Free Flight vs. Centralized Air Traffic Management

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Abstract: *The current Air Traffic Management system is subject to structural changes, which are expected over the next 20 years.*
These changes are required for a number of reasons:
- *The current system inflicts delays and fuel inefficiencies to flights (as demonstrated by the historic Paris-Miami Air France flight in April 2010)*
- *The current system has structural and operational capacity limitations*
- *Under current system, the complexity of the Air Traffic Controller’s work increases steeply with traffic*
- *Voice communication on a single radio frequency in ATC is limitative and subject to errors*
- *Safety is sometimes jeopardized and separation relies on a safety net (ACAS)*
- *The introduction of the ACAS systems as a separation safety net presents a structural risk in the classic ATC philosophy (as demonstrated by the Überlingen 2002 mid-air collision)*
- *ATM is the only system left in Civil Aviation, with virtually no automated core process*

There is a major choice to make for the future Air Traffic Management automation in both NextGen and SESAR programs: the free flight concept, and the opposite, the centralized management. This paper is an assessment of both scenarios, and their implications for traffic capacity, air traffic control complexity, safety and efficiency.

Key Words: *Air Traffic Management, Air Traffic Controller’s*

1. INTRODUCTION

The classic Air Traffic Control in effect today relies on the human controller, who is responsible for the aircraft separations at all times, by tactical control actions.

There are several limitations to this classic approach, which made the aviation community to find options to replace the current system with something else.

These limitations are well documented in the literature (3), (15), (13), (6):

- Voice-based link restricts capacity, due to the time consumed by every tactical action (voice communication frequency congestion);
- Voice-based link is more vulnerable to errors, in spite of the read-back rule;
- Air traffic complexity, workload and communication frequency usage are variable over time, causing both inefficiencies due to lack of traffic, and delays due to exceeded capacity;
- Traffic capacity for a given sector is limited by the maximum number of aircraft using the services, because the span of attention of a human controller is limited;

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- Reducing the size of the sectors is also limited by the hand-over protocols, which occupy an increasing share of the communication frequency;
- Inefficient flights, due to decisions which do not account for impact on downstream sectors, and which lack important pieces of information, such as aircraft performances.

For these reasons, adopting a new approach to air traffic management is imminent in the medium to long term, and this approach has to be based on a solution which should be chosen in the near term.

This paper is taking a number of ideas and tests in this field, discriminating them with respect to the fundamental question of decision making centre.

2. DECISION-MAKING CENTRE DISCRIMINATOR

There are two classes of solutions to the future air traffic management problem, based on opposed principles:

- *Free-flight* solutions, which use new technology to enable pilots to decide how to avoid each other; ACAS[c]/TCAS[d] systems are precursors of this concept, already in use;
- *Centralized* solutions, or *network centric solutions*, which use new technology to separate aircraft from an early (strategic) phase, by a ground-based decision; FAA's Air Traffic Control Systems Command Center and EUROCONTROL's Central Flow Management Unit are precursors of this concept.

Some researchers (15) advanced mixed solutions.

The authors believe that although mixed solutions are possible, only one of the two fundamental principles prevails.

In this case, the other principle will be serving as back-up, very much like the ACAS concept of today, which is a safety net for human controller error.

This paper advances the mutual exclusivity of the two fundamental approaches. The mixed solutions are hybrid solutions, but decision has to stay with a single entity in order to obey the unity of command principle, and in order to assign responsibility to a single decision factor.

Most research projects in this field favour the *collaborative decision making* principle. This name suggests that decisions in the future ATM systems will be made collectively, and a large share of the aviation community agree on this line of reasoning, because they see their stakeholders' interests cared for.

However, the authors are giving a slightly different interpretation to the *collaborative decision making*.

This is possible in a centralized system, by including in the objective function of the optimization process of all stakeholders' interests, but in a centralized system, the interest of an individual may be sacrificed for the good of the others.

Collaborative decision making does not mean that the decision is taken or modified by the participants in the process.

Decision is taken by a single entity, for instance by a network centric 4D trajectory automated optimizer, but that decision is the result of a collaborative process, each user having his input into the optimization criteria.

[c] Airborne Collision Avoidance System (ICAO)
[d] Traffic Collision Avoidance System, an American ACAS implementation currently in use

Free-flight solutions on the other hand resemble the road traffic, which is based on the selfishness of the participants, who try those routes, which minimize their time consumption, but inflicting time wasted by other participants.

Free-flight solutions are fundamentally bilateral, as opposed to centralized solutions, which are *global* or *multilateral*.

Experiments done by the authors in simulated heavy traffic indicate:

- Free-flight solutions are usually worse than centralized solutions in terms of total costs and risks;
- Free-flight solutions sometimes fail in very busy areas; an individual flight attempting to cross the paths of massive flows of traffic gets trapped (the *free-flight paradox*).

The existing air traffic control system is basically a fragmented centralized system. In each sector, the decision is made by an individual air traffic controller, for all the flights in the sector, and even for some flights outside the sector.

Coordination between controllers of neighbouring sectors is required to propagate the decisions across the airspace.

In the past decade, there was a trend to reduce the size of the sectors to keep up with increasing capacity demands.

This trend influenced the system performance in at least two ways:

- Coordination importance and workload increased, and as a non-automated function, coordination added to the complexity of the air traffic control;
- The economy of scale of a centralized system, which is supposed to resource the traffic efficiency, became less effective, as decisions narrowed their scope, and as more decision makers emerged for the same flight (more sectors over-flown).

Figure 1 illustrates the past and current status of the ATM system, and the dual paradigm of the future: free-flight vs. centralized.

Both future paradigms rely on a much better information exchange between each user and a ground network.

In the free-flight concept (Figure 1, c) the decision is made by each participant.

The high number of decision makers has two direct consequences:

(1) coordination overhead is huge, and this is only feasible with on-line automated coordination, similar to the TCAS 7 bilateral automated coordination standard;

(2) decisions to avoid are frequent and short term (tactical).

No decision role is left to the ground based Air Traffic Control units, which could turn to Air Traffic Monitoring functions.

If N is the number of users of a given airspace (*traffic density*) and M is the number of the corresponding decision makers, the following statements hold true:

1. Coordination process workload complexity is of the order of M^2
2. Separation is a problem of the order of N^2
3. The overall complexity of the ATM process depends on both coordination and separation decisions, making it a problem of the order of $M^2 + N^2$.

A conclusion from these statements is made evident in Table 1: the centralized approach minimizes workload complexity for a given traffic density.

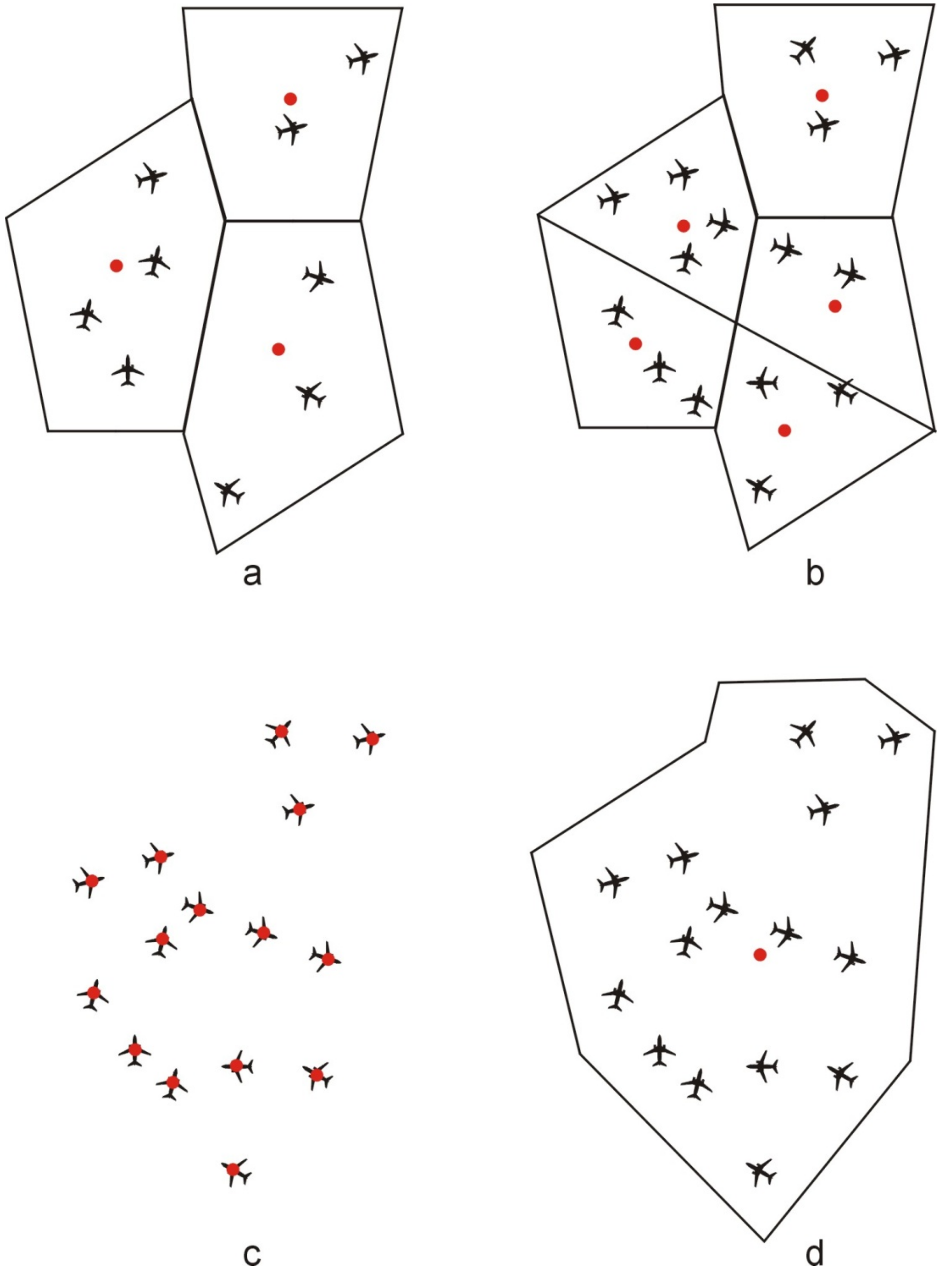

Figure 1 – Existing and future ATM solutions; each polygon represents a sector, and each decision maker is represented by a dot: a) lower traffic in the past, larger sectors; b) smaller sectors as current; c) the free-flight paradigm; d) the centralized traffic paradigm

The *free-flight* concept would not be possible without automatic coordination performed by on-board systems.

A very useful tool is the ADS/ B (Automatic Dependant Surveillance/ Broadcast) technology, which transmits automatically the position of each aircraft to all other airspace or ground users.

Thus, the ATM overall complexity of a *free-flight* solution seems not to be a concern.

A couple of points in favour of the *free-flight* concept should be also mentioned:

- Outside the controlled airspace a *centralized* system will be absent, so all aircraft should be prepared to use *free-flight* system;
- A *centralized* system could fail, and all the traffic would be in a difficult situation, because classic ATC is not able to take over in very dense traffic; *free-flight* is necessary as a back-up system in any *centralized* solution.

Table 1 – Air Traffic Management Problem Complexity

	Free-Flight	**Centralized**
Coordination	M^2	1
Separation	N^2	N^2
ATM (overall)	$2\ N^2$	$1+ N^2$

However, by *"centralized",* the authors understand a system with a unique decision-maker. This is probably a piece of software distributed across a large network, and therefore it is not physically centralized, as to raise concerns of reliability or dependability.

In order to compare the *free-flight* and the *centralized* air traffic management concepts, the authors used the air traffic simulator developed by University Politehnica of Bucharest, Faculty of Aerospace Engineering (UPB-FIA), based on the TCR (Total Costs and Risks) model (13), (14).

The airspace of FAB Danube (Romania and Bulgaria) and the Henri Coanda Bucharest International Airport Runway 08R served as simulation field.

At this stage, a single type of aircraft was used for the whole traffic, the Boeing 737-700 simulator.

The authors expect some distortions in the final results due to this approximation, but there is no ambiguity left to the final conclusions. However, future work will consider a larger diversity of types of aircraft.

To add to the relevance of the study, the authors assumed that in both cases, individual aircraft used the best 4D trajectories available: lowest individual fuel cost for *free-flight*, and lowest de-conflicted fuel cost for *centralized*.

The results were represented in Table 2.

Table 2 – Results of the Free-Flight vs. Centralized Simulation

	Free-Flight	**Centralized**
Average pre-flight TCR	100%	104%
Average actual TCR	109%	104%
Average separation on final approach for a sequence of arrivals (NM)	12.2	9.6
Runway usage – landings and take-offs (s)	157	123

The influence of the *centralized* strategy to plan de-conflicted 4D trajectories accounted for 4% of the total fuel costs, as compared to the ideal 4D trajectory as the aircraft would be alone in the sky.

This result reveals that the traffic scenario considered was not dense enough. Future work will be based on denser traffic scenarios.

Although the optimization objective function is TCR (Total Costs and Risks), only the fuel cost was considered relevant to this simulation.

Free-flight aircraft wasted 9% of fuel to find separation solutions. The look-ahead for each aircraft was 40 NM in this simulation, and this parameter is believed to be sensitive to the results. More work is needed for a sensitivity analysis of this parameter.

The worst performance of the *free-flight* method was found with the sequencing of arrivals on the final approach.

The simulation assumed that each flight did their best to minimize the time to the moment of landing (intrinsic selfishness), and competed for the landing slots on a first to arrive at Final Approach Point basis, while maintaining horizontal or vertical separations at all times.

The *centralized* method did significantly better in arrival sequencing.

3. PROJECTS AND POSSIBLE IMPLEMENTATIONS

3.1 Programme for Harmonized Air Traffic Management in Europe – PHARE

PHARE was a European research program which ended in 2000, based on the idea of contractual “4D tubes” (4D trajectories and surrounded by a tolerance cross-section) negotiated between the air segment and the ground segment.

The project failed due to the lack of data link technology and suitable flight management systems functions at the time.

Another problem was how to implement the conflict resolution criteria.

However, the project was useful, because it proved that given the right technology in place (most of which is already in progress to be implemented), a trajectory based approach could work.

3.2 Center TRACON Automation System – CTAS

CTAS was an American project based on a trajectory predictor for each flight based on available flight data information from the host ATC computer, accurate aircraft performance models, and other database information.

Accurate 4D flight trajectory prediction enables CTAS to create schedules for runway occupancy, final approach and meter fixes; detect future separation violations; recommend shortcuts; and/or provide advisories to controllers that result in efficient descent paths (15).

The CTAS tools that were experimented or are currently under tests in the US are:

- Passive Final Approach Spacing Tool (P-FAST);
- Traffic Management Advisor (TMA);
- Direct-To (D2);
- Enroute Descent Advisor (EDA);
- Active-Final Approach Spacing Tool (A-FAST).

P-FAST and TMA were designed to support traffic management rather than air traffic control operations, using the results of trajectory computations for scheduling and sequencing purposes.

This information is presented to traffic managers as timelines and load graphs, and to sector controllers as a meter list, a sequence number in the data tag, or runway assignment recommendations.

D2 allows sector controllers to visualize, and if desired modify aircraft trajectories to provide routing shortcuts that save time and reduce fuel consumption.

Other more sophisticated 4D trajectory based functions are EDA and A-FAST, which aim at generating conflict free trajectories for arriving aircraft that meet scheduling constraints.

Advisories are displayed that enable sector controllers to issue clearances that guide aircraft along de-conflicted trajectories.

These experiments revealed that a near optimal set of de-conflicted trajectories, taking into account airline operations center preferences and flow management constraints can be generated for controllers.

However, the practical execution of these optimal trajectories faces a number of operational challenges, including:

- Uncertainties in the trajectory prediction due to unknown conditions and input parameters not factored in;
- Human factors issues for controllers and flight crews in modifying, communicating, and monitoring trajectories under time pressure;
- Imprecise execution of clearances on the flight deck by flight crews or flight management automation systems.

(4) and (13) proposed methods to address these problems by automating most of the air traffic management and communication functions.

These concepts require a significant amount of additional automation, and a comprehensive re-organization of the airspace.

3.3. Distributed Air Ground - Traffic Management − DAG-TM

The DAG-TM project (NASA) was an en-route concept and advanced the use of a trajectory-oriented approach, distributed between air and ground segments, to prospect the feasibility and potential benefits of trajectory negotiation and autonomous flight deck operations, respectively. DAG-TM focuses on the development of automation and procedures that provide controllers and flight crews with advanced tools for managing, modifying, and communicating trajectories.

The trajectory-oriented approach to ATM has been investigated in several research projects. Recently, high fidelity, human-in-the-loop DAG-TM simulations have been conducted at NASA’s Ames Research Center.

A detailed description of the experimental conditions and the results of these experiments can be found in (16).

This experiment of 4D trajectory-based operations resulted in:

- A significant reduction in the variance of the inter-arrival spacing at the metering fix; indicating that aircraft were delivered more consistently;
- More efficient descent paths, i.e. many aircraft were able to remain longer at a higher altitude, and then flew uninterrupted idle descents;
- Reduced sector controller workload at the low altitude position, which is responsible for merging aircraft at the meter fix;
- No workload increase in the high altitude feeder positions, which set up the trajectories for the low altitude position;
- Better (self-reported) performance by the controllers than in a current day control condition.

The main problems encountered in this experiment were:

- Trajectory de-confliction along the paths to the metering fix;
- Usability of some of the ground automation tools, especially the responsiveness of the trial planning tool that the controllers used to generate new trajectories.

A detailed description of these results and recommendations on how to resolve the problems can be found in (16).

3.4. Simultaneous Flight and Traffic Management Optimization System − SFTMS

This is a pure 4D trajectory-based approach, which relocates the Flight Management System software from the on-board computer to the ground (13).

A ground network computes optimal readily-separated 4D trajectories, and returns the best trade-off 4D trajectory to be flown.

Unlike other ideas, which leave freedom to the operators for the choice of the individual trajectories (the so-called user preferred routes), SFTMS base the optimization process under a dual objective: de-conflicted trajectories and the minimum costs and risks trajectories.

The aircraft separation is treated as one of the risks taken into account, but the trajectories are not only de-conflicted, but also optimal in terms of fuel consumption, time of flight, and other costs.

By coupling the individual flight optimization with the air traffic management optimization, a major source of negotiation overhead is eliminated.

The research in the SFTMS domain is conducted within the Aerotrafic project of the Romanian Space Agency, UPB-CCAS, and INCAS.

3.5. Airborne Separation Assistance System – ASAS

The ASAS is a development of the free-flight concept, providing local separation based on the coordination between the on-board equipment of airspace users. No predictability of trajectories is possible with this system in use.

Separation algorithms decide avoidance schemes based on relative kinematics of the two aircraft during the coordination process.

ASAS is the next level of ACAS, providing pilots with awareness of the surrounding traffic, their trajectories and intentions.

3.6. Trajectory Based Operations and ASAS Limited Delegation Hybrid Strategy – TBO-ASAS-LD

This is a hybrid concept using trajectory-based operations to create efficient, nominally conflict-free trajectories that conform to traffic management constraints and maintain local spacing between aircraft with airborne separation assistance.

It is discussed at length in (15).

The idea of the limited delegation reconciles with the unity of command principle, and the major difficulty in implementing this is the moment and the mechanism of the responsibility translation.

Awareness of all participants on ground and in the air is a delicate issue in any hybrid strategy.

CONCLUSIONS

Air Traffic Management will probably face a major change of paradigm in the decades to come. This paper analyzes the possible methods using the decision-making as a discriminator. Thus, all methods are split in two major groups: *free-flight* and *centralized* based on de-conflicted 4D trajectories. Preliminary simulation tests with both types of methods showed that *free-flight* methods perform worse than *centralized* methods on two counts: the overall fuel consumed, and the usage of the landing runways. However, in order for the aviation community to accept a *centralized* system, a *free-flight* system has to be made available as back-up, and for the flights outside the controlled airspace.

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