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Improving air traffic control by combining centralized and decentralized solutions

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Abstract: Air Traffic Control is the most critical component of Air Traffic Management, essential for ensuring passenger and aircraft safety as well as the commercial profitability of airlines. The problem studied remains quite broad and is based on decomposing the processing into several stages. This study aims to enhance traffic flow performance without altering the structure of the airspace. The paper explores two solutions for air traffic control: centralized and decentralized systems. The primary goal is to optimize air transport flows by selecting appropriate route networks and preventing collisions between aircraft. The analysis addresses the efficiency of these systems, considering the challenges posed by increasing air traffic volumes, and proposes innovative approaches for conflict resolution and system optimization. Additionally, the study considers potential benefits such as fuel savings and reductions in greenhouse gas emissions. The results demonstrate the potential of advanced automation and distributed systems to improve the efficiency and safety of air traffic management.
Keywords: *Air traffic control, Airspace management, Automation, Centralized systems, Collision free path, Conflict resolution, Decentralized systems.*

1. Introduction

Air traffic has long been a rapidly growing sector. With traffic doubling every ten years, air traffic control and regulation services have had to find solutions to manage this increase: hiring additional personnel, restructuring airspace, implementing technical innovations, and adopting new working methods to enhance controller productivity. These measures and innovations have enabled the absorption of more traffic while maintaining or improving a high level of safety. The advancements made include the use of radar, the automation of inter-center coordination, the introduction of advanced human-machine interfaces, the subdivision of airspace into smaller sectors, and the definition of "air highways".

Despite these efforts, it remains challenging to significantly increase the capacity of air traffic management systems. Small variations in traffic volume can cause substantial delays at departure [1, 2]. In recent years, the exponential rise in departure delays indicates that we are facing a "capacity wall," where the causes are structural rather than temporary. Increasing resources yields diminishing returns in terms of capacity gains.

These observations have led to several research avenues to overcome this impasse as improving the traffic regulation process, offloading certain tasks from air traffic controllers through automation, fully automating the system, delegating conflict detection and resolution to aircraft, imagining new ways to control or manage traffic, and optimizing airspace structure and traffic flow management.

These attempts aim to achieve two fundamentals, not necessarily exclusive, goals: the first is to adapt traffic demand to the limitations of the existing system, and the second is to modify the system to increase its capacity to handle traffic while maintaining equivalent safety levels. Our work focuses on this second goal: improving the flow of air traffic by automatically resolving trajectory conflicts based

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on duration and fuel consumption criteria.

Karagoz, et al. [3] studied specific technologies that will have a major impact on the development of smart airports. The Internet of Things (IoT) forms the basis of this project, as we believe it is the key technology for smart airports. It demonstrates that IoT plays a vital role in connecting physical assets, equipment, people, and applications, thereby improving operational efficiency, passenger experience, and creating new revenue streams for airports. Mansour et al. emphasize the importance of connectivity between automobiles for smarter urban environments, to improve transportation and support environmentally friendly growth. We will extend these studies to en-route aircraft conflict management. Our approach remains broad, following a multi-step process. We aim to enhance traffic flow without altering airspace structure. Our objective is to optimize origin-destination flows by managing the route network to avoid aircraft collisions. Since this two-dimensional approach does not utilize vertical separation of air traffic flows, we will assess the potential benefits of allocating separate cruising levels to major traffic flows.

This paper consists of four parts. The first presents the state of the art and the current context of air traffic control. The second part focuses on the selection and optimization criteria. And the third part presents the result of our approach in the field by combining centralized and decentralized methods. Finally, we conclude with a conclusion and our perspectives.

2. Related Works

Several studies have already been conducted on airspace sectorization [4, 5] the construction of air route networks [6] the allocation of cruising flight levels, and the definition of separate direct routes [7]. Although highly relevant, these studies remain somewhat fragmented, addressing the issue from only one perspective: for instance, focusing solely on the two-dimensional plane for route networks or considering only the cruising phase for level allocation.

Apart from the TOSCA study [8] which makes a genuine effort in validation, the results of these studies are not adequately validated in terms of their capacity to handle increased traffic safely. Additionally, new traffic management concepts regularly emerge—such as free flight, free route, sector-less, and super-sector systems—whose proponents hope they will outperform the current system. However, these concepts are still in their infancy, particularly the newer ones, and their expected benefits are not always well-validated.

The study of Stathis Malakis, et al. [9] explored how decision trees and classification rules can be used for realistic classification of air traffic scenarios and which factors reflect better operational complexity. It applied machine learning methods to the data and developed decision trees and classification rules (Figure 1) [9].

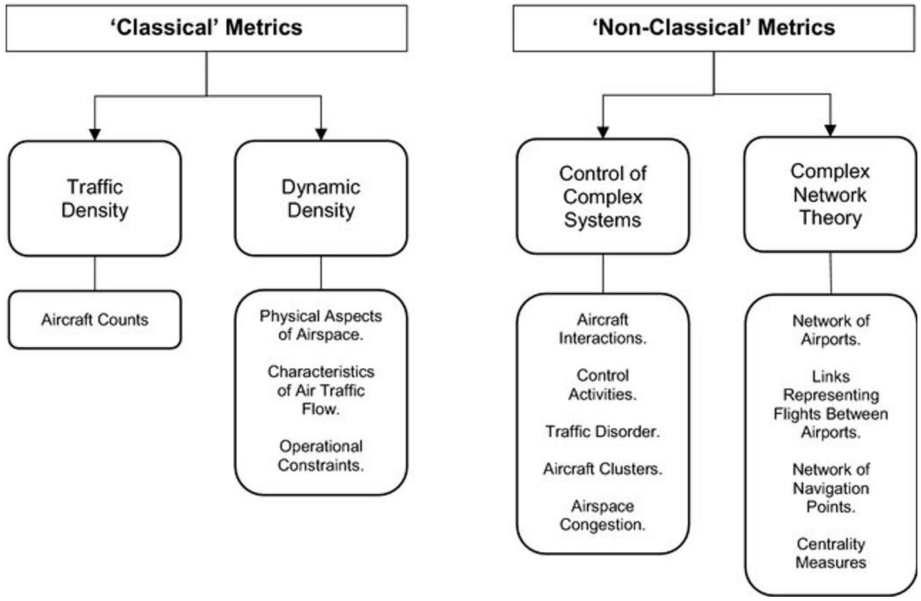

Figure 1.
Different approaches to traffic complexity Malakis, et al. [9].

Previous research has focused on trajectory prediction Chryssanthacopoulos and Kochenderfer [10] using neural networks and automated conflict resolution in airspace [11, 12] within centralized or distributed systems, employing various deterministic or stochastic methods. Conflict resolution during taxiing has also been explored [13]. Other studies have investigated airspace sectorization using genetic algorithms [14] and the application of constraint programming to certain air traffic management problems [15] primarily focusing on demand regulation and, to a lesser extent, cruising level allocation, which is more closely related to our research.

2.1. Overview of the Existing System

First, for readers unfamiliar with the field of Air Navigation, we will clarify some concepts essential for understanding the rest of this document. Civil air traffic is generally divided into two main types: Approach Traffic and En-Route Traffic.

Approach Traffic refers to air traffic around airports. Traffic is typically dense and the role of air traffic controllers is to guide incoming aircraft from their entry point in the approach zone to the runway and to direct departing aircraft from the runway to their exit point, all while adhering to the maximum usage rates of the runway(s).

En-Route Traffic covers the movement of aircraft between the departure approach zone and the arrival approach zone.

Traffic flow is generally organized according to departure or arrival routes. The challenge for Air Traffic Control is to advise aircraft's pilot to maneuver horizontally, vertically, or by adjusting their speed within a confined and congested space, in order to sequence them along their flight travel (Figures 2 and 3).

Figure 2.
Air Traffic Control Room.

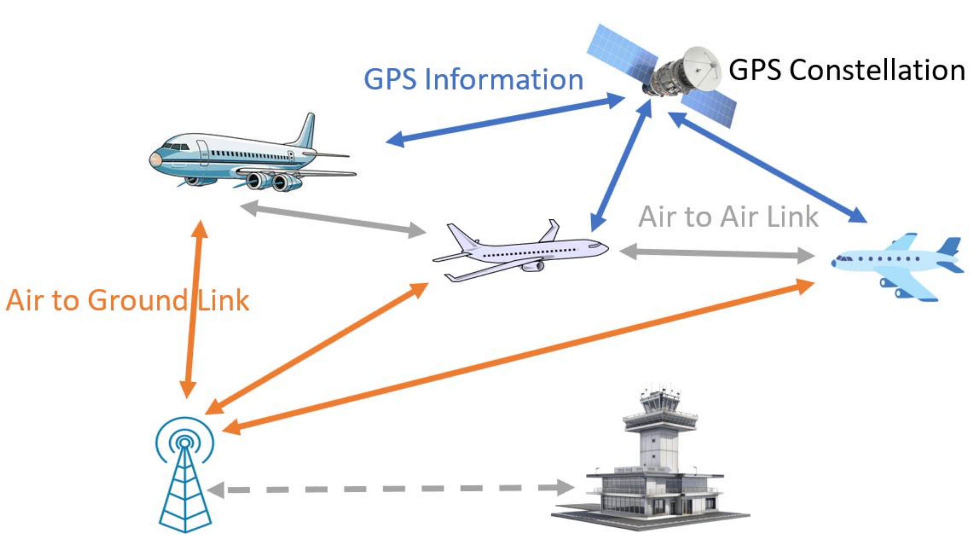

Figure 3.
Future Approach of ATC: Automatic Dependent Surveillance ADS.

En-route air traffic is organized along predetermined routes known as "air corridors," marked by mandatory reporting points and radio beacons. Traffic density is typically higher around airports. Civil airspace is divided into sectors, each managed by an airspace control unit (Figure 4). This unit comprises a team of two controllers responsible for resolving trajectory conflicts between aircraft following routes that cross the sector or group of sectors under their supervision.

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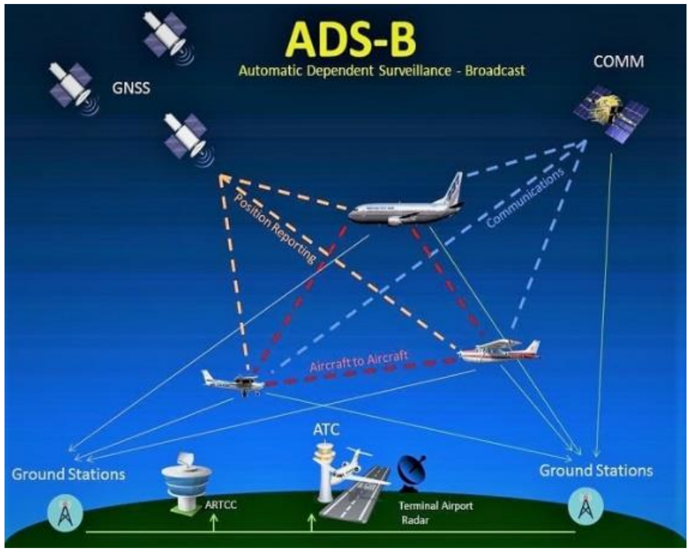

Figure 4.
The Agency for the Safety of Air Navigation in Africa and Madagascar launched the new "Automatic Dependent Surveillance-Broadcast" (ADS-B) surveillance system in January 2020 at the Regional Air Traffic Control Headquarters in N'Djamena.

2.1.1. Current Design

The objective of organizations responsible for managing air traffic is to ensure the safety and efficiency of air traffic flow. Air traffic management is often described as a series of interlinked processes aimed at preventing collisions between aircraft operating in the airspace:

- Strategy: This involves the long-term organization of airspace structure (routes, sectors, military zones, etc.) and the allocation of traffic flows across the route network.
- Pre-Regulation: Two days prior (D-2), a pre-regulation scheme is defined for day D, based on the anticipated traffic and a provisional sector opening plan by control centers.
- Real-Time Regulation: On day D, the regulation scheme is adjusted according to actual traffic and unforeseen events.
- Tactical Control: This is the key phase aimed at ensuring separation between aircraft crossing the airspace. The control horizon ranges from approximately 30 minutes for early conflict detection to a few minutes before the conflict for actual resolution.
- Emergency Collision Avoidance: These are onboard systems designed to detect nearby traffic and inform the pilot, and, as a last resort, to provide avoidance advisories when a collision is anticipated. The collision avoidance horizon is approximately 45 seconds before the presumed collision.

2.1.2. System Saturation

As the air transport sector is a rapidly growing field, air traffic continues to increase, leading to saturation in air traffic control systems. Several solutions have been considered to address these overloads, primarily increasing system capacity or adapting traffic to the existing capacity.

2.2. Possible Developments

2.2.1. Conceptual Changes

Several emerging concepts propose radical changes in the way air traffic is managed. In a liberal approach originating from across the Atlantic, "free flight" [9, 16] would allow aircraft to follow direct routes of their choice in airspace with relatively low traffic density. This concept can be considered in different ways depending on the following assumptions:

- Assuming data links between ground and aircraft, an air traffic control system would provide navigation instructions to the aircraft's Flight Management System (FMS), with potential trajectory negotiations between the aircraft and control, to ensure collision avoidance.
- Assuming sophisticated collision avoidance (TCAS/ACAS) onboard equipment and data links between aircraft, the aircraft would ensure their own collision avoidance by negotiating trajectories automatically with each other (Fig. 6).

These two assumptions reflect two opposing concepts in air safety: the "free-flight" concept, initially developed in the United States, favors a more distributed approach, while the "free-route" concept [9, 16] proposed by European states, leans towards a more centralized approach.

These concepts, still under investigation, require a complete redefinition of the air route network, awaiting proof that they will lead to an increase in the capacity to handle more traffic safely compared to the current system.

2.2.2. Automation in Aircraft

Alongside the debate between a centralized system on the ground and a distributed system across all aircraft, the fundamental question of automation arises. Why not, in the near future, consider pilotless aircraft? In addition to the productivity imperatives driving automation, statistics show that human error is one of the leading direct causes of accidents in air transport. The debate is therefore no longer about whether or not to automate, but rather how to do so.

However, with autopilot systems and efficient ground-to-air communications, it is conceivable that we could one day see an air transportation system entirely controlled by ground-based organizations, which would determine the trajectories to be followed by automated pilots.

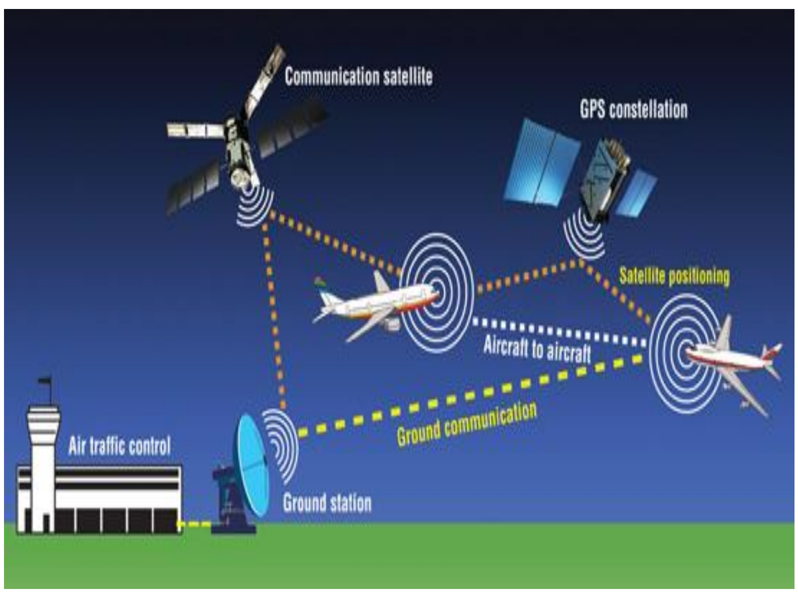

Figure 5.
Future Air Traffic Control Architecture.

As a result, onboard equipment increasingly provides assistance in aircraft navigation and positioning, weather information, and surrounding traffic, even offering collision avoidance maneuvers to the pilot. However, the same alternative with autopilot and efficient collision avoidance system is also not out of the question.

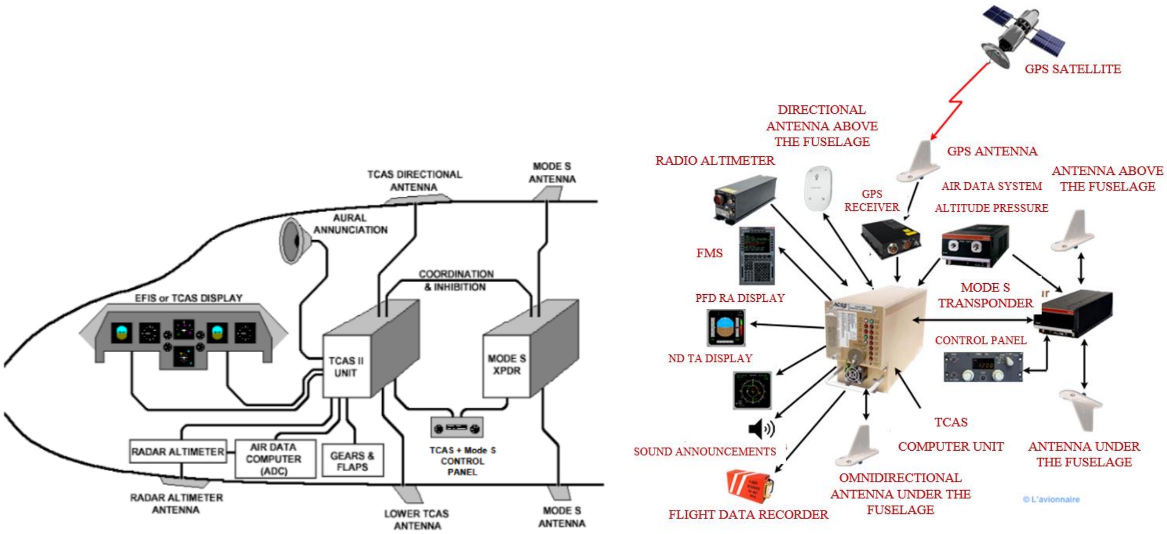

Figure 6.
Onboard Equipment for TCAS.

2.2.3. Automation of Air Traffic Control Systems

Regarding ground-based air traffic management systems, the issue is quite similar. The evolution of traffic suggests that it will no longer be possible to cope with the increasing volume of traffic by simply adding more controllers and further subdividing the airspace into smaller sectors. Such a method, which significantly increases inter-sector coordination and associated tasks, has its limits. As a result, certain control tasks will need to be automated to lighten the workload of air traffic controllers, potentially changing control methods as well. The key question remains which tasks to automate and how to do so.

The tasks of the "radar" controller, who gives instructions to aircraft, can roughly be divided as traffic monitoring, conflict detection, resolution of ongoing conflicts, and coordination tasks, which involve managing incoming traffic on the radio frequency when entering a sector or providing instructions for frequency changes to aircraft leaving the sector.

Additionally, one or more "organic" controllers handle other coordination tasks, including planning and pre-detecting conflicts. Conflict resolution is the least time-consuming task for the controller and the most difficult to automate. Therefore, other tasks will likely be automated first, which requires efficient ground-to-air data links. Regardless of future developments, the safest way to automate control tasks seems to be to offer controllers the option to offload certain tasks to machines. The current approach, therefore, is to provide "intelligent" automated aids for conflict detection and resolution, as well as traffic surveillance and coordination.

3. Context of The Study and Optimization Criteria

In the previous section, we discussed that future developments in air traffic management systems cannot be predicted with certainty. Here, we will first clarify a few basic assumptions adopted in our work and then discuss the various criteria that may be chosen for optimization.

3.1. Problem formulation

The goal is to enable each aircraft to avoid other traffic by providing the pilot with a visualization of surrounding traffic, along with advisories or trajectory change orders generated by an onboard computer. In this context of distributed traffic management, aircraft are expected to choose their own routes, eliminating the need to organize traffic flows or divide the airspace into control sectors. Although appealing at first, this solution becomes more complex when applied to high-density traffic situations, requiring the use of distributed algorithms to coordinate the trajectory choices of aircraft [17]. Many studies have addressed the challenges of automating certain tasks of the controller such as conflict detection and resolution, and even full automation of the system, in both centralized and distributed contexts.

Identifying the optimal time to maneuver and the maneuver itself is formulated as minimizing a given cost, i.e. a mathematical function which defines what is an undesirable outcome. In addition to the cost function, operational constraints are also considered and formulated as inequalities or domain definitions. The decision making is frequently a step-by-step process, based on dynamic programming. This means that at each stage, decisions or controls are based on both the current cost and on the future expected cost. This method ensures an optimal control of a dynamic system over a finite number of stages (i.e. a finite horizon time). However, it should be noticed that this decision-making process is not proposed as a new conflict resolution algorithm, but rather a mean to investigate different decision making strategies.

The problem lies in minimizing the cost function depending on the state variables $y=(x1, x2, \alpha)^T$. There are three state variables to reduce the problem complexity. Two of them are the position coordinates in a 2D plan, and the third one is the current plane heading (Figure 7).

At the moment, there is only one control variable due to the restriction on the resolution maneuver which is a combination of heading changes based on the next waypoint or intersection point while keeping the speed constant. The speed will also be controllable in our case to solve coordination problems between air sectors.

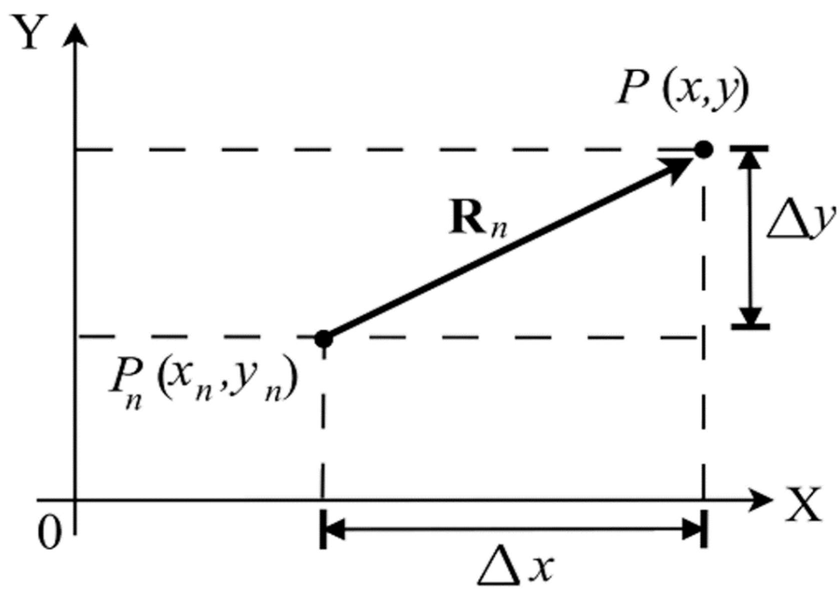

Figure 7.
Illustration of a Cartesian coordinate plane. Two points, $P_n(x_n,y_n)$ and $P(x,y)$, are marked. The directional vector between these points is R_n, and the x and y increments are denoted as Δx and Δy, respectively.

3.2. Criteria

Beyond assumptions about the context, another question to consider is which criteria should be optimized in the system? Depending on the chosen context and the specific problem, we might aim to:

- Reduce the number of trajectory conflicts (intersection with collision),
- Minimize trajectory extensions,
- Reduce departure delays,

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- Lessen the air traffic controller's workload,
- Better to distribute the workload among controllers,
- And more...

Note that these criteria may be conflicting. For example, resolving conflicts typically leads to trajectory deviations and extensions. On the other hand, several criteria may be improved simultaneously. Most of the problems will be multi-objective: separating major traffic flows while minimizing trajectory extensions or optimally distributing the workload among multiple control teams while staying below sector capacity limits, and so on.

4. Our Approaches for Air Traffic Control

The SESAR program (Single European Sky ATM Research) [18] is a European project aimed at improving air traffic management by 2020, creating a single European sky. From a technological perspective, this project involves the integration of telecommunications and satellite navigation, particularly through GALILEO. Currently, air traffic controllers issue instructions to pilots via a VHF radio link. One of the principles developed in SESAR is the central role of the trajectory (business trajectory). In this concept, the optimal 4D flight trajectory for an aircraft is defined by the users and the Air Navigation Service Providers (ANSPs). This would eliminate the current air route system and allow for reductions in fuel consumption and flight time.

4.1. Limitations

When traffic increases steadily, the usual solution of regulating by delaying flights on the ground is no longer sufficient. It becomes necessary to increase capacity by splitting certain sectors into two and hiring additional controllers. Unfortunately, this division method cannot continue indefinitely, as there is a minimum sector size below which sectors become uncontrollable, with aircraft spending too little time within them.

The current route network also results in longer distances traveled by aircraft. Indeed, aircraft cannot follow an orthodrome, which is the shortest path between two points on the sphere, between their origin and destination. The total difference in distance traveled was 5.6% in 2008, representing about 500 million additional kilometers and approximately 9 million tons of CO_2 emitted [18].

4.2. Our Contributions

We distinguish two methods to solve this problem: centralized control and decentralized control. Centralized control involves a single authority for gathering and processing information (for example, an air traffic controller), while decentralized control involves each aircraft in the collection and processing of information, proposing trajectory decisions autonomously.

We will have all the necessary information on aircraft positions and characteristics to share via the Business Trajectory, which will be updated in real-time with aircraft masses, fuel reserves, and estimated arrival times. Our research has enabled us to summarize a classification of the various approaches and implement two contributions as follows.

4.2.1. Approach For Separation by Moving Intersection Points

Our approach is centralized solution. Successful air traffic planning requires trajectory planning for aircraft that can be modeled to avoid collision between multiple aircraft. Trajectory optimization with collision avoidance constraints can be described as a linear program designed to minimize the cost based on flight times and other parameters. Our approach is based on using a directed graph, where the nodes represent intersections between trajectories [6, 7]. Figure 8 shows the steps of our approach to separating aircraft. Initially, airline pilots declare their flight plans. An air traffic controller is assigned to a sector. The controller will display the trajectories according to the air corridors of their sector, reserved by the different flight plans (Figure 9).

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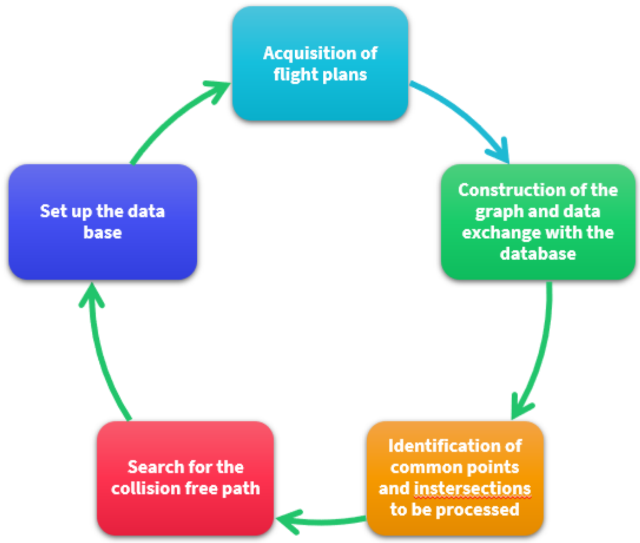

Figure 8.
Architecture of Our Approach.

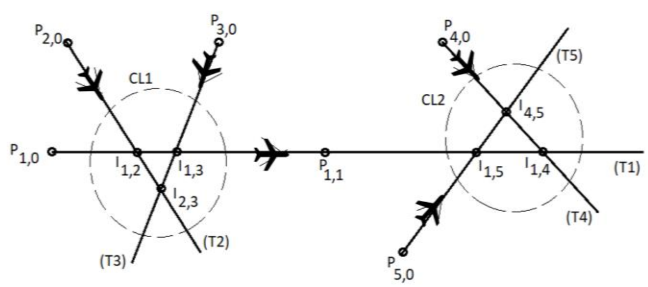

Figure 9.
Example of 5 aircraft trajectories.

A flight plan is a sequence of straight segments connecting headings Pi,j. The separation system transforms the visual display into a directed graph structure, identifying intersection points Ii,j for subsequent separation processing (Figure 10).

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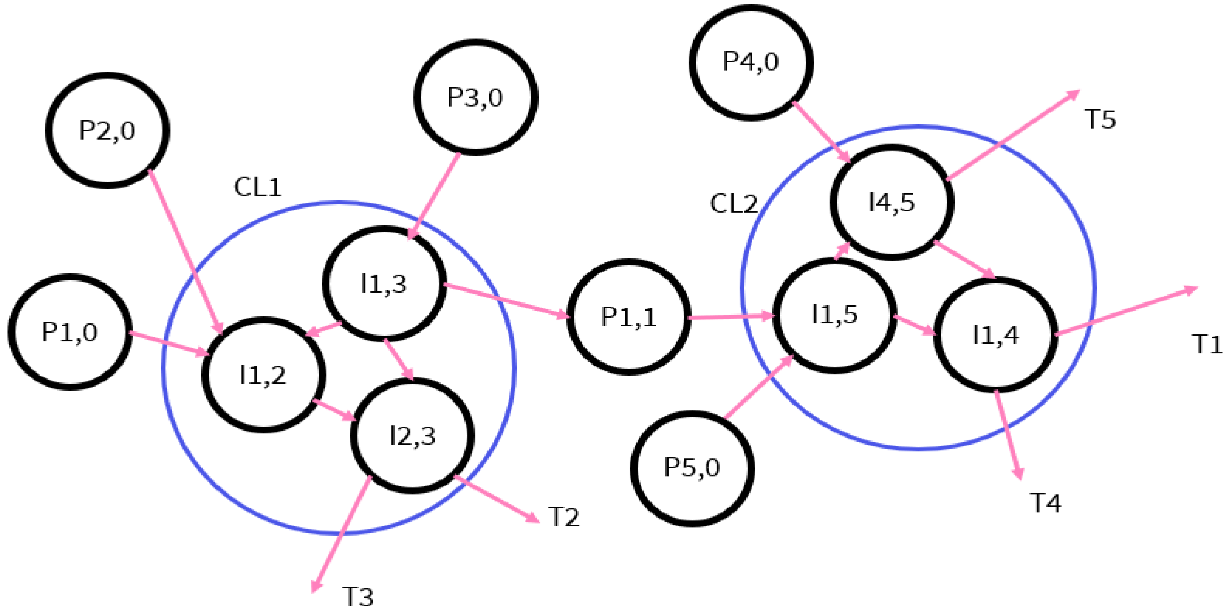

Figure 10.
Transformation into directed graph. CL1 and CL2 are two clusters to be processed

The system performs separation calculations by adjusting aircraft according to criteria that may include fuel consumption, fuel availability, flight distance, flight criticality (private flights), etc. (Fig. 11).

The result must be reported back to the flight information database to update the visual display on other sectors.

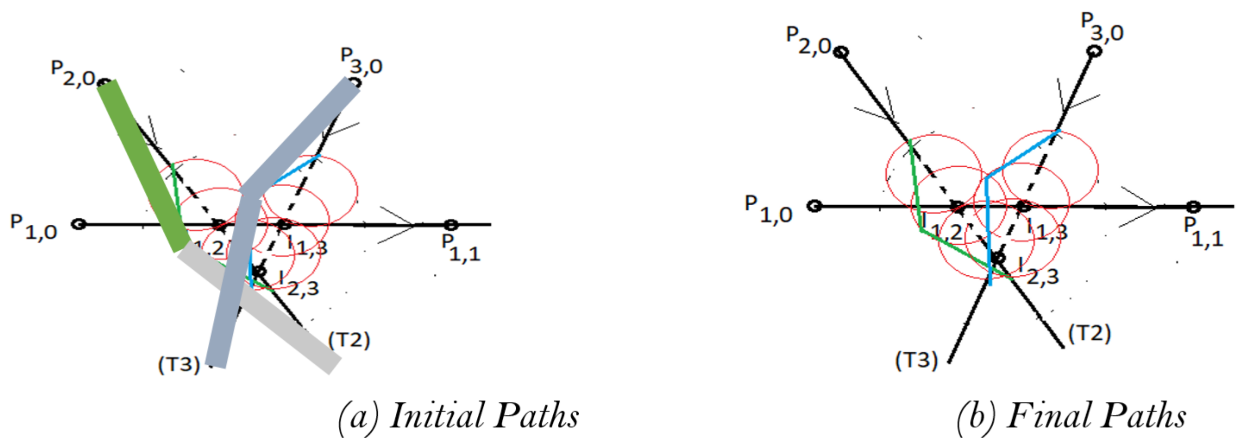

Figure 11.
Each iteration of our approach moves the intersection points.

For aircraft that have undergone trajectory changes, pilots can change speed in coordination with an air traffic controller to adjust travel time within the sector and reduce coordination issues between sectors and arrival management at airports (Fig. 12). Pilots are allowed to change their speeds by +/- 10 kts. When calculating new speeds, it must be taken into account that ground speed may vary depending on altitude.

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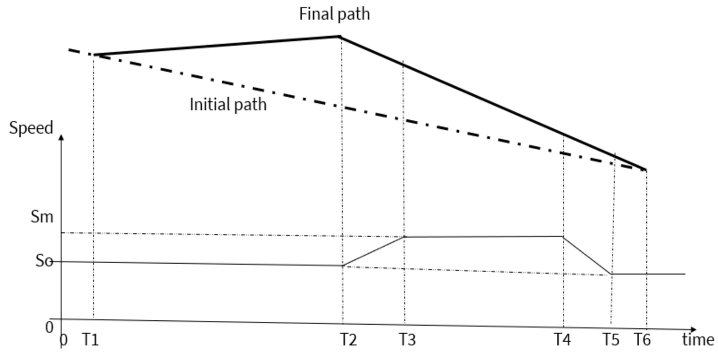

Figure 12.
Speed profile and trajectory in a sector.

4.2.2. Simulation and Results

Our simulation is made with Matlab. The aircraft and trajectories are defined by the parameters in a simple way to show the feasibility of our approaches (Fig. 13). Let us start with the 4-plane roundabout problem.

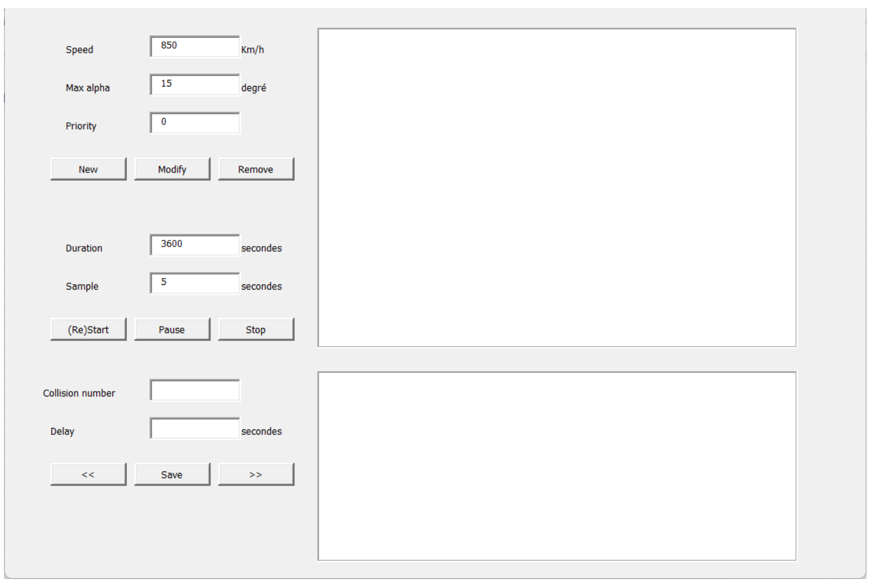

Figure 13.
HMI of our simulator under Matlab.

The solution obtained is shown in Figure 14. The solution corresponds to the expected resolution of an automatic conflict resolution method: all planes turn in the same direction.

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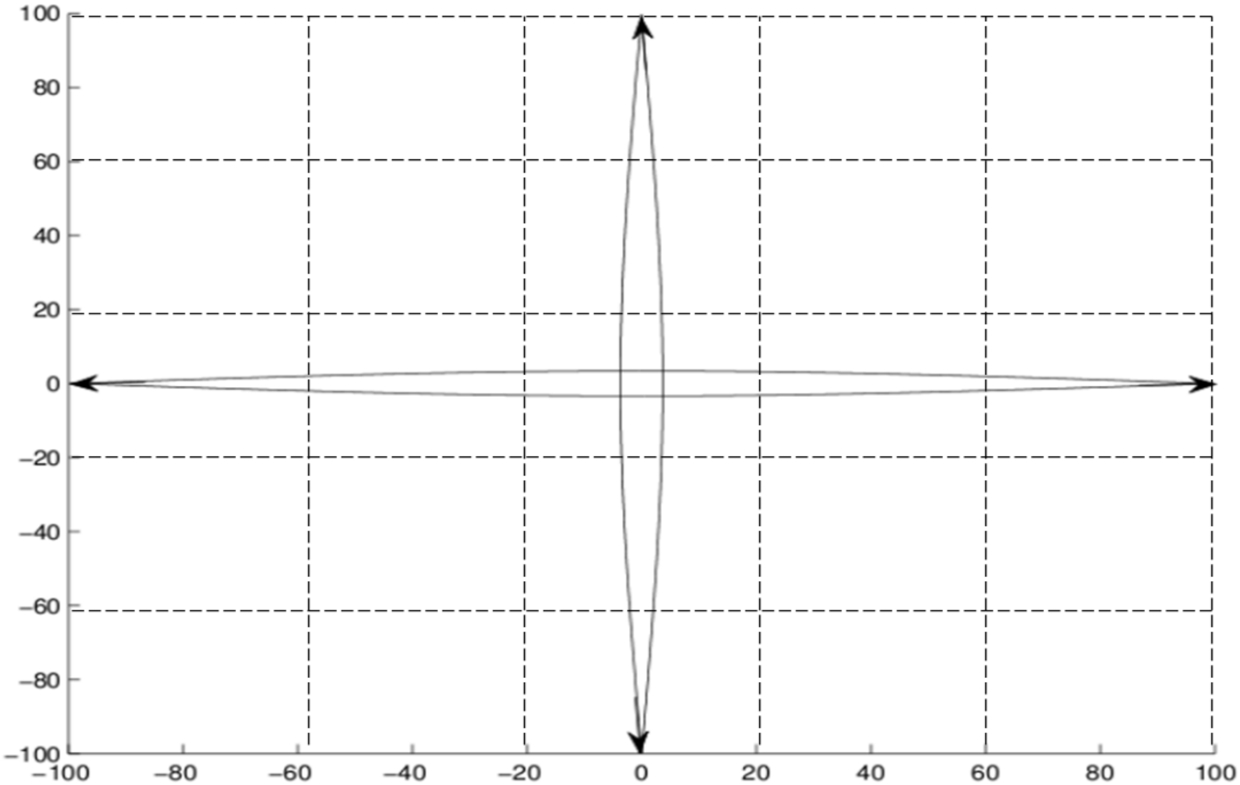

Figure 14.
An example of 4 planes with opposite and perpendicular trajectories.

In the case of the roundabout with 6 planes, we obtain similar results and the observations are similar. The solution obtained is presented in Figure 15. We observe again that, as expected, all the planes turn in the same direction to avoid each other.

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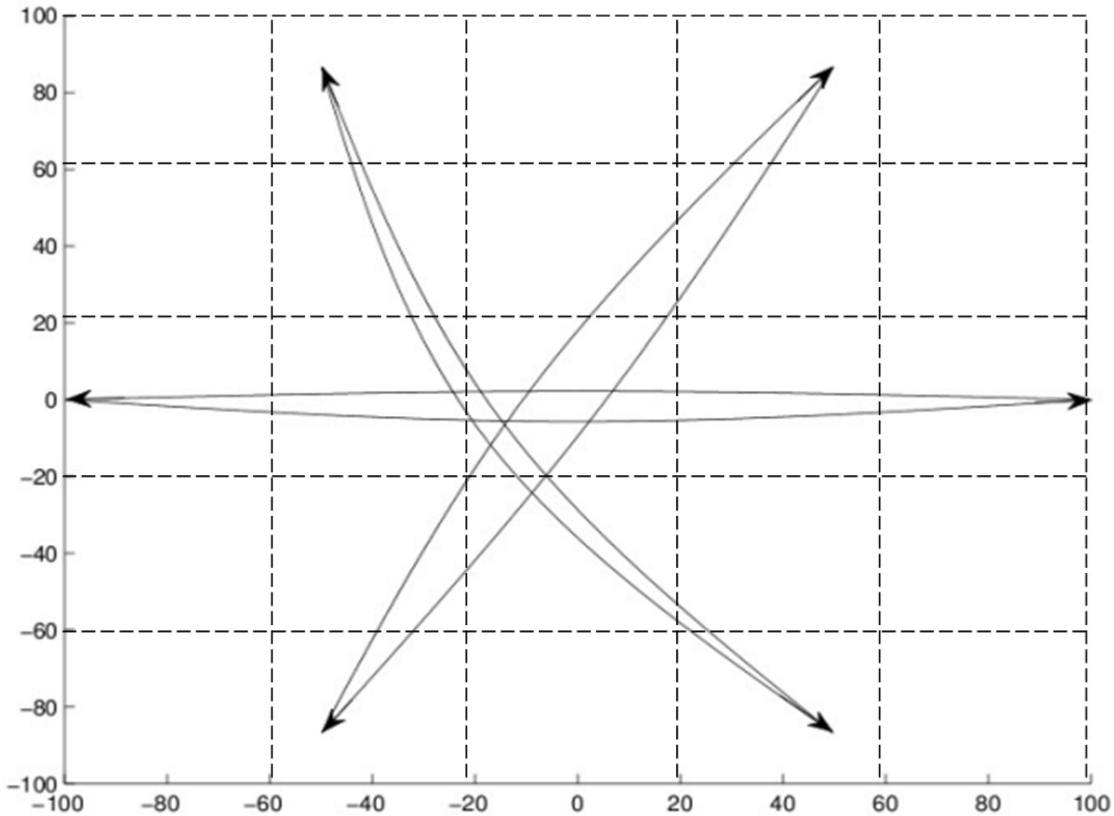

Figure 15.
An example of 6 planes with opposite and perpendicular trajectories.

4.2.3. Coordination Approach for Ensuring Separation Based on Low Earth Orbit (LEO) Satellite Utilization

This is a decentralized method to solve the collision avoidance problem with discrete time and multiple decision points. The optimization framework integrates the structure of inherent elements, where each decision-maker (pilot or automated system) has a model that captures only the local dynamics and the global interconnection constraints associated with information exchanges with a cloud-based system, relying on satellite communications.

Figure 16 demonstrates the usefulness of communication exchanges between the aircraft and the Low Earth Orbit (LEO) satellite constellation. Separation occurs on the aircraft's computer, which proposes solutions to the pilot that are in agreement with the results of computations from other aircraft. The pilot, upon accepting a proposal, locks their trajectory, and it is the responsibility of the others to perform the new calculations.

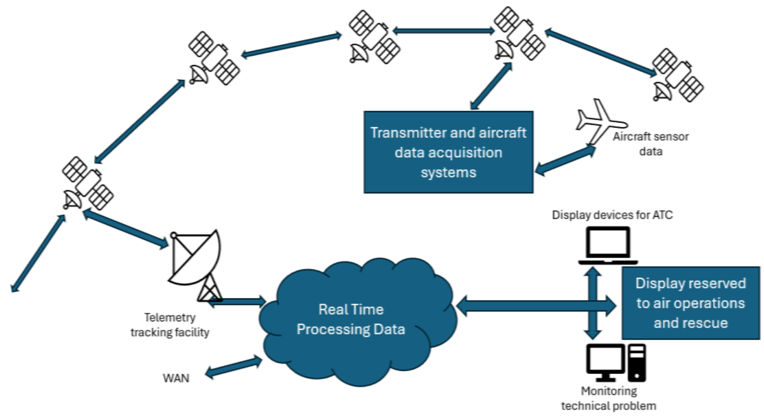

Figure 16.
Architecture of Our Approach.

The strength of our solution lies in its application even to non-collaborative aircraft that do not have a TCAS system onboard. The LEO satellite constellation will enhance the reliability of the exchanged information and will present a connectivity issue known as "Handover" [19, 20]. The aircraft passes through several coverage areas during its flight. The communication system must ensure that the connection is maintained using a Handover policy.

The information exchanged on the cloud is available for multiple applications. We cite the Flightradar24 application as an example. This application informs us about the flight situation in real time (Figure 17). The user has an idea about the estimated time of arrival and the flight conditions such as altitude and speed.

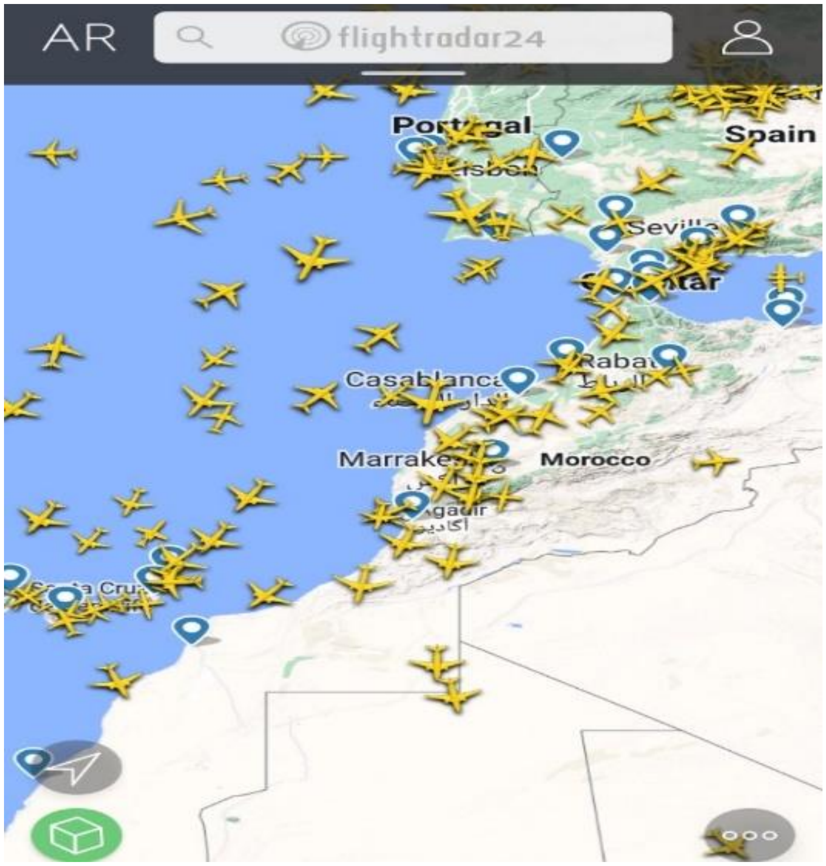

Figure 17.
Flightradar24 allows you to visualize the positions of aircraft based on information collected in real time.

Our approach could also be applied to multiple unmanned flying machines (drones), with kinematic models of aircraft, coordinating in a shared airspace with separation requirements between aircraft.

5. Conclusion

This paper presents an analysis of air traffic management system approaches, in line with current projects and those under study. All the approaches converge on the main goal of reducing the number of conflicts and, flying on optimal consumption routes to reduce gas consumption and environmental impact. To achieve this, our studied proposed two solutions based on centralized and decentralized approaches.

The work of air traffic controllers still focuses on resolving residual conflicts. The systems studied are highly organized, particularly in terms of timing, as they require aircraft to follow a set of specific points.

Our future work will contribute further to the spatial separation of trajectories and the imposition of speed profiles on aircraft, which will increase traffic capacity.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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