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Future Air Traffic Management: A Perspective on Distributed Automation

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Abstract

In this paper we present our perspective on some key issues regarding current trends in Air Traffic Management (ATM). We review results and observations from integrated air ground simulations that we conducted over the last few years at NASA Ames Research Center. In those high fidelity simulations we introduced new flight deck and/or ground automation and procedures for human-machine and human-human interaction to experienced pilots and controllers and evaluated/observed the impact. We present some specific and general findings as well as potential benefits and problems. We describe our current approach to investigating distributed air ground traffic management in the framework of recent, current and upcoming projects.

Introduction

Several concepts for a safer and more efficient air traffic system are currently being developed. One characteristic of all concepts is the continued introduction of advanced decision support tools for air traffic controllers and managers and the increased use of advanced automation. Flight deck automation is already at a fairly advanced state and existing systems as well as novel approaches are researched in depth. Most of the flight deck research is conducted in isolated aircraft simulators with scripted stimuli from the external environment. This may result in some aircraft automation such as vertical navigation (VNAV) working so poorly in busy air traffic that it cannot be used – thus eliminating the potential efficiency benefits.

Air Traffic Control (ATC) facilities are only at the beginning of the automation age. Integrating new display and control systems, decision support automation and data link into ATC facilities can be compared to introducing "glass cockpits" instead of "steam gauges". There is a multitude of possible effects that new automation may have on how operators interact with their computer tools and each other. These effects need to be identified and carefully regarded when modifying a system as complex and safety critical as the air traffic system. While looking at the local impact of new automation in well-defined specific experiments is a required step, it is just as important to understand the impact of this automation on the interaction of pilots and controllers in an operational environment.

Future Air Traffic Management in the Arrival Environment

If current airspace operations remain unchanged, increasing traffic demands are expected to compromise both on-time performance and safety. Coping with these increasing airspace capacity requirements will require substantial modifications and improvements to current-day operations. One approach to addressing this problem is to give airlines more freedom in scheduling and selecting preferred traffic routes while continuing to assign responsibility for separation and arrival planning to the Air Traffic Service Providers (ATSP). ATC-oriented approaches focus on airspace restructuring and/or development of new tools for air traffic managers and controllers that enable them to manage air traffic more safely and efficiently. Tools like COMPAS [1], URET [2] and CTAS TMA and FAST [3] are being developed and fielded in several ATC facilities.

We investigated this ATC-oriented approach within NASA's Terminal Area Productivity (TAP) program from several angles over the last four years. The first section of this paper summarizes this research. The second section introduces our current work in the more radical concept of Distributed Air Ground Traffic Management (DAG-TM).

Terminal Area Productivity (TAP) Research

In the ATM portion of the TAP program, we investigated the integration of future ground-based ATM decision support systems and Flight Management System (FMS) equipped aircraft within the terminal area. The experiments and demonstrations focused on increasing airport capacity for arriving traffic by using the Center TRACON Automation System (CTAS) for generating efficient trajectories, data link for communicating those trajectories to the aircraft and FMS equipped aircraft for flying them precisely.

We looked at the problem of aircraft arrival rushes into major airports. The goal was to provide a safe, highly efficient flow of traffic from enroute into TRACON airspace that reliably delivers aircraft to the runway threshold, while maintaining as much flight crew flexibility and authority as reasonable. Successful planning and execution of an efficient arrival flow requires a thorough understanding of all aircraft, operator, traffic management and spacing constraints, and involves coordination between controllers, flight crews, dispatchers and traffic management. We envision a human-centered system in which controllers and pilots use procedures, flight management automation and decision support tools to actively manage arrival traffic. We targeted a future air traffic system controlled and managed by the Air Traffic Service Providers (ATSP) and expected to be operational in the 2010 time frame [4].

The operational concept for achieving efficiency enhancements over today's operations is to plan an efficient arrival stream ahead of time and then execute the "arrival plan" as precisely as possible. We introduced a "multi-sector arrival planner" ATC position to bridge the gap between traffic managers, dispatchers and sector controllers. The planner's tasks involve creating the most efficient schedule and sequence for all arriving aircraft and conflict-free flight paths that meet this schedule. The planner coordinates the generated flight paths with the sector controllers using a graphical coordination tool. After reviewing the proposed flight path, the sector controllers issue appropriate clearances to the flight crews. Flight crews follow the cleared flight path precisely using their flight management automation. Sector controllers are responsible for maintaining separation and adjusting the arrival plan to new circumstances. Automation and procedures are designed to help with all these tasks.

This TAP concept is more strategic than today's systems but the controllers are actively involved in every step of the process of developing and executing a traffic flow plan for the arrival rush. Even though it significantly changes the roles of the stakeholders, it does not change their responsibilities. Observations and pilot and controller feedback from simulations demonstrating this concept can be found in [5,6,7,8] and are summarized below.

TAP-ATM Simulations

In addition to several interface reviews and engineering tests the following experiments were conducted in order to investigate the different aspects of this concept:

1. Full mission flight simulator study of the human factors of flying CTAS descents in the Terminal Area conducted at NASA Ames Research Center
    a. Use of data link with different pilot interfaces in the Terminal Area
    b. Use of Flight Management Automation (LNAV/VNAV) in the Terminal Area
    c. The impact of a Vertical Situation Display to help with these tasks
2. Part task flight simulator study of arrival time errors when flying CTAS descent clearances conducted at NASA Langley Research Center
    a. Trajectory prediction accuracy between FMS and CTAS
    b. Arrival time errors at the Final Approach Fix for FMS-managed descents vs. vectored arrivals
3. Initial demonstration of CTAS/FMS operations with controllers conducted at NASA Ames Research Center
    a. Acceptance and usability of operational concept
    b. Controller interaction with advanced automation tools
4. Main demonstration of CTAS/FMS operations with pilots and controllers conducted at NASA's Ames and Langley Research Centers
    a. Acceptance and usability of operational concept
    b. Controller interaction with improved automation tools
    c. Pilot controller interactions in a strategic ATM environment
    d. Flight crew factors in the CTAS/FMS environment

Experiments Focused on Ground or Air Side

1. The first flight deck oriented full mission simulation demonstrated that data link usage in the terminal area was acceptable and desirable for flight crews. A streamlined FANS-type CDU datalink interface was acceptable to the flight crews. Most crews preferred a Boeing 777 like data link implementation that reduced heads-down time in the cockpit. Flight crews could successfully use the lateral flight management function LNAV to the final approach fix. Using the vertical flight management function VNAV close to the ground was a concern to pilots [6]. A Vertical Situation Display (VSD) prototype was introduced to help using FMS automation closer to the ground and received high ratings by the flight crews. Significant workload or performance differences could not be found between conditions with and without the VSD [7].

2. A flight simulation at NASA Langley Research Center found that arrival time errors at the final approach fix can be significantly reduced when flying TRACON trajectories with FMS guidance rather than heading vectors. Again the streamlined FANS data link interface on the CDU was found to be acceptable for TRACON operations.

3. The initial demonstration of CTAS/FMS operations with controllers demonstrated the potential for increasing the efficiency of arrival streams by using the CTAS tools for planning

and monitoring. The designed controller interface with the automation and the data link was acceptable, but could use further improvements. Too much information in the standard data block, a clumsy and complicated route trial planning interface and the three-button mouse were mentioned as some of the main shortcomings. The operational concept received very positive feedback and the controllers were enthusiastic about its potential.

The main demonstration of CTAS/FMS operations with pilots and controllers in the loop

We conducted a set of simulations combining all the different elements. We staffed two full mission flight simulators at Langley and Ames, 3 to 5 center controller positions, 3 TRACON controller positions, and 9 pseudo pilot positions, each of which handled multiple aircraft. The flight simulator at Ames was additionally connected to the Crew Activity Tracking System (CATS) for model-based on- and offline evaluation of task performance [13].

Most of the prior findings and observations held true during these tests and all subjects were very impressed with the potential of a futuristic ATM system like the one they participated in. However, several issues were raised that did not come up in any of the previous experiments.

Flight crew perspective

To study flight crew factors under integrated CTAS/FMS operations with controllers-in-the-loop we included the NASA Advanced Concepts Flight Simulator (ACFS) in the distributed simulation. The ACFS is FMS-, VSD- and datalink-equipped. Eight qualified flight crews received a briefing on ACFS cockpit systems, FMS Arrivals and Transitions, and data link operations. Each crew then flew six descents, alternating between two scenarios. The ‘Center scenario’ started at cruise altitude outside the Center airspace, and the ‘TRACON scenario’ started at the TRACON boundary.

In both scenarios, crews first established data link communications. In the Center scenario, crews received forecast winds via data link. They could also downlink a preferred descent speed to CTAS. The controller could issue a data link message or voice clearance to modify the cruise and descent according to a CTAS advisory, or modify the lateral route. The controller then issued an FMS descent clearance to begin the descent on the FMS trajectory. Speed and/or route adjustment could occur in the low altitude sector by voice or data link. In both scenarios, the TRACON feeder controller issued a clearance to fly an FMS Approach Transition to a given runway. In the TRACON scenario, the final controller sometimes issued a route modification clearance via data link. In both scenarios, the final controller then cleared the aircraft for the approach and handed it off to the tower controller for landing.

We evaluated crew performance on each descent using measures that address the operational concept, specifically, the ability of crews to precisely follow a flight plan using the aircraft’s FMS, and to coordinate air and ground operations via data link. We used CATS to analyze digital data from the ACFS; videotape was used to confirm and analyze key observations in greater detail. Crew acceptability of the proposed procedures was evaluated with a questionnaire.

We obtained data for 22 Center scenarios and 23 TRACON scenarios. In 60% of 45 flights, the lateral portion of the route was flown entirely in LNAV mode; this measure reflects positively on the success with which controllers were able to issue FMS clearances without resorting to vectors. During times when the flights were cleared on FMS routing (which, at the very least, included the descent on the FMS Arrival in the Center scenario), crews complied with 82% of speed restrictions and 93% of altitude restrictions. Lastly, of the 80 data link messages crews received, 96% were handled in a correct and timely manner. As in the previous ACFS study, however, crews often switched to a tactical control mode instead of VNAV whenever other tasks assumed a higher priority than monitoring the automation.

More detailed analysis identified several issues that deserve slight modifications or further training. First, the data link message text designed to cue the entry of a preferred descent speed needs clarification. Second, some pilots were confused about how far they were cleared on charted routing, indicating a need for separate charts for FMS routes to a particular runway. Third, if controllers issued a voice clearance while the crew was responding to a data link clearance (or vice versa), crews had to request clarification as to which portions of each to comply with. Pilots sometimes also found it confusing to have a check-in call simply acknowledged with no mention of a recently issued datalink clearance. Controllers sometimes also issued ambiguous clearances on check-in, such as a clearance 'direct to' the same waypoint that is already active in compliance with a previous FMS arrival clearance; some pilots were uncertain whether such a clearance should be interpreted as a cancellation of the FMS Arrival. Fourth, one pilot thought that data link clearances were guaranteed to be flyable, negating the procedural requirement to review the clearances carefully before accepting and executing them. Fifth, we designed FMS Arrivals and Transitions to be flown in VNAV with the last charted altitude restriction set as the limiting target altitude. Pilots from airlines whose policy is to 'step down' the altitude target to the most constraining altitude at times were unwilling to set the last charted altitude as the limit altitude. Finally, some crews over-committed to an "expect" clearance by re-programming the FMS route. This resulted in increased workload when a clearance different from the "expect" clearance was issued.

The questionnaire covered FMS procedures, charts, FMS clearance phraseology, automation usage, data link clearances, and data link response procedures. Again pilots found workload under the CTAS/FMS integration concept to be slightly lower than in current-day operations; however, more monitoring is required. The FMS procedures as a whole were acceptable, but the experiment FMS arrival charts required some improvements. Using LNAV mode to fly precise lateral routing was acceptable, even at low altitudes in the TRACON airspace. On the other hand, pilots gave VNAV generally lower acceptability and comfort ratings. Pilots generally viewed data link usage positively. However, some pilots did not know whether the data link speed clearance phraseology meant flying a Mach value in the descent until the Mach/CAS transition, or whether the CAS should be flown immediately. Performing FMS edits in the TRACON airspace also elicited a range of opinions. Pilots who over-committed to "expect" clearances found FMS edits less agreeable than those who left route discontinuities in the route until they were actually cleared on the routing.

Overall, from the flight crew perspective, procedures developed for FMS and data link operations can work in concert with CTAS tools. In general pilots found the concept favorable, and with some modifications and additional pilot familiarity, the concept appears especially promising. A more detailed description can be found in [8].

Controller perspective

Our simulation scenarios were based on the northwest arrival stream into Dallas Ft. Worth, which currently experiences at least two major arrival rushes every day. The main scenario was derived from recorded traffic and weather data from a day with IFR weather conditions in spring 1999. Traffic loads in different scenarios ranged from moderate to more than current day peak rush demand.

From a controller's perspective the arrival scenario develops as follows: Aircraft arrive at the center's airspace on direct routes or in-trail. The ground automation (CTAS) estimates feeder fix arrival times for these aircraft. The CTAS Traffic Management Advisor (TMA) software automatically creates an initial sequence for these aircraft, taking all airport flow control constraints into consideration. The planning controller evaluates this sequence and interacts with the TMA and conflict probe to adjust the flow for spacing and scheduling. This task is supported by the CTAS Descent Advisor (DA) software, which assists the controller in creating flight paths (route and/or speed modifications) that meet the scheduled time at the feeder fix. If no significant delay has to be absorbed (~5 minutes or less), an early modification to the aircraft's cruise speed and perhaps its descent speed is usually sufficient. This flight path modification is communicated to the flight crew (by voice or data link), who set up their FMS accordingly. After an arrival clearance is given to fly the FMS computed path, aircraft automation is used to follow the plan precisely. Pilots and controllers thus know when the aircraft will start to descend and where it will be at any given time. If aircraft are data link equipped, the FMS flight path is transmitted to the ground system, and the controller can inspect it for any significant differences from the ground-predicted trajectory.

At least six controller positions managed the arrival flow in our simulation: the arrival planner, high and low altitude sector controllers in the Center; and one TRACON controller to pick up the flow managed by the center controllers; as well as two more TRACON controllers managing a second arrival flow that was initialized at the meter fix. All center positions were equipped with a TMA timeline, a conflict prediction list, access to the DA advisories and a trajectory preview tool that allowed controllers to quickly preview the predicted traffic situation to any given time in the future.

Each session took three days for the controllers. Center controllers were trained for one and a half days on the CTAS tools and FMS arrival procedures. Three or four data collection scenarios were run during the last two days of each session.

All subjects stated that the overall concept is very promising and bears a great potential for improving traffic flow into, out of, and across congested areas.

When It Works, It Works Well…

After three days of training and simulation runs, participant controllers were capable of handling complex arrival rushes. In these runs, almost the maximum throughput was achieved for the one test runway, with efficient FMS descents for about 35 consecutive aircraft.

In several runs, the three Center controller participants (Planning, High, and Low sectors) successfully handled the arrival traffic flow. During these runs, the majority of aircraft received FMS descent clearances and benefited from almost undisturbed descents into the TRACON. Most aircraft arrived at the metering fix within 15 seconds of their scheduled time and an efficient TRACON feed was provided without imposing extensive workload on the controllers. At the same time radio frequency congestion was reduced by replacing many tactical clearances with a few strategic ones.

…But the Strategic Plan May Fall Apart

In some runs controllers reverted to tactical control of the traffic. The strategic FMS arrival plan was disturbed or even fell apart. Successful implementation of the arrival plan is sensitive to good planning and aircraft compliance with the planned flight path.

The role of the arrival planner became increasingly important with the complexity of the arrival rush. The planning job required very good skills in traffic management and control, and proficiency with the tools. Arrival plans that set up aircraft well within their performance limits and used similar descent speeds among aircraft were generally easier to handle for downstream controllers. If the plan did not provide sufficient buffers against separation loss for the sector controllers, they were likely to change it or not execute it. Aircraft that did not comply with their clearance or did not receive the descent clearance on time often caused significant problems for the controllers in implementing the arrival plan. Because of the use of high-energy FMS descents, non-compliance or late descents typically required controllers to vector the problem aircraft to meet the TRACON restrictions.

One problem of FMS arrivals is the increased compression effect created by high-energy FMS descents. In today’s environment controllers adjust speeds and altitudes step by step to maintain consistent states between aircraft. Aircraft performance on idle FMS descent profiles varies significantly by aircraft type, weight and descend speed. This adds complexities to the task that do not exist in today’s environment.

Data Link

Data link in this concept needs to be viewed from several angles. Even though the concept does not require the availability of data link per se, passive data exchange seems to be very helpful. Controllers had different opinions and showed different behavior for issuing clearances via data link. Some liked it because it cut down on verbal communication and was easy to use. It was in fact so easy to use that controllers sent more speed updates to the aircraft than they would have issued by voice, causing some confusion in the aircraft. Other controllers did not like to have to wait for the data link response, which is delayed compared to the immediate readback they receive in the voice environment. They stated that having to continuously monitor the data link status indication in the data block was an additional task, whereas by using voice they did not have to closely monitor the aircraft for a while after giving the instruction.

Dealing with the Automation

The shift between manual flight control and automated flight management in modern aircraft has been discussed and researched in depth. Our 2010 scenario requires controllers to use and trust the automation in the aircraft and on the ground to manage a more complex arrival problem than could be controlled without the automation’s support. Similar automation issues arise for controllers as for flight crews, including the potential for mode confusion, clumsy entry procedures, problems with shifting between tactical and strategic control, and difficulty maintaining the “big picture” as situation complexity increases.

Distributed Air Ground Traffic Management

We try to apply some lessons learned for ongoing and upcoming work in NASA’s Distributed Air Ground Traffic Management (DAG-TM) research project [9]. DAG-TM is targeting a free-flight environment in which flight crews play a more active role in the decision making process.

Instead of simply executing controller instructions, crews will have some freedom in requesting and selecting flight paths. Advanced on-board automation for conflict detection and resolution will impact pilots' behavior, thus affecting controller behavior and putting more requirements on ground automation and information sharing

The DAG project's Concept Elements (CE) 5 *En Route Free Maneuvering* [10] and 11 *Terminal Arrival: Self Spacing for Merging and In-Trail Separation* [11] give flight crews in fully equipped aircraft some or all of the responsibility for separation, thus changing the role of air traffic controllers and flight crews. Concept Element 6 *En Route Trajectory Negotiation* [12] addresses the issue of negotiation of strategic trajectories.
Previous and ongoing research in free flight and Cockpit Display of Traffic Information (CDTI) will be combined with our ongoing research work. Advanced flight deck prototypes will be integrated into the simulation environment.

Two Extremes in DAG Arrival Management

The DAG concepts encompass a variety of possible ways to manage arrivals ranging from uninterrupted free-flight to fully ground-controlled. Two extremes are described below.

Free-flight to the threshold

One extreme has the flight deck responsible for path planning and separation from the aircraft throughout the arrival. The aircraft arrives at the Center in free flight and is responsible for separating itself from other traffic. Traffic flow management constraints for entering the terminal area are made available to the flight crew, who adjusts their terminal arrival plan (i.e. FMS descent trajectory) accordingly. When approaching TRACON airspace, the flight crews select the aircraft that they want to trail to the threshold and select the proper merging and spacing parameters. They then follow the lead aircraft to the runway.

Ground (ATSP) controlled arrival

The other extreme in arrival management is very close to the concept demonstrated in our previous TAP research. When entering the terminal airspace free flight is cancelled for the arriving traffic. Ground based traffic managers create the schedule and arrival trajectories and communicate those to the aircraft. The aircraft can at any time downlink flight path requests that the ATSP may or may not accept. The controller determines candidate aircraft for self-spacing approaches and appropriate spacing intervals and issues clearances to self-space.
Responsibility for separation and trajectory planning remains on the ground throughout the arrival phase. The flight crew receives more strategic FMS and spacing clearances than in today's tactical environment.

Designing for DAG Arrival Management

Free flight to the threshold will require additional aircraft equipage, which may include Required Time of Arrival (RTA) capabilities, Cockpit Display of Traffic Information (CDTI), conflict detection and resolution algorithms, self-spacing and merging algorithms, etc. Ground controlled arrivals do not use the aircraft capabilities in the most efficient manner and put the entire flow management burden on the controller. The future air traffic system will manage arrivals in a way that lies somewhere between the two extremes, possibly gradually moving from ground-controlled to more free-flight.

Research and operational practice will show which concept appears to be most appropriate. The amount of free flight vs. ATC control can depend on the traffic situation, facility practice, aircraft equipage, and airline preferences. It may be different between facilities and even time of day. We believe that the air traffic system should be designed to accommodate all possible modes of operation between the extremes. Therefore all enabling technologies have to be developed, integrated and evaluated, including

- CDTI with airborne conflict detection and resolution
- FMS with RTA capability
- On-board merging and spacing tools
- ADS-B and CPDLC data link communication
- Traffic Management advisory tools
- Ground-based conflict detection and resolution
- Ground based tools for trajectory generation with meet time constraints

Most of these technologies are already available in more or less isolated research prototypes. We are currently in the process of integrating them at NASA Ames Research Center to create a simulation environment that allows researching these issues.

Initial Arrival Concept for DAG

We are developing an arrival concept that provides the flexibility to adapt the amount of self separation to traffic flow management constraints and other requirements. We initially intend to keep the free-flight airspace separate from the ground-controlled airspace. The boundary can be specified as an arc around the meter fix or the nearby arrival gate or a simple altitude floor. This can be adjusted for traffic complexity. In very low traffic situations, the free flight area may be as close to the airport as the meter fix itself.

The arrival scenario begins with aircraft arriving at the Center in “free maneuvering mode”. The flight crews are responsible for separation. Traffic management constraints at the metering fix are communicated from the planner utilizing the CTAS TMA to the flight deck as arrival information. The flight crew is expected to plan their flight path to arrive at the metering fix close to the expected time, if scheduling is required. The flight crew will also be told where the free flight boundary currently ends and when to check in with the controller. The arrival planner keeps evaluating the situation using Descent Advisor tools and tries to create an arrival plan for the ground-controlled airspace that he or she relays to the sector controllers. When the sector controller receives the check in from the free maneuvering aircraft, he or she cancels free flight and issues the arrival clearance to the aircraft based on aircraft preference and arrival plan. Aircraft are expected to fly the arrival clearance to the meter fix precisely. The CTAS TRACON tools (Final Approach Spacing Tool FAST) aid the TRACON controllers in determining proper aircraft pairs for receiving in-trail spacing clearances. Separation responsibility remains with the controller throughout the TRACON.

This scenario allows us to investigate most aspects of the relevant DAG-TM concept elements and builds on our previous arrival research. Recent discussions with controllers and pilots gained positive feedback. Initial demonstrations are planned for fall 2001.

Concluding Remarks

The concept of strategic arrival management demonstrated in the TAP research appears to be very promising. The DAG research moves from a ground-controlled environment to a more distributed environment with possibly shifting separation responsibilities. NASA Ames is currently preparing a research environment to investigate DAG-TM with all major technologies integrated. Initial concepts and scenarios have been defined and discussed with pilot/controller focus groups.

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