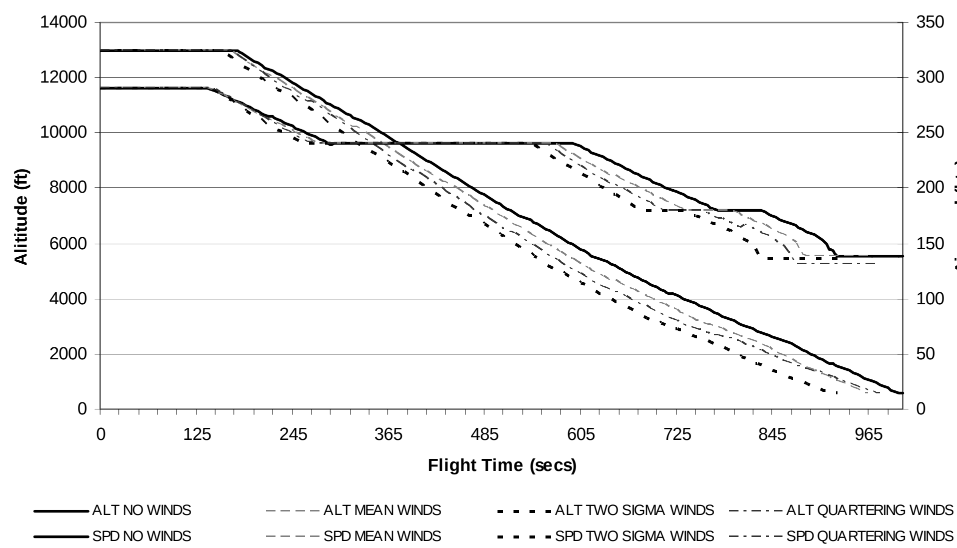

Figure 2. TCSim altitude and speed profiles for an FMS procedure in four different altitude-varying wind conditions.

ATC Automation Modeling in TCSim

In addition to general 'domain analysis,' researchers can also use TCSim to investigate improved ATC automation and control strategies. For example, TCSim's trajectory computations enable it to model different approaches for scheduling aircraft. Built-in scheduling functionality sets TCSim apart from other air traffic simulation tools, because it enables TCSim to automatically create arrival scenarios with specific characteristics.

TCSim can perform fast-time Monte Carlo-style simulation using randomly generated scenarios. For example, TCSim can derive the expected optimal throughput for a particular mix of aircraft types, winds, and routes to a given runway. On each trial, TCSim computes FMS trajectories for each aircraft, schedules them based on their computed flight times, and constructs a scenario in which aircraft arrive at the runway threshold(s) with correct spacing. TCSim then simulates the flights and measures the elapsed time from the first arrival to the last. The same process may be used to compute how many 'miles in trail' aircraft should arrive at a given waypoint so as to achieve proper spacing at a downpath point. For early-phase CDA flight tests, where it may be desirable to limit ATC-aircraft interaction, this analysis produces a 'safe value' for miles-in-trail spacing at the TRACON boundary that, once established, ensures aircraft will arrive at the runway with adequate spacing.

By applying probabilistic deviations to arrival schedules, TCSim can create control problems of varying complexity. Researchers can visualize the 'perturbed' schedule via a timeline display to see how air traffic controllers will need to adjust aircraft to arrive on time. Researchers can also load predefined traffic scenarios into TCSim, create schedules, and examine them. Moreover, TCSim enables researchers to edit the scenarios graphically. Whether a scenario is created randomly or edited using TCSim, researchers can run it on Multi Aircraft Control System[4] stations with human operators. Together these capabilities have helped make TCSim a useful tool for supporting ATM human factors research. For example, NASA researchers are using TCSim to create TRACON merge problem scenarios, as well as large DAG-TM scenarios in en route airspace.

Beyond scheduling, TCSim also uses its trajectory computations to simulate more advanced 'advisory' automation. Advisories are clearances computed to yield specific outcomes (e.g., a speed to fly such that an aircraft will meet a specified RTA). TCSim computes advisories for controlling to scheduled arrival times based on range of clearance types. Air traffic controller agents in TCSim may then clear the aircraft per the advisories, as described in the next section.

Air Traffic Controller Agent Modeling in TCSim

Air traffic controller agent models can actively control aircraft in TCSim. The agent models may be complex[5], but even simple models can answer some important questions. For example, for the TRACON merge problem, researchers have used TCSim to evaluate the effectiveness of speed advisories, with air traffic controller agents issuing advisory clearances at various 'control points' to null schedule deviations[6]. Figure 3 shows the control authority afforded by speed advisories under calm winds for arrivals coming from one direction—with longer routes than aircraft they are to merge with (Figure 4). Speed advisories for the flow in Figure 3 provide nearly twice the control authority. Thus, other control methods are likely needed to make major adjustments to the other flow in Figure 4. Results like these could lead to the development of air traffic controller heuristics or tools that improve performance without ATC automation.

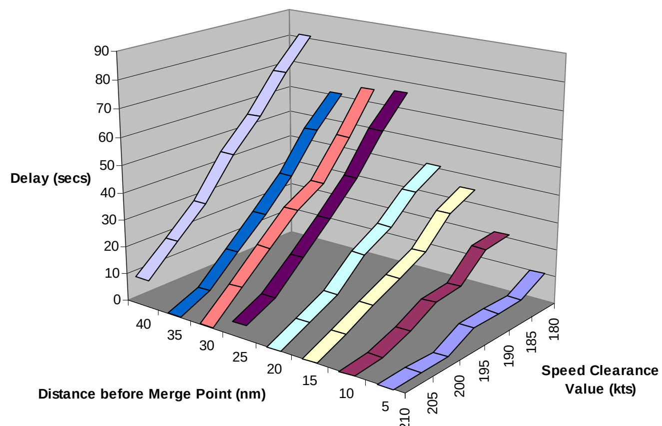

Figure 3. Delay that can be absorbed using speed clearances issued at specific distances from a merge point along an FMS arrival route (southwest flow).

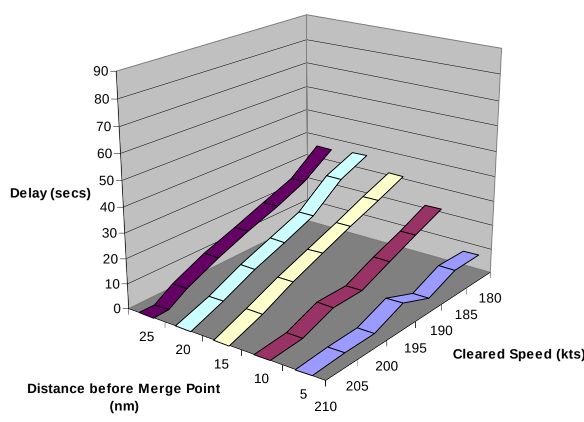

Figure 4. Delay absorbed with speed control for the merging (northwest) flow.

Concluding Remarks

Computational modeling of FMS trajectories is useful for analyzing trajectory-oriented ATM concepts. TCSim's idealized trajectories support cross-concept comparisons and enable efficient fast-time aircraft simulation. Researchers can configure TCSim to simulate various future ATC automation and control methods. TCSim can conduct Monte Carlo simulations to estimate the values of key ATM safety and efficiency metrics. Furthermore, TCSim produces results that reflect the impact of ATC using air traffic controller agent models and the capability to actively control aircraft.

Finally, TCSim complements other important ATM human factors methods such as human-in-the-loop simulations and field studies. NASA researchers are using TCSim's editing and visualization capabilities to create and analyze ATM scenarios. Future research will focus on methods for analyzing the range of eventualities that can occur when a complex air traffic scenario unfolds under time-varying environmental conditions. This capability could help reduce the costs of crucial human-in-the-loop studies by identifying relevant experimental conditions inexpensively.

Reference

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