AIR TRAFFIC CONTROL BY OPTIMAL PATH PLANNING

A THESIS SUBMITTED TO
THE SCHOOL OF GRADUATE STUDIES
OF
UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION

BY

GEORGE MUSHAYIJA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ELECTRICAL AND COMPUTER ENGINEERING

AUGUST 2024

AIR TRAFFIC CONTROL BY OPTIMAL PATH PLANNING

A THESIS SUBMITTED TO
THE SCHOOL OF GRADUATE STUDIES
OF
UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION

BY

GEORGE MUSHAYIJA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ELECTRICAL AND COMPUTER ENGINEERING

SUPERVISOR: Assoc. Prof. Dr. KANBEROĞLU

AUGUST 2024

Approval of the thesis:

AIR TRAFFIC CONTROL BY OPTIMAL PATH PLANNING

submitted by **GEORGE MUSHAYIJA** in partial fulfilment of the requirements for the degree of **Master of Science in Electrıcal and Computer Engıneerıng, University of Turkish Aeronautical Association** by,

Assoc. Prof. Dr. Adnan GÜZEL
Dean, Graduate School of Social Sciences, UTAA _______________

Assist. Prof. Dr. Aytun ONAY
Head of The Department,
Electrical and Computer Engineering, UTAA _______________

Assoc. Prof. Dr. Habib KANBEROĞLU
Supervisor, Computer Engineering, UTAA _______________

Examining Committee Members:

Assoc. Prof. Dr. Orhan ERDEN
Industrial Design Engineering
Gazi University _______________

Assist. Prof. Dr. Fatih KASIMOĞLU
Industrial Design Engineering

University of Turkish Aeronautical Association

____

Assoc. Prof. Dr. Habib KANBEROĞLU
Computer Engineering,
University of Turkish Aeronautical Association _______________

Date: 01 August 2024

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

George MUSHAYIJA

ABSTRACT

AIR TRAFFIC CONTROL BY OPTIMAL PATH PLANNING

George, MUSHAYIJA
Master of Science, Electrical and Computer Engineering
Supervisor: Assoc. Prof. Dr. Habib KANBEROĞLU

AUGUST 2024, 100 Pages

The rising demands of the global aviation industry require innovative solutions to meet the challenges of air traffic control (ATC) management. This study sees the integration of optimal trajectory planning and tracking, specifically leveraging the control computation algorithms (CCA) used to optimize path planning in air traffic control by using the non-linear system to adjust the heading angle and velocity based on the current position and its rate of change and also uses numerical integration method called the Runge-Kutta 4th order (RK4) to solve a system of differential equations. This research presents a kinematic model as a point-mass model for aircraft trajectory planning and tracking, using a series of differential equations that govern the motion of an aircraft. The model considers the tangential and normal components of acceleration to describe the velocity and heading angle changes, respectively. This kinematic framework enables the computation of an optimal path using the MATLAB optimization tool by defining a specific path and ensuring the aircraft adheres to the desired trajectory through precise control of its velocity and heading angle. The approach leverages the kinematic equations to continuously update the aircraft's position and orientation, ensuring that it follows the planned mission with high accuracy. The MATLAB/SIMULINK tool has been used to describe the simulation setup and data collection protocols to evaluate the effectiveness of the models used. It also provides a robust solution for path planning and path tracking in air traffic control, allowing for efficient route optimization and improved safety. The effectiveness of the proposed model is validated through simulations, demonstrating its capability to handle complex flight paths and adjust dynamically to changing flight conditions to ensure collision-free between aircraft.

Keywords: Air Traffic Control, Path Planning, Path Tracking, Aircraft Kinematics, Trajectory Optimization, Flight Safety, Landing process

ÖZ

OPTİMAL YOL PLANLAMASI İLE HAVA TRAFİK KONTROLÜ

George, MUSHAYIJA
Yüksek Lisans, Elektrik ve Bilgisayar Mühendisliği
Tez Danışmanı: Doç. Prof. Dr. HABİB KANBEROĞLU

01 Ağustos 2024, 100 Sayfa

Küresel havacılık endüstrisinin artan talepleri, hava trafik kontrolü (ATC) yönetiminin zorluklarını karşılamak için yenilikçi çözümler gerektiriyor. Bu çalışma, mevcut konum ve hıza göre yön açısını ve hızını ayarlamak için doğrusal olmayan sistemi kullanarak hava trafik kontrolünde yol planlamasını optimize etmek için kullanılan kontrol hesaplama algoritmalarından (CCA) yararlanarak, optimal yörünge planlama ve izlemenin entegrasyonunu görmektedir. Onun değişim hızı. Bu araştırma, bir uçağın hareketini yöneten bir dizi diferansiyel denklem kullanarak, uçağın yörünge planlaması ve takibi için nokta-kütle modeli olarak kinematik bir model sunmaktadır. Model, sırasıyla hız ve yön açısı değişikliklerini tanımlamak için ivmenin teğetsel ve normal bileşenlerini dikkate alır. Bu kinematik çerçeve, belirli bir yol tanımlayarak ve hızının ve yön açısının hassas kontrolü yoluyla uçağın istenen yörüngeye uymasını sağlayarak MATLAB optimizasyon aracını kullanarak en uygun yolun hesaplanmasını sağlar. Yaklaşım, uçağın konumunu ve yönelimini sürekli olarak güncellemek için kinematik denklemlerden yararlanıyor ve planlanan görevi yüksek doğrulukla takip etmesini sağlıyor. Kullanılan modellerin etkinliğini değerlendirmek amacıyla simülasyon kurulumunu ve veri toplama protokollerini açıklamak için MATLAB/SIMULINK aracı kullanılmıştır. Ayrıca, hava trafik kontrolünde yol planlama ve yol takibi için sağlam bir çözüm sunarak verimli rota optimizasyonuna ve gelişmiş güvenliğe olanak tanır. Önerilen modelin etkinliği, karmaşık uçuş yollarını idare etme ve uçaklar arasında çarpışmayı önlemek için değişen uçuş koşullarına dinamik olarak uyum sağlama yeteneğini gösteren simülasyonlar yoluyla doğrulanmıştır.

Anahtar Kelimeler: Hava Trafik Kontrolü, Yol Planlama, Yol Takibi, Uçak Kinematiği, Güzergah Optimizasyonu, Uçuş Emniyeti, İniş süreci

DEDICATION

This work is dedicated to the almighty Godfather, my country, my parents, my wife Yvonne UWAMWEZI, my children, and my friends, whose unconditional love, support, and encouragement have been my greatest source of strength. Your unwavering belief in me has propelled me forward even during the toughest times.

I thank a lot my supervisor Assoc. Prof. Dr. Habib KANBEROĞLU, your guidance and wisdom have been invaluable throughout this journey. Your dedication to my academic growth has been inspiring. This work is a testament to the incredible people in my life who have shaped me into the person I am today.

ACKNOWLEDGMENTS

Predominantly, I thank the almighty the God who indorsed me good health and wisdom to pass all modules without failure in my academic journey.

I would like also to express my deepest gratitude to my supervisor, Assoc. Prof. Dr. Habib KANBEROĞLU, for his unwavering support, invaluable guidance, and insightful feedback throughout the course of this research. His expertise and encouragement were instrumental in the completion of this thesis.

My heartfelt thanks go to all University of Turkish Aeronautical Association lecturers who gave me knowledge on different areas of my field.

Finally, I would like to express my deepest appreciation to my family and friends for their unwavering love, patience, and support. Their belief in me kept me motivated and focused during the challenging moments of this journey.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

ATC	: Air traffic control
CCA	: Control computation algorithms
PID	: Proportional integral derivative
RK4	: The fourth-order Runge-Kutta method
ADS–B	: Automatic dependent surveillance–broadcast
ODEs	: Ordinary differential equations
ICAO	: International civil aviation organization
SESAR	: Single European sky air traffic management research
RTS	: Remote tower service
RTC	: Remote tower center
CDM	: Collaborative decision making
AERAC	: Automated En-route air traffic control
URET	: User request evaluation tool
VERA	: Verification of separation and resolution advisory
ERATO	: En-route air traffic organizer
ATM	: Air traffic management
PHARE	: Program for harmonized air traffic research in Europe
HMI	: Human machine interface
MTCD	: Medium term conflict detection
HIPS	: Highly interactive problem solver
TLS	: Tactical load smoother
MOTO	: Multi objective trajectory optimization
4DT	: 4-Dimensional Trajectories
FACET	: Future air traffic management Concepts Evaluation Tool
LAN	: Local area networks
RL	: Reinforcement learning
MAS	: Multi-agent system

FIFO	: First-in-First-out
TFM	: Traffic flow management
MPC	: Model predictive control
GPS	: Global postioning system
PBN	: Performance-based navigation
ASL	: Above sea level
MSL	: Mean sea level
NM	: Nautical miles
AGL	: Above ground level
FL	: Flight level
IFR	: Instrument Flight Rules
VFR	: Visual flight rules
IAPs	: Instrument approach procedures
SUA	: Special use airspace
RA	: Restricted Areas
PA	: Prohibited areas
TFR	: Temporary Flight Restrictions
ATM	: Air traffic management
ATS	: Air traffic services
ATFM	: Air traffic flow management
ASM	: Airspace management
VORs	: VHF Omnidirectional Range
ILSs	: Instrument Landing Systems
ACARS	: Aircraft Communications Addressing and Reporting System
INS	: Inertial Navigation Systems
IMU	: Inertial measurement unit
GPS	: Global positioning system
GNSS	: Global Navigation Satellite Systems
CPDLC	: Controller-Pilot Data Link Communications
TBO	: Trajectory Based Operations
NAS	: National Airspace System

DAC	: Dynamic airspace configuration
TOAS	: Terrain and Obstacle Avoidance Systems
EASA	: European Aviation Safety Agency
FAA	: Federal Aviation Administration
TBM	: Time-based management
PBN	: Performance-based navigation
SWIM	: System-wide information management
DME	: Distance Measuring Equipment

LIST OF SYMBOLS

SYMBOLS

a_t	Tangential acceleration (m s^{-2})
a_n	Normal acceleration (m s^{-2})
ψ	The actual current heading angle of the aircraft (radians)
$\dot{\psi}$	Change on heading angle of the aircraft over time (rad/s)
V	The actual current velocity of the aircraft (m/s)
$\dot{V}$	Change on actual velocity of the aircraft over time (m/s)
V^{com}	Desired command velocity (m/s)
ψ^{com}	Desired command heading (radians)
e_v	Error in the actual current velocity of the aircraft
$\dot{e}_v$	The rate of change of the velocity error
e_ψ	Error on actual current heading angle of the aircraft
$\dot{e}_\psi$	The rate of change of the heading angle error
X	The state vector, which describe the state of the system
$\dot{X}$	The derivative of the state vector X with respect to time
A	The system matrix, which defines the dynamics of the system
B	The input matrix, which defines how control inputs affect the state of the system
u	The control input vector, representing the inputs or actions applied to the system
G	The disturbance matrix, which defines how external disturbances affect the state of the system
r	The disturbance vector, representing external disturbances or inputs that are not controlled
K	The gain matrix of the system
r_0	The initial position vector represents the starting point in the two-dimensional space

L_i	The magnitude of the *i-th* vector represents length of the step taken in the *i-th* direction
ℓ	The air density.
S	The reference area of the aircraft (typically the wing area).
C_D	The drag coefficient, a dimensionless number representing the drag per unit area.

CHAPTER 1

INTRODUCTION

Air traffic control (ATC) involves the management and regulation of air traffic to ensure the safety and efficiency of aircraft operations (Bicchi & Pallottino, 2000). It encompasses various tasks, such as providing clearances, separation between aircraft, and guidance for takeoff, landing, and en-route operations. ATC aims to prevent collisions between aircraft and to minimize delays.

Optimal path planning in air traffic control refers to the process of determining the most efficient routes for aircraft to follow. This involves considering factors such as airspace congestion, weather conditions, fuel efficiency, and aircraft capabilities. By optimizing the paths that aircraft follow, ATC can enhance the overall efficiency of the airspace and creates separation distance to reduce the potential conflicts between flights. The management of aircraft trajectories in air traffic control (ATC) is a complex task that involves ensuring safe and efficient flight paths. This process encompasses both path planning, where the optimal trajectory is designed before the flight, and path tracking, where the aircraft is guided along the predetermined path in real-time (Saeed et al., 2022). The kinematic and the trajectory tracking equations supplementary provides a foundational understanding of how these trajectories can be mathematically modeled and controlled. The motion of an aircraft can be described by a set of kinematic equations that account for both translational and rotational Dynamics, and the trajectory tracking is modeled by segmenting flight path, where the aircraft moves from an initial position to a final position by minimizing series of objective function. Path planning involves determining the optimal paths that the aircraft should follow to reach its destination efficiently and safely. And Path tracking, on the other hand, focuses on the real-time control of the aircraft to ensure it adheres to the planned path. This involves adjusting the aircraft's velocity and heading angle based on the kinematic equations to correct any deviations from the intended path using proportional-derivative (PD) and model predictive control (MPC) as the control strategies(Saeed et al., 2022). The integration of kinematic equations into the path planning and path tracking algorithms is essential for modern air traffic control systems (Moon et al., 2013). By understanding and applying differential equations, ATC can enhance the safety and efficiency of aircraft operations, ensuring that each aircraft follows its intended path while avoiding conflicts.

1.1 Historical Background

Long ago, the air traffic management system encountered difficulties concerning the growing number of aircrafts in the sky, congestion in airspace, and the necessity for streamlined routes. In 1980s the advent of digital computing technology allowed for the development of more sophisticated ATC systems (Breitler et al., 1996). However, path planning and tracking were still largely manual processes where ccontrollers used standardized airways, waypoints, and flight levels to separate traffic and ensure safety. Efforts made by several Engineers were to modernize the system by implementing technologies like Automatic Dependent surveillance–broadcast (ADS–B) and satellite-based navigation systems, such as GPS to improve the accuracy of aircraft positioning. ATC systems began to incorporate these technologies, enhancing situational awareness and control capabilities with the intention of providing precise and frequent updates regarding aircraft positions (Ostroumov et al., 2022). Integration of path planning and tracking Algorithms in early 2000s advances in computer science and optimization algorithms led to the development of path planning and path tracking algorithms. These algorithms use real-time data to compute optimal flight paths and adjust trajectories dynamically, considering factors like weather, air traffic, and fuel efficiency (Gopalakrishnan & Balakrishnan, 2021). Modern ATC systems integrate advanced algorithms for optimal path planning and path tracking, enabling more efficient and safer air traffic management. These systems utilize data from multiple sources, including radar, satellite navigation, and aircraft sensors, to continuously update and optimize flight paths (Woo et al., 2021).

1.2 Problem Definition

The optimal path planning in air traffic control aims to address the increasing challenges and inefficiencies in the current airspace management systems. As air traffic continues to grow, the demand for more efficient routes that minimize fuel consumption, reduce emissions, enhance safety, and optimize airspace utilization becomes paramount. The existing air traffic control systems struggle to dynamically adapt to changing conditions, leading to suboptimal routes, increased congestion, and potential delays. Therefore, developing advanced algorithms and technologies for optimal path planning in air traffic control is crucial to streamline air traffic, enhance resource utilization, and mitigate the environmental impact of aviation. This research seeks to explore and implement innovative solutions that optimize flight paths in real-time, considering various factors such as weather conditions, airspace constraints, and aircraft capabilities, ultimately contributing to a more sustainable and efficient aviation system. Figure 1.1 and figure 1.2 (Srisaeng et al., 2022) shows the global aircraft fleet sizes by region in 2016 and 2036 (measured in units) and the statistics of regional estimates of the annual growth rates for passenger air traffic between 2022 and 2042 which as the our problem in the future of air traffic (Srisaeng et al., 2022).

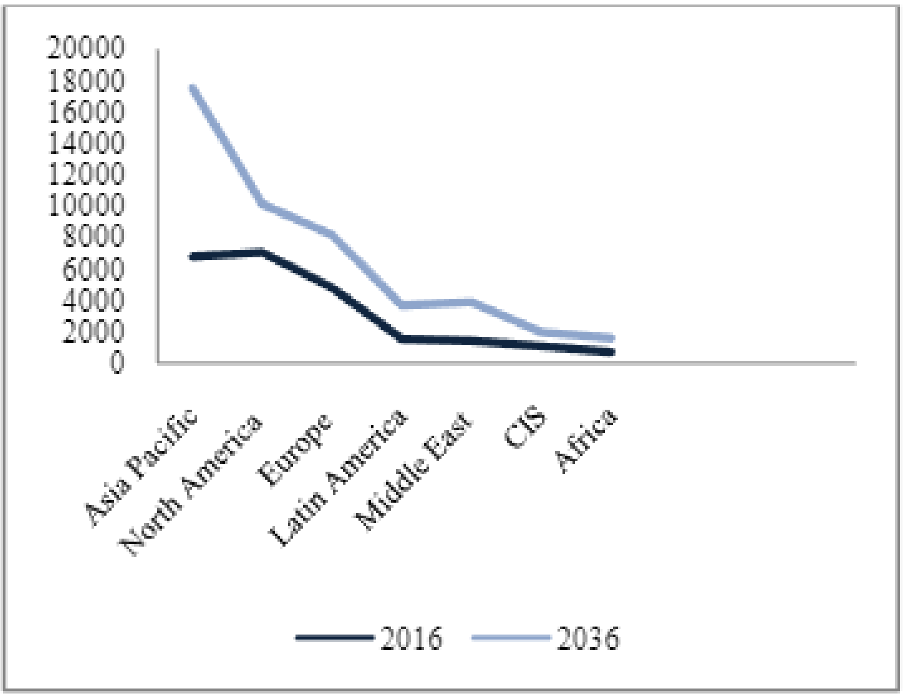

Figure 1.1: The global aircraft fleet sizes by region in 2016 and 2036 (measured in units).

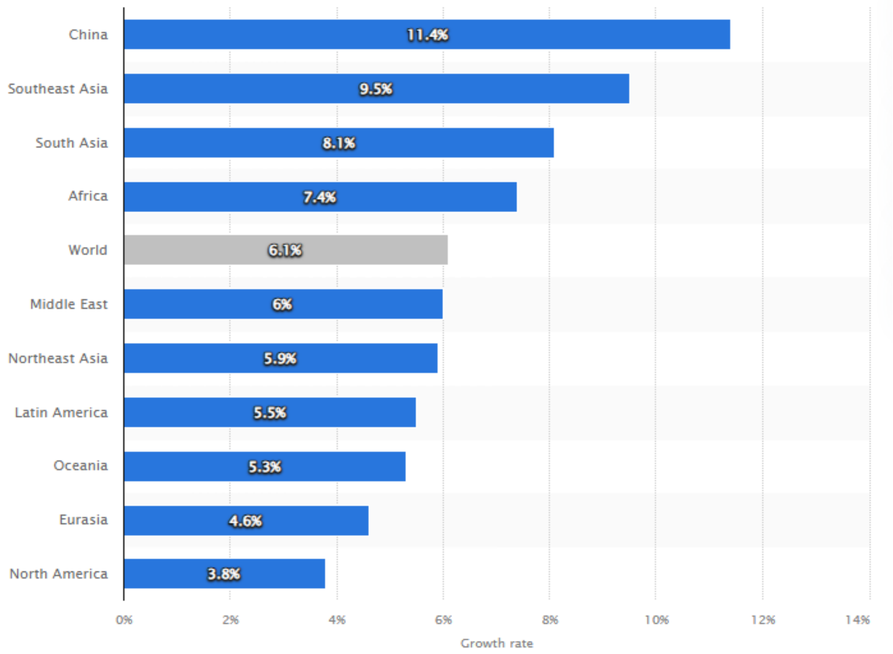

Figure 1.2: Regional estimates of the annual growth rates for passenger air traffic between 2022 and 2042.

1.3 Motivation and Objective

The rapid growth of air traffic globally has heightened the need for advanced systems capable of ensuring safety, efficiency, and punctuality in air travel. Despite numerous studies on optimal path planning, there is a lack of comprehensive research on optimal path planning in air traffic as the density of air traffic continue to increase, hence, the complexity of managing multiple aircraft within shared airspace becomes more prominent. This necessitates sophisticated techniques for path planning and tracking to mitigate risks and optimize flight operations. Our motivation is to employ optimal path planning and tracking in air traffic control using advanced algorithms aiming to address the problem of future air traffic.

The main importance of this research is to design automatic air traffic control (ATC) algorithm that could significantly reduce the workload on the human air traffic operators in order to enhance overall safety and efficiency of air traffic operations with the goal of balancing and optimizing air traffic flow, reduce congestion, avoid collision between aircrafts, improve fuel efficiency and overall system performance. And also, the concept of optimal path planning in air traffic control can be used in control guidance of landing swarm of drones in a confined area without collision between them. International coordination is necessary for optimal path planning, and advanced technology integration, such as performance-based navigation (PBN) which enables more precise and flexible routes. In this research, we consider the problem of optimal trajectory planning in a more limited context: that of air traffic control. The task of this problem is to define flight paths for aircraft to enforce "safe" separation criteria, while trying to optimize for several objectives.

Safety Enhancement: Ensuring the safety of passengers and crew is paramount in air traffic control. Optimal path planning and tracking minimize the risk of mid-air collisions and other safety incidents by providing precise and predictable flight trajectories. By maintaining safe separation distances and avoiding conflict zones, these systems enhance overall flight safety.

Efficiency Improvement: Optimal path planning helps in reducing flight time, fuel consumption, and emissions by identifying the most efficient routes. Efficient tracking ensures that aircraft adhere to these planned paths, reducing the need for frequent and costly in-flight corrections. This leads to significant operational cost savings for airlines and contributes to environmental sustainability.

Reliability and Predictability: Reliable and predictable flight operations are essential for maintaining schedules and minimizing delays. Optimal path planning and tracking provide consistent and accurate flight paths, allowing air traffic controllers and airlines to predict aircraft positions more reliably. This predictability is crucial for coordinating takeoffs, landings, and ground operations.

Adaptability to Changing Conditions: The dynamic nature of air traffic control requires systems that can adapt to changing weather conditions, airspace restrictions, and other unforeseen events. Optimal path planning and tracking systems are designed to be flexible, allowing for real-time adjustments to flight paths while maintaining optimal performance and safety.

Enhanced Decision-Making: Advanced path planning and tracking tools provide air traffic controllers with detailed and actionable information, enhancing their decision-making capabilities. These systems support the controllers in managing complex scenarios, prioritizing aircraft efficiently, and responding swiftly to emergencies or deviations from planned paths.

1.4 Literature Review

For many decades, aviation experts have been working actively on the creation and implementation of new on-board navigation systems and ground-based control systems, which would make passenger and cargo air transportation safer and more efficient. The rapid growth of air traffic in recent years and the increasing number of aircraft in the airspace bring to the fore the solution of the problem of appointing aircraft optimal routes to their individual flights taking into account the position, speed, and flight restrictions set in each particular segment of the trajectory (Garza et al., 2015). Therefore, before the systems of on-board guidance of the aircraft and ground-based air traffic control systems, such as air traffic management systems, the task arises of determining the optimal path of the aircraft in terms of a number of criteria that arise from the fact that the aircraft must have time to fly and land in the appointed airports (or box centres), as well as that the need to perform intermediate activities (e.g., refuelling, performing other necessary activities, etc.) can lead to the necessity of introducing some additional intermediate airports.

Optimal path planning is a decisive aspect of air traffic control (ATC) that aims to find the most efficient and secure routes for aircraft in the airspace to ensure efficient and safe flight operations. Early systems focused on deterministic approaches, but as technology advanced, probabilistic and AI-based methods gained prominence. Essentially, in utilizing advanced technologies like radar, satellite navigation, and sophisticated algorithms to calculate the best flight paths for aircraft, considering factors such as weather conditions, aircraft capabilities, airspace limitations, and overall air traffic conditions. This process is essential for improving safety, reducing fuel consumption and emissions, and enabling aircraft to avoid turbulence, congestion, and other potential risks. Moreover, by optimizing aircraft trajectories, ATC can minimize flight delays, increase airspace capacity, and ultimately create a more streamlined and sustainable air transportation system. This research will cover subtopics like Optimization and path planning and intelligence swarm algorithms, Air traffic control of space crafts.

When aircraft got slightly more sophisticated in the 1920s, there was less of a need to prevent collisions; air traffic controllers were created to guide pilots on when to land and take off at London's Croydon Airport by waving flags (Gilbert, 1973). Then, in the 1930s, the Cleveland Airport saw the construction and operation of the first air traffic control tower equipped with radio. Following World War II, the Chicago Convention on International Civil Aviation was established, which resulted in the creation of the International Civil Aviation Organization (ICAO) and the development of internationally recognized standard practices that serve as the cornerstone of international air traffic management (Mackenzie, 2010). According to the International Air Transport Association's 2036 prediction, the number of air passengers would almost double to 7.8 billion (Srisaeng et al., 2022). This indicates that aviation traffic will grow dramatically, causing significant traffic jams, delays, and pollution. New control strategies and optimized procedures are required to keep the large number of aircraft at safe separations from one another, to lead them during take-off and landing from airports, to steer them around inclement weather, and to guarantee that traffic moves freely with few delays.

Research programs like the Next Generation Air Transportation System (NEXT GEN) in the United States and the Single European Sky Air Traffic Management Research (SESAR) (Scovel & General, 2013), in Europe have as their primary goal the enhancement of the air traffic management system. As a result, numerous studies were started in an effort to automate and optimize the global air traffic control system (Bolić & Ravenhill, 2021).

In order to achieve a safe, orderly, and efficient flow of air traffic on and around an aerodrome with the goal of preventing collision, aerodrome controllers are required to provide information and clearances to aircraft under their control. In order to accomplish these goals, they must anticipate and assess the potential risk of a future situation. In these studies, three variations of an algorithm for resolving the taxi scheduling problem are devised and examined (Jiang et al., 2015). These algorithms are employed in the tactical scheduling of taxis. All three variations involve rolling horizon algorithms that divide the problem into sets of a limited number of planes. The reactions to the smaller inquiries are combined to form a schedule for the entire day. A formulation of Mixed Integer Linear Programming is used to solve the sub problems. The first two variations divide the collection of aircraft into smaller problems by dividing it into specified time periods. An algorithm with a sliding window is the third variation. A busy day at Amsterdam Airport Schiphol was used as a test scenario. This problem instance involves 406 airplanes that need to be scheduled in 5 hours. The individual ideal taxi time is used as a lower bound for the found solution. By using the technique of optimization, the average delay was reduced from 20% to 2% (BENADDY & KRIT, 2018).

With the planned air traffic controllers at the remote tower center (RTC), made headlines. They gave a presentation on a general optimization framework design for the RTC's staff planning automation. Subsequently, they emphasized the issues encountered with actual airport flight schedules and demonstrated the best shift assignments for five Swedish airports selected for remote access (Cantone et al., 2011). One of the operational and technological solutions that Single European Sky ATM Research (SESAR) has provided for implementation is the Remote Tower Service (RTS). This revolutionary idea, which makes it feasible to manage multiple airports from a single distant center, will drastically alter how operators deliver air traffic services. An air traffic controller in such a situation works at the Remote Tower Center (RTC) in a position known as a "multiple position," meaning that he or she is able to manage two or more airports from a single Remote Tower Module (controller working position) (Kearney et al., 2020).

Mevlüt Uzun developed a method of air traffic control operator tactical trajectory prediction automatic movements based on takeoff weight inaccuracy (Uzun et al., 2017). Based on the aircraft's negotiation in a dynamic scenario modeled under the Rubinstein protocol (2015) and collaborative decision making (CDM) principles, Victor Filincowsky Ribeiro suggested a collaborative decision making model to enable efficient departure sequence (Ribeiro et al., 2015).

Among the responsibilities of an En-route air traffic controller are the removal (or minimization) of aircraft conflicts by adjusting the longitudinal or vertical distance between aircraft, modifying the aircraft's velocity, and using vectoring to deviate from risk regions. The En-route air traffic control system has undergone a great deal of historical innovation and research, including the following: four-dimensional trajectory control concepts, automated En-route air traffic control (AERAC), user request evaluation tool (URET), verification of separation and resolution advisory (VERA) (Munoz et al., 2013), En-route air traffic organizer (ERATO) (Özgür & Cavcar, 2008), program for harmonized ATM research in Europe (PHARE) (Philipp), human machine interface (HMI), medium term conflict detection (MTCD), highly interactive problem solver (HIPS), and tactical load smoother (TLS)

(Ehrmanntraut, 2010). D. S. A. N. L. E. G. a. V. D.Alexandre d'Aspremont proposed an optimal path planning for air traffic flow management to minimize system latency imposed on by unpredictable weather conditions, capacity limitations, or sector saturation as shown in the (figure 1.3) (d'Aspremont et al., 2006).

Through the use of a stationary Markov chain to describe both the sector capacity limitations and weather patterns, the optimal path planning problem is solved. Every network node and weather pattern have an ideal path generated by the algorithm. In order to minimize the anticipated delay, this method offered a set of the best choices for a single aircraft that begins traveling in the direction of its destination along a particular path. The model was then expanded to include multiple aircrafts.

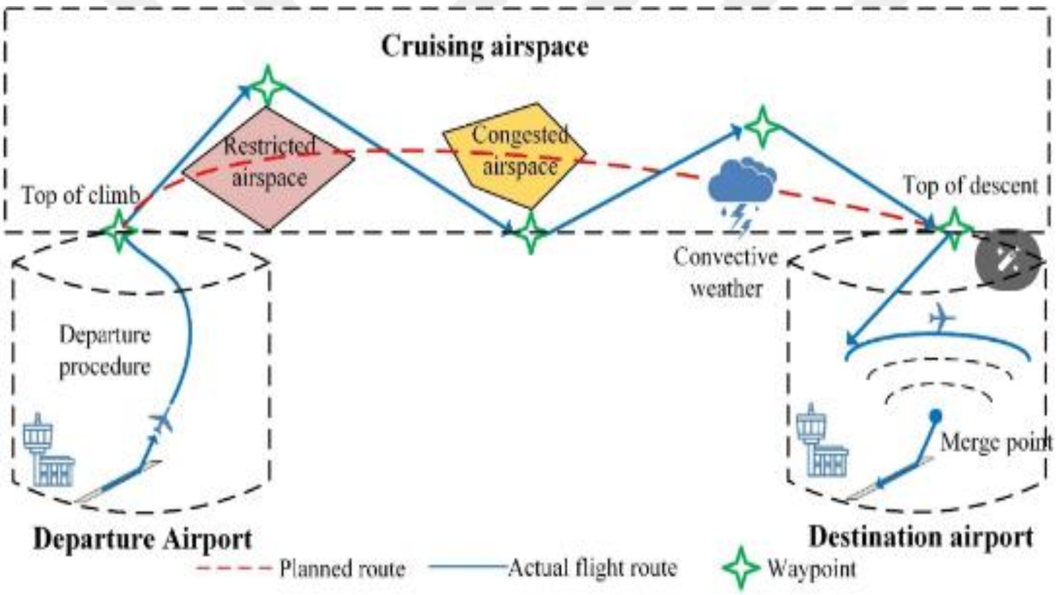

Figure 1.3: The trajectory of the aircraft and potential causes of inefficient flight

Using Multi Objective Trajectory Optimization (MOTO) algorithms, R. S. M. K. Alessandro Gardi presented a 4-dimensional Trajectory Optimization Algorithm for Air Traffic Management Systems (Gardi et al., 2016). MOTO was developed for the automation-assisted re-planning of 4-dimensional Trajectories (4DT) when unanticipated perturbations occur at strategic and tactical online operational timeframes. C. H. F. M. E. R. K Agnaldo Volpe Lovato offered a control idea that relies on adjusting an aircraft's longitudinal speed when it is in cruise mode without altering its course (Lovato et al., 2018). This method makes use of two series-arranged fuzzy models. The first problem consists of five flight levels, each with two aircraft, giving each aircraft more freedom to accelerate or decelerate. The second strategy offers a systematic way to set the acceleration to be applied in each aircraft over time based on the dynamic behavior of the conflict level (Lovato et al., 2018). The first strategy provides a metric to quantify the level of longitudinal conflict between two aircraft.

Future ATM Concepts Evaluation Tool (FACET) is a software application that can generate and analyze thousands of aircraft trajectories in a short amount of time. It gives researchers a simulation environment to test complex ATM concepts in an early stage (figure 1.4). The tool predicts the flight paths for every kind of aircraft during the climb, cruise, and descent phases using airspace models, meteorological information, and flight schedules (Bilimoria et al., 2001).

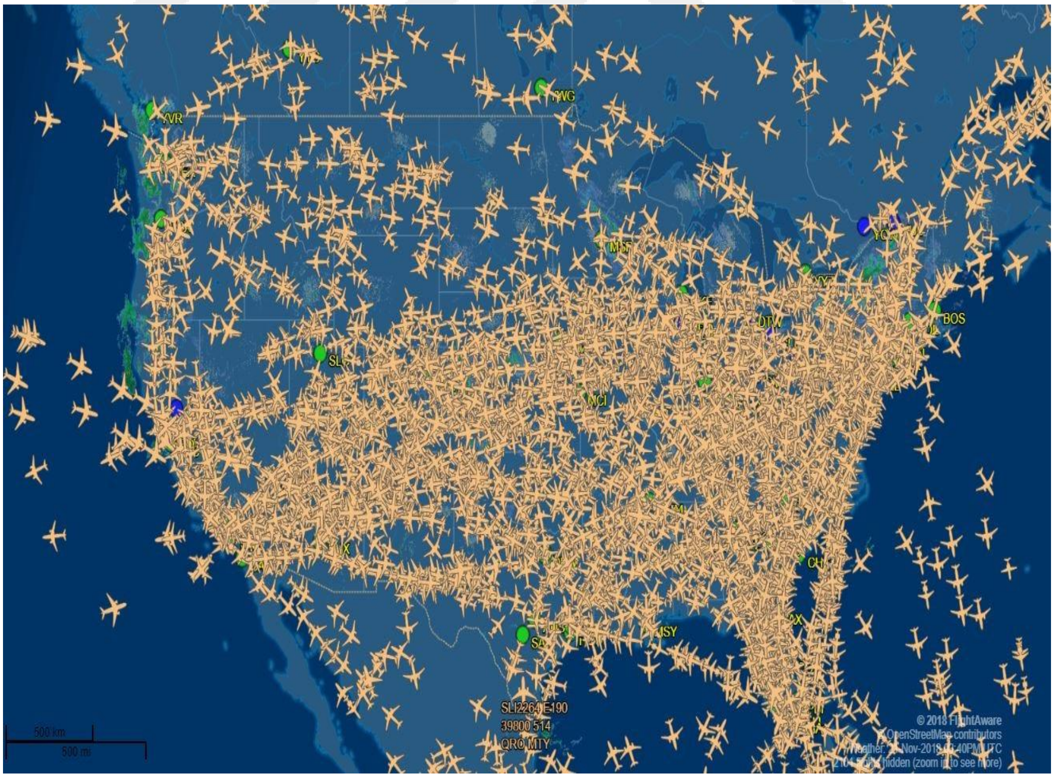

Figure 1.4: Future ATM concepts evaluation tool (FACET).

The air traffic control system assimilates a number of modern automation techniques and technologies, some of which are listed below: commercial processors, color raster displays, advanced software languages (ADA, C++), commercial databases (Postgrad, SQL), data mining, and standard database access languages. Figure 1.4 (Bilimoria et al., 2001) shows Future ATM concepts evaluation tool (FACET). Open system LAN-based architecture, as noted in Handbook for Networked Local Area Networks in Aircraft.

Numerous optimization techniques are used in studies aimed at enhancing air traffic control systems to address problems that arise in this domain. Perhaps may notify you to the following: Reinforcement learning (RL), Mixed Integer-linear programming, Multi-agent system (MAS), Routing Algorithm, Genetic algorithms, First-in-First-out(FIFO), Branch-and-Bound Mixed integer-linear programs, which occur naturally in many applications, are linear programs in which certain variables must take integer values (Jiménez, 2012). The same method used to solve integer problems is also used to solve mixed integer-linear programs, or vice versa. An example of an algorithm that can take use of the linear relaxation is the branch-and-bound algorithm, which restricts its branching mechanism to integer variables.

A Multi-Agent System (MAS) describes itself as a network of interconnected entities (agents) that collaborate to solve challenges that exceed the individual capacities or expertise of each entity (agent). The fact that agents in a multi-agent system collaborate suggests that individual agents will need to work together in a particular way. The designation, potential classifications, etc., are considerably more frustrating than in the case of agents since the concept of cooperation in MAS is, at best, ambiguous and, at worst, extremely inconsistent. This makes any attempt to present MAS as a difficult problem challenging. Figure 1.5 shows typology of collaboration serves as the foundation for the MAS classification system (Hill et al., 2005).

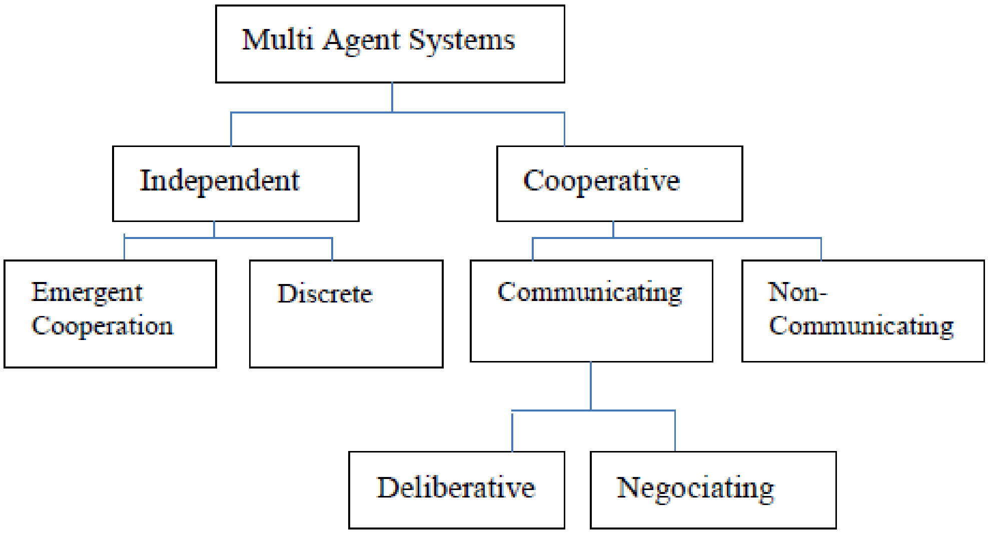

Figure 1.5: Topology of MAS Cooperation

Research on air traffic control systems has made human manual labor easier, but there is no denying that more scientific study is required in this area in order to achieve the goal of automated air traffic management.

According to Banavar Sridhar, Shon R. Grabbe, and Avijit Mukherjee (Sridhar et al., 2008), Air traffic controllers employ decision-making tools to carry out the conflict detection and resolution task, which is known as "separation assurance." The planning of aviation traffic to prevent going over airport and airspace capacity while efficiently utilizing available capacity is known as traffic flow management (TFM). Under the current system, TFM is disorganized, multi-level, and procedure-oriented as shown in figure 1.6 below.

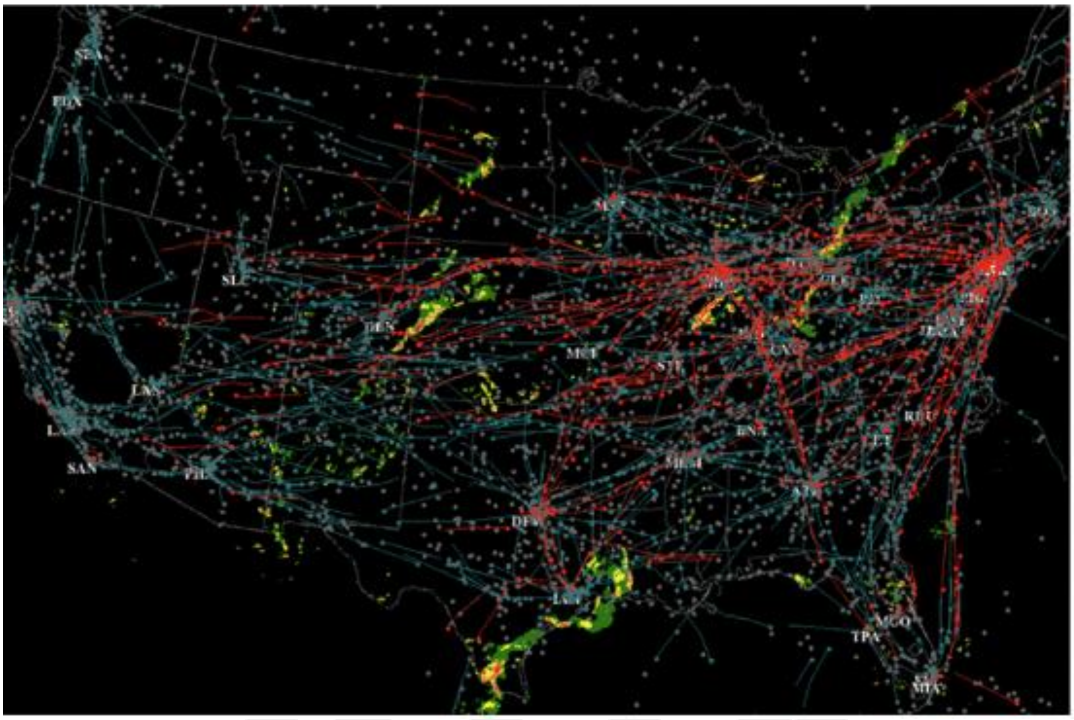

Figure 1.6: Traffic display showing flights that are on time in gray, those that are delayed by 15 minutes to 2 hours in blue, and those that are delayed by more than 2 hours in red.

The TFM problem's complexity and the length of the planning interval naturally divide the problem into national TFM decisions made at the Command Center, which provide guidance to centers or groups of centers (regions), and regional TFM decisions made within the regions. Local TFM plans are tailored to specific regions, offering greater detail, focusing on shorter time frames, and relying on more accurate traffic and weather data.

1.5 Airspace Structure and Classification

Airspace structure and classification refers to the organization and classification of airspace over a country or region to ensure safe and efficient air traffic management. This involves dividing airspace into different classes based on factors such as altitude, traffic density and the type of aircraft operating there.

1.5.1 Airspace Classification

Airspace classification is a system for dividing the world's navigable airspace into three-dimensional segments (Couluris et al., 2003), each with specific rules and regulations for aircraft operations. This system ensures the safe and efficient movement of air traffic by separating aircraft based on factors such as speed, altitude, and purpose. It is divided in several classes which is shown in figure 1.7 (Frolow & Sinnott, 1989), (Elenkov et al., 2019).

	Class A	Class B	Class C	Class D	Class E	Class G
Entry Requirements	ATC clearance	ATC clearance	Prior two-way communications	Prior two-way communications	Prior two-way communications*	Prior two-way communications*
Minimum Pilot Qualifications	Instrument Rating	Private or Student certification—local restrictions apply.	Student certificate	Student certificate	Student certificate	Student certificate
Two-Way Radio Communications	Yes	Yes	Yes	Yes	Yes, under IFR flight plan*	Yes*
Special VFR Allowed	No	Yes	Yes	Yes	Yes	N/A
VFR Visibility Minimum	N/A	3 statute miles	3 statute miles	3 statute miles	3 statute miles**	1 statute mile†
VFR Minimum Distance from Clouds	N/A	Clear of clouds	500' below, 1,000' above, 2,000' horizontal	500' below, 1,000' above, 2,000' horizontal	500' below,** 1,000' above, 2,000' horizontal	Clear of clouds†
VFR Aircraft Separation	N/A	All	IFR aircraft	Runway operations	None	None
Traffic Advisories	Yes	Yes	Yes	Workload permitting	Workload permitting	Workload permitting
Airport Application	N/A	• Radar • Instrument approaches • Weather • Control tower • High density	• Radar • Instrument approaches • Weather • Control tower	• Instrument approaches • Weather • Control tower	• Instrument approaches • Weather	• Control tower

*Exception: temporary tower or control tower present
**True only below 10,000 feet
†True only during day at or below 1,200 feet AGL (see 14 CFR part 91)

AGL—above ground level
FL—flight level
MSL—mean sea level

Figure 1.7: Classification airspace

Visual Flight Rules (VFR)

Applies when weather conditions are good enough that the pilot can navigate and control an aircraft with reference to the ground and other landmarks visually. It usually requires a minimum of visibility and distance from clouds and operates in all the classes of airspace.

Instrument Flight Rules (IFR)

Are the regulations and procedures whereby a pilot conducts flight by reference to instruments that indicate aircraft attitude, altitude, and velocity rather than by visual reference to the ground.

Class A Airspace: This is the most tightly controlled airspace and is used by commercial jets and other large aircraft. It extends from an altitude of 18,000 feet above sea level (ASL) to a flight level (FL) of 600. In Class A airspace, all aircraft must be controlled by Air Traffic Control (ATC) and must follow specific flight plans. Requires aircraft to operate under Instrument Flight Rules (IFR) and maintain constant communication with air traffic control. The planning algorithm needs to strictly adhere to the IFR rules and coordinate with ATC, increasing the complexity. It also allows for efficient high-altitude flight. Aircraft can fly at their optimal cruising altitudes, reducing fuel consumption and flight times. Controllers can also utilize advanced technologies like ADS-B (Automatic Dependent Surveillance-Broadcast) to optimize spacing and minimize delays. Optimal path planning and tracking in ATC significantly enhance the safety, efficiency, and capacity of Class A airspace. They ensure that aircraft are managed in a way that maximizes the use of available airspace, reduces environmental impact, and maintains high safety standards.

Class B airspace: This airspace surrounds major airports and is used by commercial and general aviation aircraft. It reaches 10,000 feet above sea level. In Class B airspace, all aircraft must communicate with ATC and must follow specific procedures for taking off, landing, and flying within the airspace. This airspace is highly regulated, with specific requirements for aircraft operations, including altitude, speed, and communication procedures. Optimal path planning in Class B airspace involves balancing various factors, including safety, efficiency, and predictability. The planning algorithm must consider the specific rules and procedures for each class, as well as the potential for conflicts with other aircraft.

Class C airspace: This airspace is less restrictive than Class B airspace and is used by a combination of commercial, general aviation, and military aircraft, which extends from the surface to 4,000 feet ASL. In Class C airspace, aircraft are exposed to ATC when operating at altitudes below 2,500 feet ASL and must follow specific procedures for takeoff, landing, and flight within the airspace.

Class D airspace: This airspace is the least restrictive and is used by a variety of aircraft, including small private jets, gliders, and helicopters. This extends from the surface to 2,500 feet ASL. In Class D airspace, aircraft are not required to make contact with ATC, but they must follow specific visual flight rules (VFR) and must avoid other aircraft.

Class E airspace: This airspace is uncontrolled airspace and is used by all types of aircraft. It extends from the surface to FL 18,000. In this class, aircraft are not required to come into contact with ATC, but they must follow specific VFR rules. The planning algorithm has more flexibility in terms of routing, but must still account for potential conflicts with other aircraft and obstacles.

Different airspace classifications have impacts of impose varying restrictions on aircraft operations, influencing the optimal path planning. For example, Class A airspace requires instrument flight rules (IFR) and constant communication with air traffic control, while Class G airspace allows for more flexibility.

Class G airspace: Airspace not classified as Class A, B, C, D, or E. Class G airspace is not controlled by ATC except when associated with a temporary tower.

1.5.2 Airspace Structure

Airspace structure refers to the way airspace is organized and managed to ensure the safe and efficient operation of aircraft. This involves dividing the airspace into different classes, each with its own set of rules and regulations (Holland et al., 1973).

Controlled airspace

Is a general phrase that includes the several classes of airspace (class A, class B, class C, class D, and class E airspace) as well as the specific areas where IFR and VFR flights get air traffic control services based on airspace classification. En-route airways, terminal control areas, and the airspace around the airport are usually considered.

Uncontrolled airspace

This is airspace that does not provide ATC services and pilots are responsible for maintaining safe separation from other aircraft. These are typically rural areas and airspace located at higher altitudes.

1.6 The outline of the Thesis

In Chapter 1, history of air traffic control, problem definition on the existing air traffic control systems, summary of the related literature review on the existing ATC systems, airspace structure and classification, motivation, and the outline of the thesis. In Chapter 2, Air traffic management (ATM), navigation and communication systems, and collision avoidance. In Chapter 3, Weather and environmental considerations, human factors and safety. Chapter 4, Mathematical model and control strategy. Substantial simulation study is discussed in Chapter 5. In the final chapter, conclusion and future work are summarized.

CHAPTER 2

AIR TRAFFIC MANAGEMENT (ATM)

By optimizing path planning, air traffic management (ATM) in air traffic control comprises the strategic coordination and planning of aircraft trajectories inside airspace to maximize capacity, safety, and efficiency (Menon & Park, 2016). In order to find the best routes for aircraft, sophisticated algorithms and decision-support systems are used. A number of factors, including weather, airspace congestion, aircraft performance, fuel efficiency, and environmental concerns, are taken into consideration. ATM uses advanced path planning techniques to reduce fuel consumption, lessen environmental impact, increase overall airspace capacity and safety, and minimize aircraft delays. This makes air travel more efficient and affordable. There are multiple important aspects to comprehend when it comes to optimal path planning and air traffic management (ATM) in air traffic control (ATC). The safe, cost-effective, and efficient management of air traffic and airspace through the provision of facilities and seamless services in cooperation with all stakeholders, involving both airborne and ground-based functions. This includes air traffic services, airspace management, and air traffic flow management.

2.1 Air Traffic Services (ATS)

The overarching goals of ATS are to maintain safe and orderly traffic flow, which is made possible by the air traffic control (ATC) service, as well as to supply flight crews with the information they need through the flight information service (FIS) and, in the event of an emergency, alert the relevant authorities (such as SAR) (alerting service) (Doc, 1992). Air traffic controllers are primarily responsible for ATS. Their primary responsibilities include preventing collisions by enforcing suitable separation standards, issuing prompt clearances and instructions to maintain an orderly flow of air traffic, and accommodating crew requests for preferred levels and flight paths.

2.2 Air Traffic Flow Management (ATFM)

Air Traffic Flow Management (ATFM) is a system used to optimize the flow of air traffic by planning optimal paths for aircraft and enhances safety by managing traffic demand against available capacity, especially in constrained environments within the airspace system (Rosenow et al., 2019). While balancing demand and capacity, ATFM coordinates and optimizes aircraft flow to prevent overcrowding, reduce delays, and improve overall efficiency. It ensures optimal traffic flow when demand exceeds the capacity of the air traffic control system. Improving capacity is an integral part of ATFM, as it strives to enhance the flow of air traffic at an optimal rate while adhering to capacity limits. It aims to improve safety, efficiency, and capacity of airspace utilization. It involves measures such as adjusting departure times, rerouting flights, and managing airspace capacity to optimize traffic flow. ATC capacity, which is measured in terms of the number of aircraft that enter a particular area of the airspace in a given amount of time, indicates the system's ability to provide service. In addition to helping ATC fulfill its primary goals, ATFM facilitates the most effective use of airport and airspace resources as it requires coordination and collaboration between airspace users and ATC units in order to be effective. There are a number of factors that can prevent an ideal flow of air traffic, including competing user demands, limits in the air navigation system, and unforeseen weather. When the ATC system is unable to handle the volume of air traffic, relieving measures such controlling air traffic flow will need to be taken into account. Such measures often lead to the following: aircraft operator economic and fuel penalties, flight schedule disruptions, in-flight holdings, rerouting and diversions, prior flight delays, passenger dissatisfaction, congestion on aerodromes. ATFM is done in three phases (Sridhar et al., 2008).

- **Planning:** This involves Strategic planning, pre-tactical, and tactical operations for analyzing demand and capacity, identifying potential conflicts, and developing strategies to manage the flow of traffic. The ATC unit notifies the ATFM unit when traffic demand is anticipated to surpass a specific sector's or aerodrome's capacity, enabling the application of suitable limitations. Expected delays and limits are also communicated to affected operators.

- **Implementation:** This phase involves putting the ATFM plan into action, issuing instructions to airlines and pilots, and monitoring the flow of traffic.
- **Monitoring:** This phase involves continuously monitoring the flow of traffic and making adjustments to the ATFM plan as needed.

2.3 Airspace Management (ASM)

ASM in air traffic control involves optimizing flight paths to ensure efficient use of airspace, catering to both civil and military users. It encompasses allocating airspace through routes, zones, and flight levels. ASM is categorized into three levels: strategic (ASM1), pre-tactical (ASM2), and tactical (ASM3) (Mihetec et al., 2011). ASM1 involves periodic reviews of airspace usage, ASM2 focuses on planning and coordination, while ASM3 handles real-time operations. These levels ensure the efficient and safe movement of aircraft within designated airspace.

ASM contributes to improving air traffic safety and efficiency in several ways:

- **Conflict avoidance:** By optimizing flight paths and airspace allocation, ASM helps avoid conflicts between aircraft, reducing the risk of mid-air collisions and enhancing safety.
- **Efficient routing:** ASM facilitates the efficient routing of aircraft, minimizing delays and fuel consumption. This not only reduces operational costs for airlines but also decreases environmental impact through lower emissions.
- **Flexible use of airspace:** ASM supports the flexible use of airspace, allowing for dynamic adjustments based on traffic demand and changing conditions. This agility enhances the overall efficiency of air traffic management.

- **Collaborative decision making:** ASM promotes collaborative decision-making among air traffic control authorities, airlines, and other stakeholders.

By incorporating optimal path planning, ASM ensures that aircraft follow routes that are not only efficient in terms of time and fuel but also conducive to maintaining safe separation between flights.

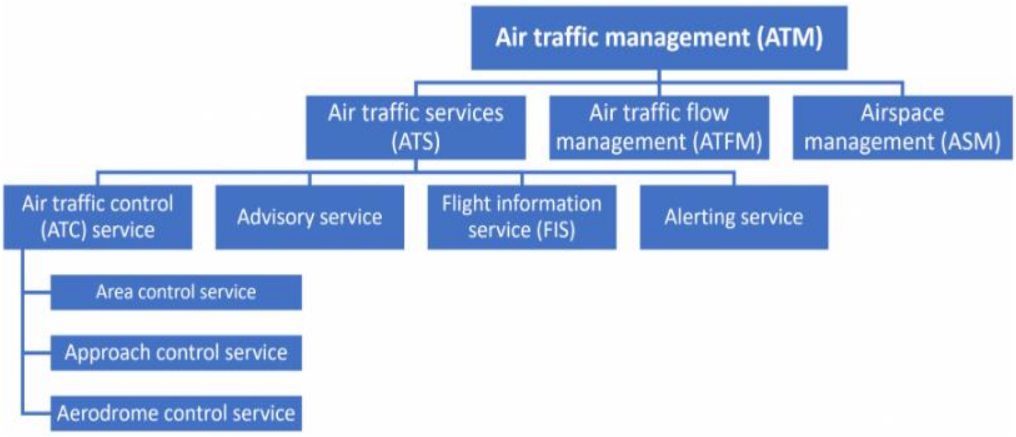

Figure 2.1: ATM structure

2.4 Collaborative Decision-Making (CDM)

CDM in air traffic management (ATM) involves stakeholders like airlines, airports, and air traffic management organizations working together to optimize air traffic flow. It enhances communication, coordination, and information sharing among these parties, leading to improved efficiency and safety. CDM in ATM offers several benefits, including reduced delays, increased airspace capacity, and improved fuel efficiency (Vail et al., 2015). It promotes a shared understanding of the air traffic situation and enables stakeholders to make informed decisions collectively, resulting in smoother and more efficient air traffic management. CDM in air traffic operations enables stakeholders to share information and make informed decisions, leading to optimized resource utilization and improved situational awareness. By providing a shared platform for information sharing, CDM prioritizes safety and promotes collaboration and coordination, reducing the risk of incidents and accidents. CDM facilitates real-time data exchange and coordination among air traffic controllers, airlines, and airport operators which allows for proactive planning and adjustments to flight schedules, reducing delays and improving turnaround times (Sikirda et al., 2021).

Figure 2.2: Collaborative Decision-Making process

2.5 Navigation and Communication Systems

Navigation and communication systems involves use of several sensors to help pilots and controllers to deal with air traffic management, this describes the use of systems and technology to manage aircraft movement inside airspace. In order to guarantee secure, effective, and well-organized air traffic control, it entails the integration of navigation and communication technologies. Finding the most effective and efficient routes for aircraft to fly is the goal of optimal path planning, which is a crucial component of air traffic management (Elfatih et al., 2023).

Pilots can safely travel across airspace by using navigation systems, which give them the required information to identify their position. These systems include satellite-based navigation systems like global positioning system and ground-based navigation aids like VHF Omnidirectional Range (VORs), and Instrument Landing Systems (ILSs) (Eltahier & Hamid, 2017).

Effective communication between pilots and air traffic controllers ensures situational awareness and coordination. VHF radios, ADS-B (Automatic Dependent Surveillance-Broadcast), and ACARS (Aircraft Communications Addressing and reporting system) are some examples of these systems (Smith, 2010). The significance of communication and navigational systems in air traffic control, with an emphasis on the best possible route planning to improve air travel efficiency, safety, and fuel economy.

2.5.1 Navigation Systems

Systems used to determine the position, orientation, and movement of aircrafts that helps pilots to deal with air traffic. These systems involves sensors like ILS (Instrument Landing System), Inertial Navigation System (INS), Global Navigation Satellite Systems (GNSS), VOR (VHF Omnidirectional Range), DME (Distance Measuring Equipment).

A. Inertial Navigation Systems (INS)

It a self-contained device that comprise of an inertial measurement unit (IMU) and computational unit. The IMU detects the angular rate and acceleration of the aircraft and typically consists of a 3-axis accelerometer, a 3-axis gyroscope, and occasionally a 3-axis magnetometer. Given an initial starting position and attitude, the computational unit utilized to determine the system's velocity, position, and attitude based on the raw measurements from the IMU. For the purpose of facilitation in the computation of ideal trajectories, INS offers precise and up-to-date information on an aircraft's current position. It is especially helpful in situations when there may not be as many external navigational aids available. Accelerometers and gyroscopes are used by INS to measure the vehicle's angular velocity and linear acceleration respectively as shown in figure 2.3 (Groves, 2015). After that, the data are integrated over time to determine the location and orientation of the vehicle with respect to a predetermined starting point. Short-term accuracy of INS is quite high, but long-term drift in the sensors can cause mistakes to build up. Integrating INS with other navigation systems, such GPS, which provide precise position data helps reduce drift. Inertial navigation system/GPS (INS/GPS) integration is the term for this combination of INS and GPS, which is commonly utilized in contemporary navigation systems (Mahmoud & Trilaksono, 2018). When GPS signals are scarce or unstable, as they are underground, underwater, or in crowded areas, INS/GPS integration offers precise and trustworthy navigation information.

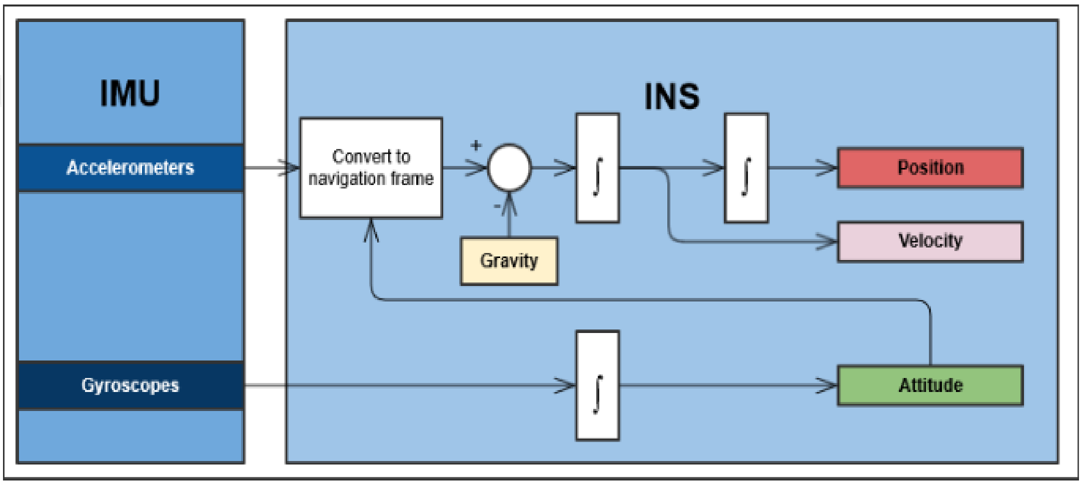

Figure 2.3: Inertial Navigation Systems (INS)

B. Global Navigation Satellite Systems (GNSS)

Is network of satellites used for locating and navigation that broadcasts time and orbital data. Satellites deliver signals to Earth-based receivers to enable GNSS to function. The signals are used by the receivers to determine their time and position. The quantity of satellites in view and the signal quality determine the accuracy of position and time information. GNSS enables the use of waypoints (geographic coordinates that define a flight path), allowing for precise navigation along predefined routes as shown in figure 2.4 (Sabatini et al., 2017). By improving aircraft positioning accuracy, GNSS aids in the creation of ideal routes. It is extensively utilized for navigation and route planning for both in-route and terminal operations.

Approach and landing: During approach and landing, aircraft can obtain exact location and velocity data. By using this information, the aircraft may avoid obstructions and make sure it is on the proper glide path.

Takeoff and departure: GNSS is used to deliver precise location and velocity data to aircraft during these phases of flight. Considering this information, the aircraft may avoid obstructions and make sure it is on the right course.

Surveillance: The position and velocity of planes are tracked using GNSS. Air traffic control uses this information to govern aircraft flow and maintain aircraft safety.

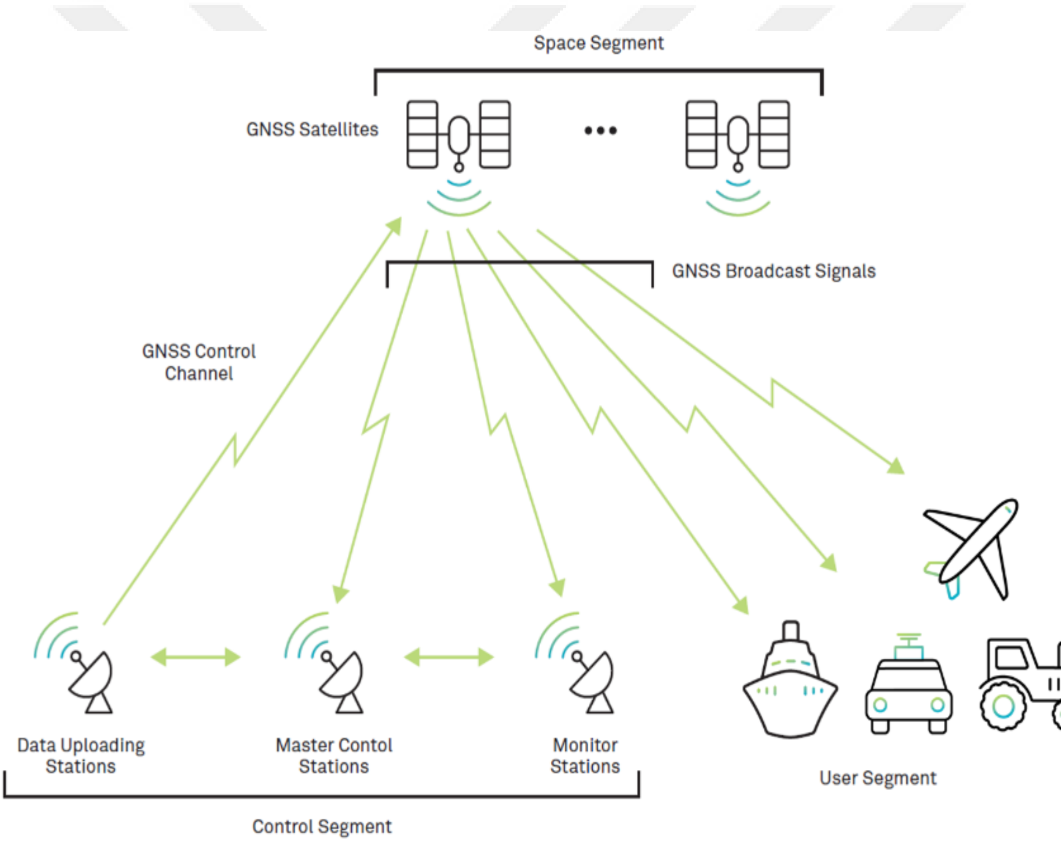

Figure 2.4: Global Navigation Satellite Systems (GNSS)

C. Ground-Based Navigation Aids

Systems that assist airplanes in navigating their position and path in relation to the ground. They can be used to help pilots avoid obstructions and terrain in addition to giving them information about their position, altitude, and speed. Ground-based navigation aids come in a multitude of forms, each with unique benefits and drawbacks (Ostroumov et al., 2018).

D. VORs (VHF Omnidirectional Range)

Are short-range radio navigation system that enables aircraft with a receiving unit to determine their position and stay on course. VORs are used in conjunction with other navigation systems, such as GPS, and DME (Distance Measuring Equipment) to provide accurate and reliable navigation information show in figure 2.5 (Frezza et al., 2021).

Figure 2.5: VORs (VHF omnidirectional Range)

E. Non-Directional Beacons (NDBs)

Are radio beacons mounted on the ground that send out a signal in all directions but don't give the station any information about the aircraft's bearing as shown in figure 2.6 (Pitor et al., 2014). The direction to the NDB station can be found using the aircraft's automatic direction finder (ADF), which can then be utilized for navigation to or from the station.

Figure 2.6: Non-directional beacons (NDBs)

2.5.2 Communication Systems

Systems that enable monitoring and management of air traffic, thereby ensuring that aircraft can safely navigate through controlled airspace. These includes sensors like Very high frequency (VHF) communication and High frequency (HF), Automatic dependent surveillance-broadcast (ADS-B), Data Link Communication (Controller-Pilot Data Link Communications, Aircraft Communications Addressing and Reporting System), SATCOM (Satellite Communication).

A. Very High Frequency (VHF) Communication

Using radio waves in the very high-frequency band of the electromagnetic spectrum is known as VHF communication. Frequencies in this range span from 30- 300 megahertz (MHz). Because of their comparatively small wavelengths, VHF waves can propagate line-of-sight, which means they move in straight lines and are easily blocked by objects like hills, trees, and buildings (CHEN, 1993). In order to adopt ideal routes, VHF communication is necessary for organizing route adjustments, acquiring clearances, and handling unforeseen circumstances. Optimal path planning for VHF communication in ATC involves a multifaceted approach that ensures continuous, reliable communication between pilots and controllers. By considering coverage, interference, redundancy, altitude, dynamic routing, and leveraging advanced technologies, ATC can manage air traffic safely and efficiently. This integrated approach minimizes communication gaps and enhances overall airspace management.

B. Controller-Pilot Data Link Communications (CPDLC)

A digital communication system entitled controller-pilot data link communications (CPDLC) allows pilots and air traffic controllers to text one another. It serves as a voice communications complement and can enhance the air traffic management system's capacity, safety, and effectiveness. Without depending exclusively on voice communication, CPDLC facilitates route modifications, clearances, and coordination, helping to optimize path adjustments as shown in figure 2.7 (Bolczak et al., 2004).

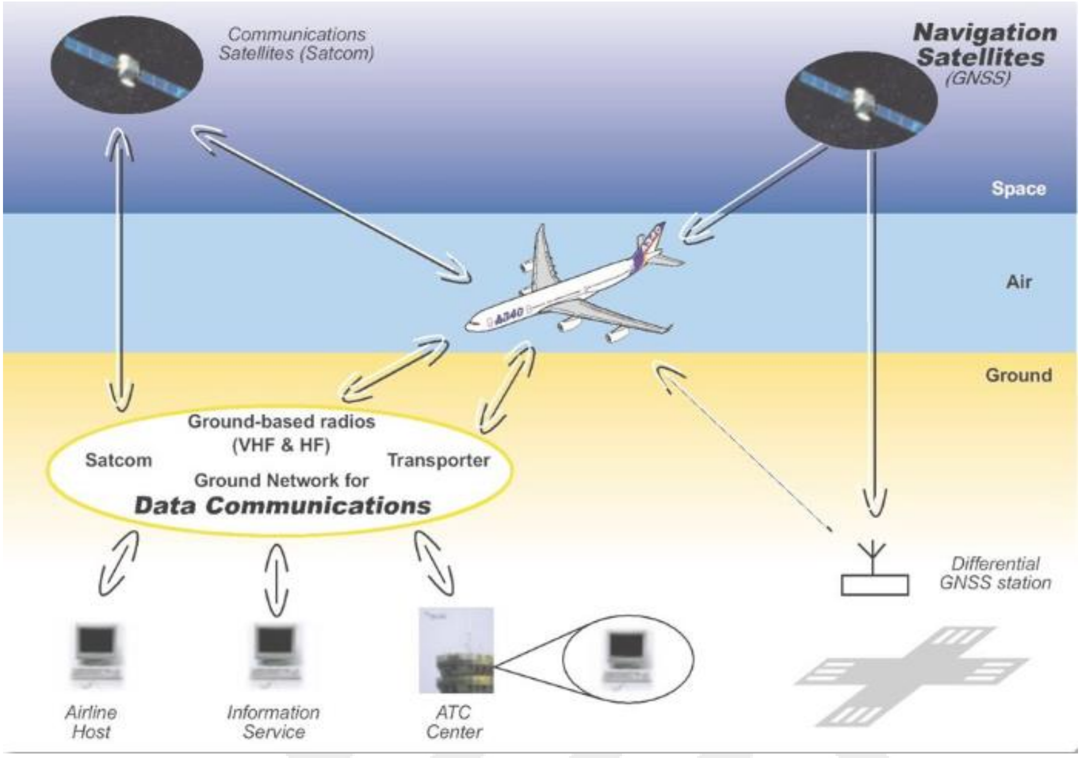

Figure 2.7: Controller-pilot data link communications (CPDLC)

C. Automatic Dependent Surveillance-Broadcast (ADS-B)

Automatic Dependent Surveillance-Broadcast (ADS-B) is a surveillance technology in aviation that allows an aircraft to determine its position via satellite navigation and periodically broadcast it, enabling other aircraft and ground stations to track the aircraft's location shown in figure 2.8 (Wang, 2015). ADS-B is based on the concept of cooperative surveillance, where aircraft voluntarily transmit their position, velocity, and other relevant data to other aircraft and ground stations. This information is then used for various purposes, including air traffic control, collision avoidance, and flight tracking. ADS-B increases the accuracy of surveillance, making it possible to track aircraft positions more precisely and promoting group decision-making for the best possible route.

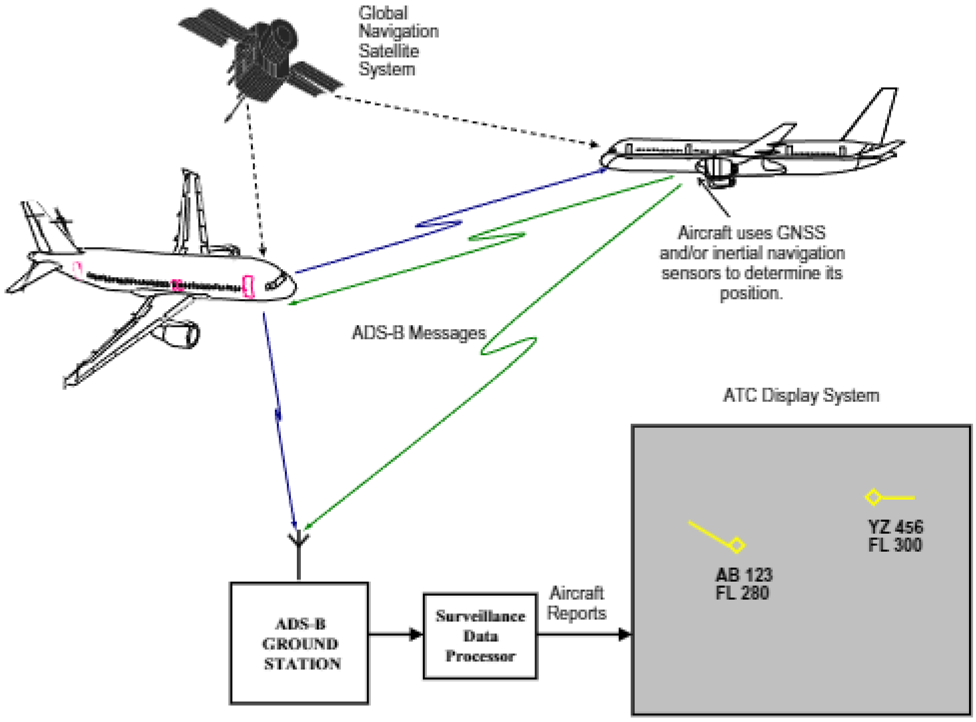

Figure 2.8: Automatic Dependent Surveillance-Broadcast (ADS-B)

Surface vehicle equipped with ADS-B can broadcast its position and other data on a regular basis without requiring byline from its recipients or knowing who they are. Insofar as it doesn't need outside assistance to send the data, the system is automatic. It's a cooperative and dependent surveillance system. For location and navigational data, aircraft avionics are required. Because all essential stakeholders must have the same equipment to participate in the system. ADS-B transmits data about the state of the aircraft, including velocity vector, altitude, horizontal position, and resolved information (Giannatto & Markowsky, 2014).

2.5.3 Integration of Navigation and Communication Systems in Path Planning

Through the integration of communication and navigation systems, aircraft are able to access a multitude of data that helps them plan their flights more efficiently. For instance, aircraft can avoid bad weather by using real-time weather data, and they can avoid crowded airspace by using traffic information (Galotti, 2019). Furthermore, air traffic control instructions can be directly transmitted from ground stations to aircraft, lowering the possibility of crashes and enhancing general safety. To optimize an aircraft's path planning, communication and navigation systems must be integrated. Air travel is made more efficient, safe, and reliable by these technologies, which facilitate communication with other aircraft and ground stations while also offering precise navigational information.

2.6 Collision Avoidance

It is evident that collision avoidance is a topic of significant interest to a wide range of contemporary transportation applications, with the aviation community being particularly interested in it. The engineering and aviation communities have been looking for technological ways to stop airplane crashes in midair since the 1950s (Williamson & Spencer, 1989). The electronics sector was asked to create an airborne collision avoidance system by the RTCA in 1955, "working through the Air Transport Association (ATA). The following year marked a terrible midair crash between two airliners over the Grand Canyon, which sharply raised the urgency for policymakers, the aviation and engineering groups, and the industry to develop a workable collision avoidance system. The subsequent national and worldwide development endeavors spanned three decades and established a foundation for the current TCAS, a restricted non-automated collision avoidance system that is the only collision avoidance mechanism mandated for all large commercial and military transport aircraft. In the late 1990s and early 2000s, several researchers proven the use of optimal control algorithms for aircraft collision avoidance in air traffic control as the best algorithm to address the problem of aircraft conflict resolution and collision avoidance (Clements, 1999). In 1995, Bowers and Cotton stated that although the systems in place now were extremely sophisticated, air traffic control would grow more sophisticated in the future due to the use of "user-preferred trajectories" and continuous automatic monitoring and control of flight trajectories from within the aircraft as well as through the appropriate air traffic control centers.

Finding "optimal" modifications to the impacted aircraft trajectories and identifying any conflicts were crucial components of these systems. Several models of collision avoidance have been studied, including Friedman's linear heading (1991), speed control avoidance strategies, and linear programming approach for solving multiple related separation problems (Friedman, 1988). Subsequently, the development of more advanced algorithms, such as optimal control and predictive modeling, control computation and minimax optimization algorithms allowed for the creation of automated collision avoidance systems that could dynamically adjust aircraft trajectories to prevent conflicts (Pistelli et al., 2011). These systems consider various factors, including aircraft performance capabilities, airspace constraints, and traffic density, to optimize collision avoidance maneuvers.

2.6.1 Cooperative Collision Avoidance (CCA)

CCA in air traffic control involves improving flight paths to prevent collisions between aircraft (Clements, 1999). It uses algorithms and techniques to calculate safe and efficient trajectories**.** CCA relies on information sharing between aircraft which allows aircraft to be aware of each other's positions and intentions, and to adjust their paths accordingly. The challenge is determining the optimal course of action for new aircraft configurations (changes in velocity and heading) in order to prevent any airspace conflicts, where a conflict is defined as the loss of the minimum required safety gap between two aircraft. Many results about robustness have been obtained from the development of the Centralized Model Predictive Control, which has also been used extensively for the cooperative control of many vehicles by enhancing the system with a binary “target state” that indicates whether the goal set is reached or not. A cooperative multi-agent model has been developed for collision avoidance in air traffic management to address the expected increase in air traffic and improve safety measures (Bollino & Lewis, 2008). The objective function consists of minimizing the of the velocity variations of aircrafts, so all possible conflicts are avoided in minimum time.

CHAPTER 3

WEATHER AND ENVIRONMENTAL CONSIDERATIONS

Optimal trajectory planning in air traffic control is significantly influenced by weather and environmental considerations. Weather conditions and environmental factors play an important role in determining the feasibility and effectiveness of a flight route (Ramée et al., 2020). Here are the details how weather and environmental considerations influence optimal path planning in air traffic control:

Safety concerns: Adverse weather conditions such as thunderstorms, turbulence, icing and poor visibility pose risks to aircraft safety. Optimal trajectory planning should prioritize flight paths that minimize exposure to dangerous weather events to ensure passenger and aircraft safety.

Aircraft Performance and Efficiency: Weather conditions, including wind, temperature, and humidity, affect the performance and efficiency of aircraft. The optimal trajectory should consider factors such as crosswinds, tailwinds and temperature gradients to optimize fuel consumption and reduce overall flight time.

Airspace capacity and congestion: Weather disruptions, such as thunderstorms can lead to airspace closures or rerouting. Optimal trajectory planning must dynamically adapt to changes in airspace capacity and congestion caused by weather events, ensuring efficient routing around affected areas.

Airport Operations: Airport weather conditions, including visibility, wind, and precipitation, affect airport operations. Optimal route planning must account for potential weather-related delays, diversions, and closures at departure and arrival airports.

Air Traffic Flow Management (ATFM): The ATFM system aims to optimize the use of airspace and manage air traffic flows. Weather considerations are important in ATFM, as adverse weather conditions may require rerouting, separation restrictions and ground delays. Optimal path planning must be consistent with ATFM strategies to maintain overall system efficiency.

Predictive models: Helps to predict weather conditions along the flight path, allowing proactive flight adjustments to avoid or minimize the impact of adverse weather conditions.

Alternative route planning: Optimal route planning involves considering alternative routes based on forecast and real-time weather conditions. Aircraft may need to deviate from planned routes to avoid areas of turbulence, strong winds or other adverse weather events, affecting the overall optimization strategy.

Environmental regulations: Environmental considerations, such as emissions reduction and noise reduction, are increasingly important in the aviation industry. Optimal route planning may involve selecting routes or elevations that comply with environmental regulations and sustainable development goals.

Communications and surveillance: Weather-related disruptions may affect communications and surveillance systems. Optimal path planning needs to take into account potential limitations in communication and surveillance range during adverse weather conditions.

Emergency Procedures: Weather-related emergencies, such as engine failure or other critical system malfunction, may require immediate changes to the planned trajectory. Optimal route planning should take into account emergency procedures, including alternative routes and diversion options. Instantly, meteorological and environmental considerations are indispensable in optimal trajectory planning in air traffic control (Mahapatra, 1999). The ability to flexibly adapt to changing weather conditions, while ensuring safety, efficiency and regulatory compliance, is essential for effective trajectory planning in complex aviation environments and dynamic.

In air traffic control (ATC), the weather and environmental factors are amongst the essential considerations as they directly affect such components of handling air flights like safety, efficiency, and also the overall management of these aerial vehicles. In different forms of environmental factors and weather condition, such as fogs and rain, the safety level should be ensured regarding the health of passengers and flights. Here are some specifics on numerous significant environmental and meteorological factors for air traffic control.

Adverse weather conditions in ATM

In the context of air traffic management, any meteorological phenomena that could jeopardize the effectiveness and safety of air travel is referred to as adverse weather circumstances. These situations could include Low visibility, Strong winds, Icing, Thunderstorms, and Tornadoes as show in the following figures 3.1, 3.2, 3.3, 3.4, and 3.5 (Di Vito et al., 2022).

Low visibility

Weather elements like fog, mist rain, snow and dust can all compromise the pilot's visibility hence reducing their ability to see other flying objects and even ground obstacles which may have a major effect on air traffic control's effectiveness and safety.

Figure 3.1: Low Visibility

Airports and air traffic control authorities use a variety of methods and technologies to minimize the effects of low visibility like reduced runway visibility minima, instrument landing systems (ILS), ground-based radar, controller training and experience.

Strong winds

Strong winds can create awkward conditions for planes or aircraft to maintain a steady trajectory and the flight, as well as creating turbulence. It may be more difficult for the aircrafts to maintain its intended flying route and altitude in severe winds due to increased drag and turbulence. This may result in lower lift, more fuel consumption, and possibly even structural stress on the aircraft. Strong winds can also have an impact on the stability of the aircraft while it is in flight or landing phase. An aircraft may encounter abrupt changes in altitude due to gusts or abrupt changes in wind direction, which could cause passengers to feel uncomfortable or possibly lose control of the aircraft.

Figure 3.2: Strong winds

Icing

Ice may collect on the wings and control surfaces of aircraft, increasing drag and reducing lift, hence causing difficulty in flight. In order to avoid icing conditions, aircraft may request to deviate from their scheduled paths, information regarding known icing places is promptly provided by controllers, and special protocols for anti- and de-icing before departure or landing.

Figure 3.3: Icing Conditions

Thunderstorms

Lightning, hail and heavy rain are produced by thunderstorms that can pose a serious threat to aircraft. Flights are rerouted to stay clear of thunderstorm cells, the application of limitations in the impacted airspace, improved communication and surveillance during thunderstorm activity.

Figure 3.4 Thunderstorms and lightning

A different aspect of monitoring thunderstorms and lightning is air traffic control (ATC). Pilots receive weather advisories and updates from ATC, which includes details on the position and motion of thunderstorms. Pilots can use this information to plan their flight routes and steer clear of dangerous weather zones.

Tornadoes

Tornado is a kind of violent storm that has the capability to cause immeasurable destruction on so many airplanes and infrastructures. When cold, dry air from the north collides with warm, humid air from the Gulf of Mexico, a tornado is created. There is an area of instability in the atmosphere as a result of warm air rising and cold air falling. Because of this turbulence, thunderstorms may arise and, under the right circumstances, a tornado may emerge.

Figure 3.5: Tornadoes

Unfavorable weather can result in accidents as well as flight delays, cancellations, and diversions. The following techniques and instruments are used by air traffic controllers to reduce the risks imposed by adverse conditions:

Weather radar: Weather radar can be used to locate hazardous weather areas and follow the path of storms.

Satellite imagery: A visual depiction of the weather over a wide area can be obtained through satellite images.

Automated weather stations: These devices can be used to gather information on the temperature, wind speed, and visibility of the present weather.

Reports from pilots: By reporting meteorological conditions they experience while in flight, pilots can assist air traffic controllers in creating a more accurate forecast of the weather.

It’s impact on air traffic control can cause delays and disruptions to flight schedules, re-routing of flights to avoid hazardous weather, increased separation between aircraft for safety, Special procedures for takeoff and landing during low visibility.

3.1 Human factors and safety in ATC

According to the (Human Factors and Ergonomics Society [HFES], it's purpose is to comprehend and improve how people interact with the diverse technology in order to improve their efficiency, safety, and usability (Salvendy & Karwowski, 2021). As it is involved in the engineering of any system, process, or product that seeks to function more effectively in harmony with a human user, HFES claims that this field is universal. A safe and effective flow of air traffic is the ultimate objective of an air traffic control (ATC) system, which is a model of a human-machine system. A vital pre-requisite for this, is the continuous supply of proficient controllers (humans) who are knowledgeable about the interaction and utilization of available technology. Since the interaction of humans and machines is a dynamic process, it is essential that humans and machines be matched effectively using the human factors data that is available in order to fully utilize the advantages of the ATC system (Inoue et al., 2012). The comprehension of human factors must be applied to both the effects of the system on the human and the effects of the human on the system in order to enhance safety and prevent accidents. To accomplish the aforementioned, controllers must also have an extensive knowledge of how the system functions while utilizing their own professional qualities. Air traffic control is a complex and critical task that involves managing the safe and efficient movement of aircraft in the sky. Human factors play a crucial role in this process, as air traffic controllers are responsible for making quick and accurate decisions based on a variety of factors, including weather conditions, aircraft performance, and traffic volume. Considering Optimal path planning, controllers can determine the most efficient and safe routes for aircraft to follow. This involves factors such as fuel consumption, flight time, and potential conflicts with other aircraft which will helps controllers reduce delays, and improve overall safety. When optimal path planning and human factors are factored into thought, air traffic management can perform better overall and make better decisions. Optimal path planning in ATC can incorporate human factors in the following ways.

User-centered design

Designing ATC systems using user-centered concepts guarantees that they are simple to use, intuitive, and supportive of human decision-making. Controllers' desire and preferences should be provided with regard when designing interfaces.

Visualization

Accurate and timely comprehension of the present situation through controllers is facilitated by the availability of clear and intuitive visualizations of airspace, aircraft trajectories, and other pertinent information. Controllers can efficiently manipulate and investigate various circumstances with the help of interactive displays.

Decision support systems

Integrating real-time data, predictions, and recommendations, the implementation of decision support systems helps controllers make the best decisions possible. These systems have the ability to evaluate complicated data and display it in a way that makes it simple for controllers to understand and take action.

Automation

Although automation might increase productivity, it's important to consider how it may impact controllers' workload and situational awareness. Automation should facilitate the decision-making processes of controllers while preserving their ability to exercise control when needed. Along with having obvious indicators of the system's status and aim, it should also be simple and easy to understand.

Training and Familiarization

For controllers to operate at their best, they must receive the appropriate training and become familiar with ATC procedures and systems. Training programs must incorporate scenarios that highlight the significance of human elements, like managing workloads, communicating effectively, and making decisions under duress.

Communication

Safe and effective air traffic management depends on effective communication between controllers, pilots, and other stakeholders. Protocols must to be established to enable unambiguous and concise communication, particularly in significant flight segments or emergency scenarios.

Workload management

To avoid cognitive overload and guarantee that controllers can keep their situational awareness; workload must be balanced. Algorithms for optimal path planning should consider the cognitive workload of controllers and adjust their help, for instance, by automating repetitive operations or prioritizing information.

Feedback and Monitoring

In order to find problems and make improvements, it is crucial to continuously monitor system performance and user input. It should be possible for controllers to offer feedback on the efficiency, usability, and potential improvement areas of the system. Systems that assist controllers in safely and effectively managing airspace while decreasing cognitive effort and optimizing situational awareness can be developed by integrating human factors concepts into optimal path planning in air traffic control. This strategy improves overall performance in ATC operations and decision-making.

CHAPTER 4

MATHEMATICAL MODEL AND CONTROL STRATEGY

This section presents the methods and computational models using MATLAB/SIMULINK environment to solve the problem of optimal path planning in air traffic control. In order to improve aircraft trajectories in a dynamic and complex airspace environment, we incorporated MATLAB optimization tools which seeks a point that minimizes the maximum of a set of objective functions.

Unicycle/point-mass model was used to simplify the analysis of an aircraft's path by treating it as a single point with mass. This allows us to focus on the essential dynamics of the aircraft's motion as initial input variables, such as its velocity, heading, longitudinal and lateral accelerations (a_t and a_n) without getting bogged down in the complexities of its physical structure and determines the control values needed to achieve optimal flight conditions.

4.1 Equations of Motion That Represents Point-Mass Model of the Aircraft

Navigation-Frame (N-Frame) or Inertial frame: Is a reference frame attached to the surface of the earth and neglect the rotaion of the Earth, $x_n = X$ and $y_n = Y$ are parallel with the North and East directions, respectively.

Body-Frame (**B-Frame)**: Is a reference frame attached to the aircraft itself. It moves and rotates with the aircraft. Velocity is align in the x direction and accelerations of aircraft are in tangential and normal directions.

The point-mass model of aircraft dynamics is a simplified approach describes the motion of an aircraft by treating it as a point mass. This model focuses on the translational motion of the aircraft without considering its rotational dynamics. The given equations provide a mathematical framework to understand the aircraft's behavior in terms of its velocity, heading angle, and position (Baruh, 1999).

$$\dot{V} = a_t - KV^2 = u_t = a'_t \tag{4.1}$$

$$\dot{\psi} = \frac{a_n}{V} = u_n \tag{4.2}$$

$$\dot{x} = V \cos \psi \tag{4.3}$$

$$\dot{y} = V \, sin \, \psi \tag{4.4}$$

u_t and u_n are supposed to be virtual inputs for dynamic system. In this condition first and second equations have linear forms. Then, one simply can design control algorithm for the system.

Where,

$\dot{V}$: The time derivative of velocity, representing the acceleration (or deceleration) of the aircraft.

a_t: The tangential acceleration component along the direction of motion. It represents the force applied by the engines to increase the aircraft's speed.

KV^2: A term representing the drag force, which is proportional to the square of the velocity. K is a drag coefficient that encapsulates factors like air density, drag coefficient, and reference area.

$\dot{\psi}$: The time derivative of the heading angle, representing the rate of turn.

a_n: The normal acceleration component, which is perpendicular to the direction of motion. It is responsible for changing the direction of the aircraft.

V: The velocity of the aircraft.

$\dot{x}$: The time derivative of the x-coordinate, representing the velocity component in the x-direction (north direction).

$\cos \psi$: The cosine of the heading angle, giving the proportion of the velocity in the x-direction.

$\dot{y}$: The time derivative of the y-coordinate, representing the velocity component in the y-direction (east direction).

$sin\ \psi$: The sine of the heading angle, giving the proportion of the velocity in the y-direction.

ψ: The actual heading of the system.

Equation (4.1) indicates that the change in velocity is influenced by both the tangential acceleration and a resistive force proportional to the square of the velocity.

Equation (4.2) indicates that the rate of change of the heading angle is proportional to the normal acceleration and inversely proportional to the velocity. This means that a higher velocity results in a slower change of direction for the same normal acceleration (Shneydor, 1998).

Equations (4.3 and 4.4) describe the horizontal component of the aircraft's velocity, indicating how the position in the X and Y coordinates changes over time based on the velocity and heading angle.

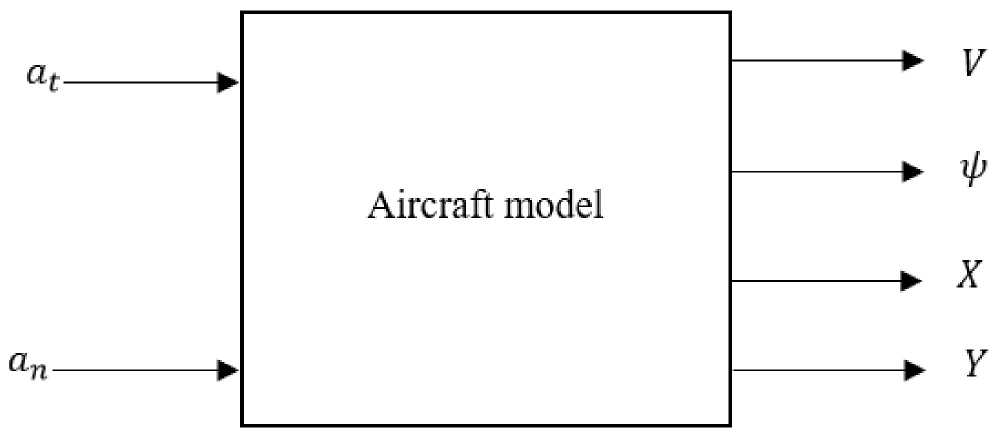

Figure 4.1: Block diagram for aircraft dynamic model

The figure 4.1 shows how the tangential and normal accelerations are used as inputs to the aircraft model to determine the speed, heading angle, and position coordinates of the aircraft.

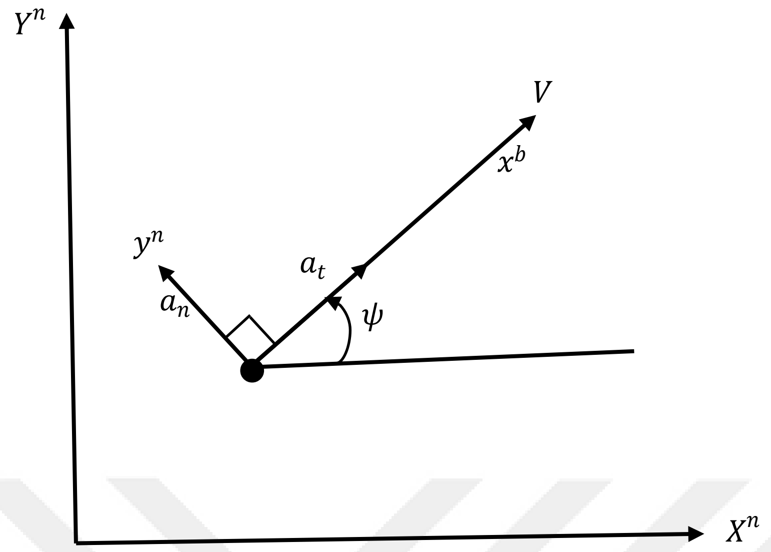

Figure 4.2: Total acceleration of aircraft in tangential and normal components.

Change in magnitude of velocity is done by tangential acceleration and direction of velocity is changed by normal acceleration. Then the aircraft will be manouvarable in horizontal plane.

The figure 4.2 describes a velocity vector **V** and its components in X and Y directions explains the decomposition of the velocity vector into its tangential and normal accelerations. It explains the kinematics and dynamics of the aircraft in 2-D plane, where understanding the changes in speed and direction of an aircraft's motion is crucial.

4.2 Velocity Control in N-Frame

Velocity control of an aircraft in the navigation frame (n-frame) involves managing the aircraft's velocity components relative to a reference coordinate system fixed to the Earth.

$$V^n = C_b^n V^b \tag{4.5}$$

V^n: Velocity of the aircraft in navigation frame.

C_b^n: Is the rotation matrix (or direction cosine matrix) that transforms vectors from the body frame (b-frame) to the navigation frame (n-frame). It accounts for the orientation of the aircraft relative to the navigation frame.

V^b: Velocity of the aircraft body.

From the equation (4.5), we ca derive the rate of change of velocity control in n-frame in following manner.

$$V^n = C_b^n V^b, V^b = \begin{bmatrix} V \\ 0 \end{bmatrix}, C_b^n = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix}$$

$$C_b^n = \begin{bmatrix} -\sin\psi & -\cos\psi \\ \cos\psi & -\sin\psi \end{bmatrix} \dot{\psi} \tag{4.6}$$

$$\dot{V^n} = \begin{bmatrix} -\dot{\psi}\sin\psi & -\dot{\psi}\cos\psi \\ \dot{\psi}\cos\psi & -\dot{\psi}\sin\psi \end{bmatrix} \begin{bmatrix} V \\ 0 \end{bmatrix} + \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} \dot{V} \\ 0 \end{bmatrix} \tag{4.7}$$

$$\dot{V^n} = \begin{bmatrix} -\dot{\psi}\sin\psi & -\dot{\psi}\cos\psi \\ \dot{\psi}\cos\psi & -\dot{\psi}\sin\psi \end{bmatrix} \begin{bmatrix} a_t \\ a_n \end{bmatrix} = C_b^n a^b, a^b = \begin{bmatrix} a'_t \\ a_n \end{bmatrix} \tag{4.8}$$

$$\dot{V^n} = \begin{bmatrix} -\dot{\psi}\sin\psi & -\dot{\psi}\cos\psi \\ \dot{\psi}\cos\psi & -\dot{\psi}\sin\psi \end{bmatrix} \begin{bmatrix} a_t \\ a_n \end{bmatrix} = C_b^n a^b, a^b = \begin{bmatrix} a'_t \\ a_n \end{bmatrix} \tag{4.9}$$

$$\dot{V^n} = C_b^n \begin{bmatrix} a'_t \\ a_n \end{bmatrix} \tag{4.10}$$

Where,

a^b:Total acceleration in the body frame.

Controlling the acceleration in the body frame involves managing a'_t, and $a_n$components to achieve desired flight dynamics, whether for maintaining level flight, executing turns, or performing landing maneuvers.

4.3 Error Velocity in the N-Frame

Refers to the discrepancy between the estimated velocity and the actual velocity in the navigation frame. This error is important to consider for accurate navigation and position estimation.

$$e_v^n = V_{com}^n - V^n \tag{4.11}$$

$$\dot{e}_v^n = \dot{V}_{com}^n - \dot{V}^n \tag{4.12}$$

$$\dot{e}_v^n = \dot{V}_{com}^n - C_b^n a^b \tag{4.13}$$

e_v^n: Defines the velocity error in navigation frame (n-frame) as the difference between the desired velocity and the actual velocity of the aircraft.

Equation (4.13) summarizes the dynamics of the velocity error in the navigation frame, highlighting the need to align the actual acceleration with the desired change in velocity to minimize the error.

For the stability of the velocity error, we consider the following error dynamic:

Using equations (4.13) and (4.14).

$$\dot{e}_v^n = \dot{V}_{com}^n - C_b^n a^b = -K_p e_v^n,$$

$$\dot{e}_v^n = -K_p e_v^n \tag{4.14}$$

Here, $K_p > 0$

Where,

K_p: This is a positive constant, known as the proportional gain. It determines the strength of the control action applied to reduce the velocity error. A larger K_p results in a more aggressive control action.

Equation (4.14), represents the stablization of the velocity error. The negative sign indicates that the control action works to reduce the error. If the velocity error is positive (actual velocity is less than desired velocity), the control action will be in the positive direction to increase the actual velocity, thereby reducing the error. Conversely, if the velocity error is negative (actual velocity is more than desired velocity), the control action will decrease the actual velocity, again reducing the error.

Then the total control acceleration in the body frame a^b will be calculated as:

$$a^b = C_n^b \left(\dot{V}_{com}^n + K_p e_v^n\right) \tag{4.15}$$

$$\begin{bmatrix} a_t - KV^2 \\ \dfrac{a_n}{V} \end{bmatrix} = C_n^b \left(\dot{V}_{com}^n + K_p(V_{com}^n - C_b^n V^b\right) = \begin{bmatrix} u_t \\ u_n \end{bmatrix} \tag{4.16}$$

When u_t and u_n from the above equation 4.16 are known, then the control inputs can be calculated as:

$$a_t = u_t + KV^2, \qquad a_n = Vu_n \tag{4.17}$$

Where,

$$0 \leq a_t \leq a_{max}^t$$

$$-a_{max}^n \leq a_n \leq a_{max}^n$$

The above saturation limits show that the aircraft cannot experience negative tangential acceleration a_t, it ensures that the aircraft maintains a positive forward velocity.

And also, normal acceleration a_n shows maximum acceptable negative and positive normal acceleration as a downward and upward acceleration relative to the flight path which indicates how sharply the aircraft can turn or maneuver in one direction or opposite direction.

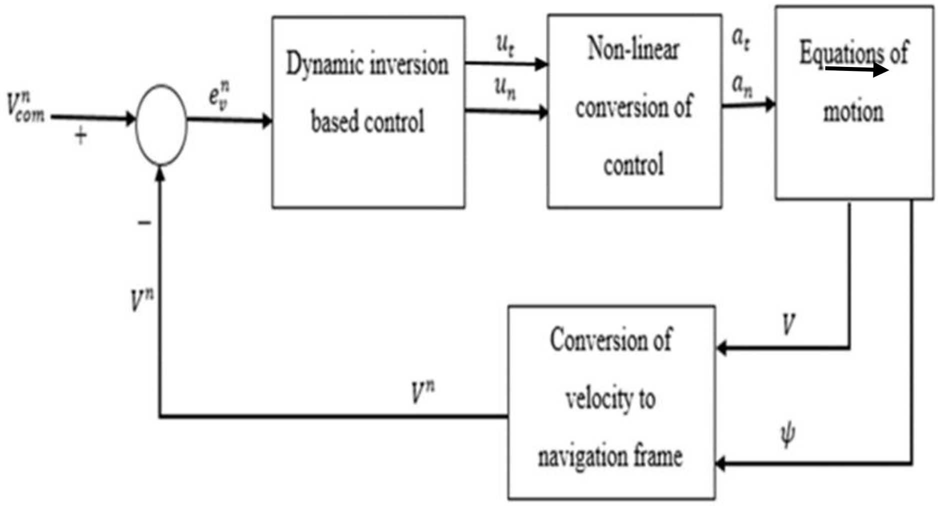

Figure 4.3: Inner loop block diagram for velocity control in n-frame

The figure 4.3 explains a control system for adjusting an aircraft's velocity based on a commanded velocity, using a dynamic inversion approach to handle the nonlinearities of the aircraft's dynamics. The system continuously monitors and adjusts the aircraft's velocity to ensure it follows the commanded trajectory.

For generating command (reference) velocity in navigation frame in y-direction, we use the following guidance strategy:

$$\dot{y} = -K_y y, K_y > 0 \tag{4.18}$$

Because above equation is a stable equation and in steady condition, y will zero.

$\dot{y}$: This represents the time derivative of y, which is the rate of change of y, with respect to time. It indicates how y is changing at any given instant.

K_y: Is the arbitrary gain for stabilizing the error in the y-direction.

The above equation (4.18) tend to reduce y to zero, then the velocity command in y-direction can be defined as:

$$V_{com}^n(\mathrm{y}) = -K_y y \tag{4.19}$$

$$\dot{V}_{com}^n(\mathrm{y}) = -K_y \dot{y} \tag{4.20}$$

Since,

$$\dot{y} = V \sin\psi$$

$$\dot{V}_{com}^{n}(\mathrm{y}) = -K_y V \sin\psi \tag{4.21}$$

Where,

V_{com}^{n}(y): Represents command velocity of the aircraft in n-frame in y-direction.

Equation 4.21 shows that the commanded velocity in the y-direction is proportional to the product of the current velocity V, the sine of the heading angle ψ, and the control gain K_y.

The negative sign indicates that the commanded acceleration in the y-direction is in the opposite direction of the current y-component of the velocity. This is often used to correct or stabilize the aircraft by reducing deviations in the y-direction.

When there is just one aircraft, we can program the velocity in x-direction as:

$$X\,(\mathrm{t}) = x_0 + V_{x0}\mathrm{t} + a_{x0}\,\frac{t^2}{2} \tag{4.22}$$

Where,

X (t): The position of the aircraft at time t.

V_{x0}: Initial velocity of the aircraft along the x-axis at time $t = 0$.

a_{x0}: Constant acceleration of the aircraft along the x-axis.

t: Time

From the equation 4.22, we can calculate the velocity of the aircraft in x-direction as follows:

$$V_x = V_{x0} + a_{x0}\,\mathrm{t} \tag{4.23}$$

Since, V_{xf} and x_f is known, then

$$V_{xf} = V_{x0} + a_{x0}\,t_f \tag{4.24}$$

$$0 = x_0 + V_{x0}t_f + t_f^2 \tag{4.25}$$

Equation 4.25 indicates that at the final time, the aircraft has to be at zero position and minimum velocity for landing.

If minimum velocity is bigger than the stall velocity, then x_0, V_{x0}, and V_{xf} are known parameters we can calculate a_{x0} and t_f as shown below:

$$t_f = \frac{-2(x_0 + V_{x0}t_f)}{V_{xf} - V_{x0}}; \quad a_{x0} = \frac{(V_{xf} - V_{x0})^2}{-2(x_0 + V_{x0}t_f)} \tag{4.26}$$

Then the reference velocity for x-direction will be:

$$V_x^{com}(\mathrm{t}) = V_{x0} + a_{x0}t; \quad \dot{V}_x^{com} = a_{x0} \tag{4.27}$$

If there is error between the desired trajectory and the current trajectory in x-direction, the following guidance algorithm can compensate it.

$$e_x = x^{com} - x \tag{4.28}$$

$$\dot{e}_x = \dot{x}\mathrm{com} - V_x^{com} = -K_x\, e_x; \;\; K_x > 0$$

$$V_{com}^n(x) = \dot{x}\mathrm{com} + K_x(x^{com} - x). \tag{4.29}$$

Then, V_{com}^n can be constructed from the equations 4.30 and 4.31 as shown below.

$$V_{com}^n = \begin{bmatrix} V_{x0} + a_{x0}t + K_x(x^{com} - x) \\ -K_y y \end{bmatrix} \tag{4.30}$$

And

$$\dot{V}_{com}^n = \begin{bmatrix} a_{x0} + K_x(V_{x0} + a_{x0}t - V_x) \\ -K_y V_y \end{bmatrix} \tag{4.31}$$

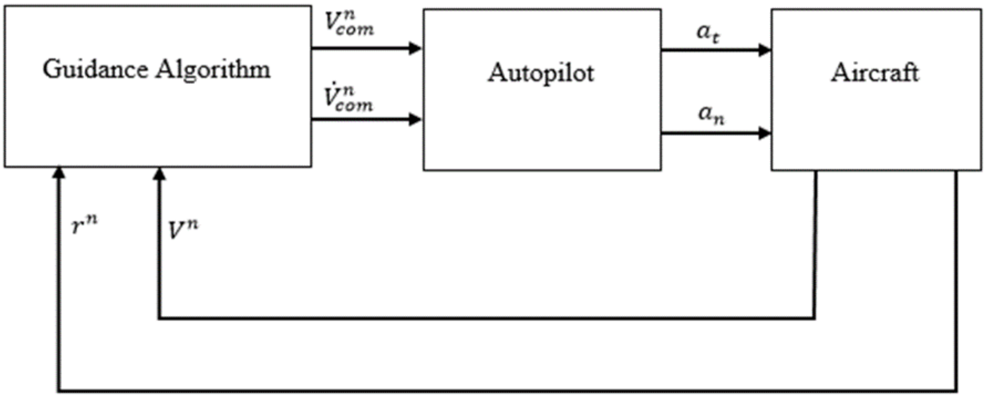

Figure 4.4: The block diagram for guidance loop.

Figure 4.4 shows how the guidance algorithm generates a commanded velocity based on the desired position and current velocity, the autopilot converts this commanded velocity into tangential and normal accelerations commands, and the aircraft responds to these commands, updating its position and velocity which are then fed back into the system to maintain the desired trajectory.

When there is more than one aircraft, the guidance algorithm uses an optimization algorithm to optimize the model in x-direction. Here, we consider a polynomial approach to do so. Any aircraft in y-direction obey the velocity command as shown from the equation (4.19). But in the x-direction, we chose a reference aircraft to compare the positions of other aircrafts with respect to the reference aircraft. Reference aircraft has lowest time to go for landing. Suppose that the position of the i^{th} aircrafts in x-direction has the following formula:

$$X_i^{com} = x_{0i} + V_{0i}t + a_{0i}\frac{t^2}{2} + J_{0i}\frac{t^3}{3!} + \dot{J}_{0i}\frac{t^4}{4!} + \cdots \qquad (4.32)$$

Where,

x_{0i}: Initial position in y-direction for the i^{th} aircraft.

V_{0i}: Initial Velocity in y-direction for the i^{th} aircraft.

a_{0i}, J_{0i} and $\dot{J}_{0i}$: Are initial acceleration and jerk and time derivative of jerk for any aircraft.

Also, suppose that the position of the reference aircraft is $X_{ref}(t)$. Now, for definition of guidance algorithm, we can define the performance index as shown following equation (4.33).

$$J = \sum_{i=1}^{m} \left(x_i - X_{ref} + id_0\right)^2 \tag{4.33}$$

Where,

J: performance index (cost function)

m: Is the number of aircrafts

X_{ref}: Is the position of the reference aircraft

d_0: Is the separation (clearance) distance between the aircrafts.

Here, we consider the $m + 1$ aircrafts in which one of them is the reference aircraft and other m aircrafts need to adjust itself relative to each other with the separation distance d_0.

As an example suppose the clearance distance between the aircrafts is 2 Km as shown on figure 4.5.

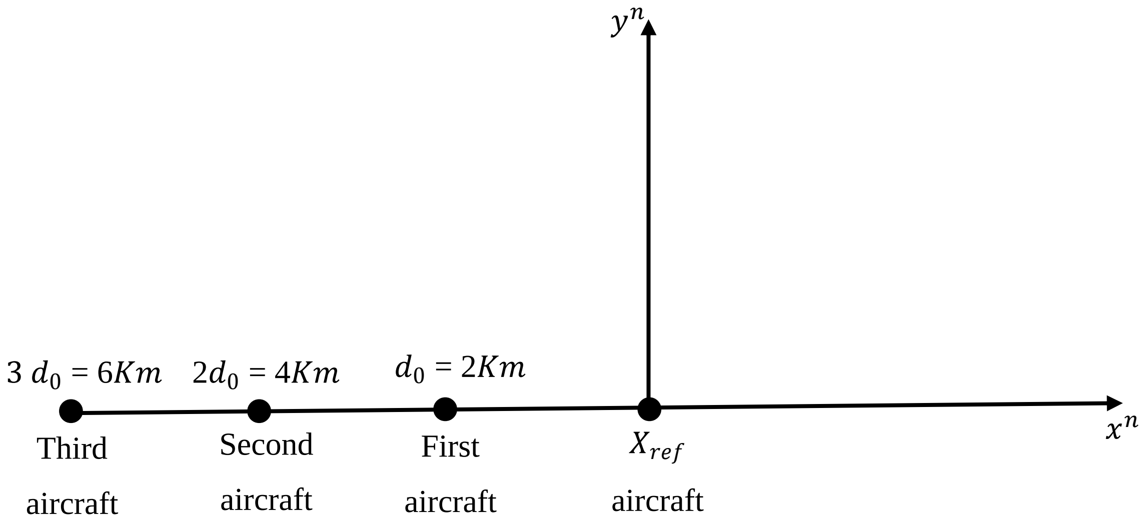

Figure 4.5: Separation distance between the aircrafts starting from the reference aircraft

The figure 4.5 shows the clearance distance of 2 Km between each aircraft starting from the reference aircraft in n – frame.

Then any aircraft has some unknown parameters which are shown of the following formula,

$$P = [\ \ a_{o1}, J_{o1,}\ \dot{J}_{o1,}\ t_{f1,}\ \ a_{o2}, J_{o2,}\ \dot{J}_{o2,}\ t_{f2,}\ \ \dots \dots \dots a_{om}, J_{om,}\ \dot{J}_{om,}\ t_{fm,}\ ]^T \quad (4.34)$$

Constraints of the system are the velocity and position at the initial and final times. Then by using optimization with constraints, we can generate command (reference) position and velocity of any aircraft.

CHAPTER 5

SIMULATION STUDY

This section provides simulation details of how integration of optimal path planning into ATC systems will significantly reduce the workload on human air traffic operators due to its automatism allowing controllers to manage more traffic with greater ease, to balance and optimize air traffic flow, reduce congestion, and avoid collision between aircraft in order to enhance the overall safety and efficiency of air traffic operations.

This chapter is divided in five sections: Section 1 contains path generation of aircraft positions shown in figure 5.1. Section 2 shows actual velocity and heading control of each aircraft in both x and y directions as shown in figure 5.2 and 5.3. Section 3 is error control in actual velocity as shown in figure 5.8. Section 4 is control inputs (a_t and a_n) adjustment as shown in figure 5.6 and 5.7. And the last section is path tracking of the desired velocities, heading of aircrafts and their control inputs a_t and a_n as shown in the figures 5.9, 5.10,5.11, and 5.12.

The simulation develops and tests a control system that would regulate the aircraft's motion in a planar environment. Implementation of the control algorithm aims to maintain the aircraft's stability and desired trajectory by adjusting its tangential and normal accelerations based on feedback from its current state.

The unicycle/point-mass model was used to design an aircraft's path by treating it as a single point with mass. This allows us to focus on the essential dynamics of the aircraft's motion as initial input variables, such as its velocity, heading, and control input variables such as tangential and normal accelerations (a_t and a_n) without getting bogged down in the complexities of its physical structure and determines the control values needed to achieve optimal flight conditions.

The simulation was performed in MATLAB and the Simulink environment. The initial conditions containing three state vectors were set randomly, each state vector includes four elements with added slight perturbations to the aircraft's velocity, heading, and separation distances that define its state in x and y positions and analyze their behavior over time. Boundary conditions ensured that the calculated speed did not exceed the aircraft's maximum safe speed or drop below its minimum operational speed.

Non-linear constraint sets up an optimization problem with inequality constraints on the final positions of three simulated scenarios and ensures that the last two constraints are non-negative. The initial conditions for the states and the specific constraints on the final positions ensures that the scenarios remain within certain bounds. The simulation models the deceleration of an aircraft during landing using exponential decay functions for velocity and calculates the total distance traveled during the deceleration phase from initial velocity to final velocity.

For each time step, we adjust the control inputs a_t and a_n for each aircraft using a control strategy function to minimize the error between the desired and actual velocities. Hence, the state of each aircraft is updated using a numerical integration method representing the aircraft dynamics. Visualizing the velocities, headings, and accelerations provides insights into the aircraft's dynamic behavior, which are essential for designing control laws that can handle various scenarios encountered in air traffic control. The simulation results are summarized in the following figures.

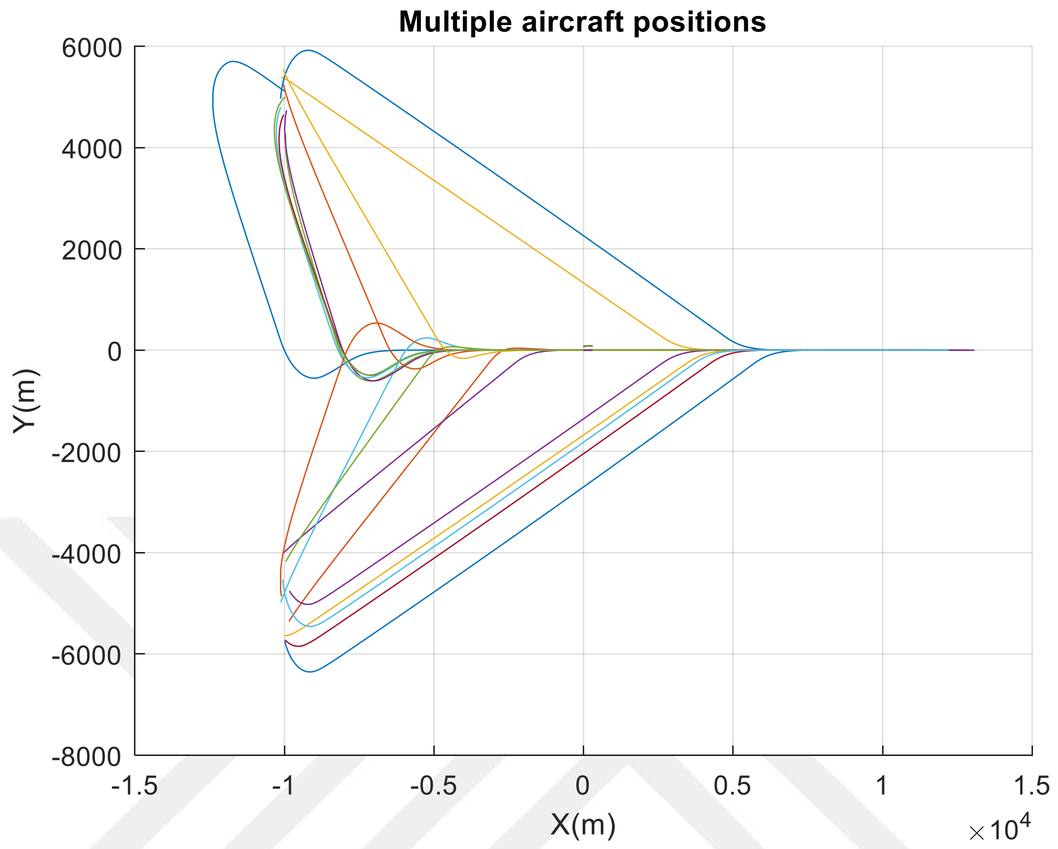

Figure 5.1: Trajectories of multiple aircrafts positions in X and Y direcrions

Fig. 5.1 shows how the plots represent the flight dynamics of multiple aircraft, in a simulation or a real-world scenario. The paths illustrate how each aircraft moves in relation to others over time. The plots show how aircraft maintain safe distances and avoid collisions in air traffic control or collision avoidance systems. The trajectories analyze specific flight patterns, maneuvers, or responses to certain conditions.

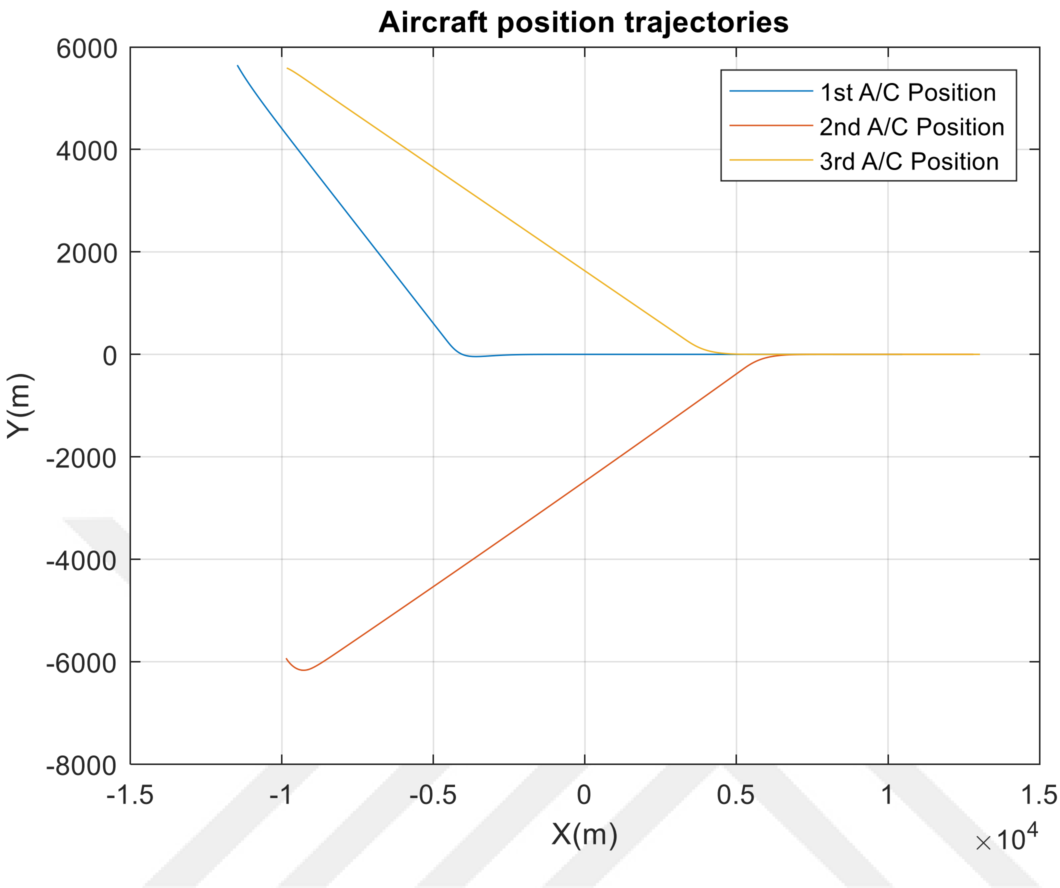

Figure 5.2: Trajectories of three aircraft positions in X and Y direcrions

Fig 5.2 shows how the trajectories describe the changes in the aircraft positions over time, which represents a coordinated maneuver or adjustment in flight paths to ensure safe separation and avoid conflicts.

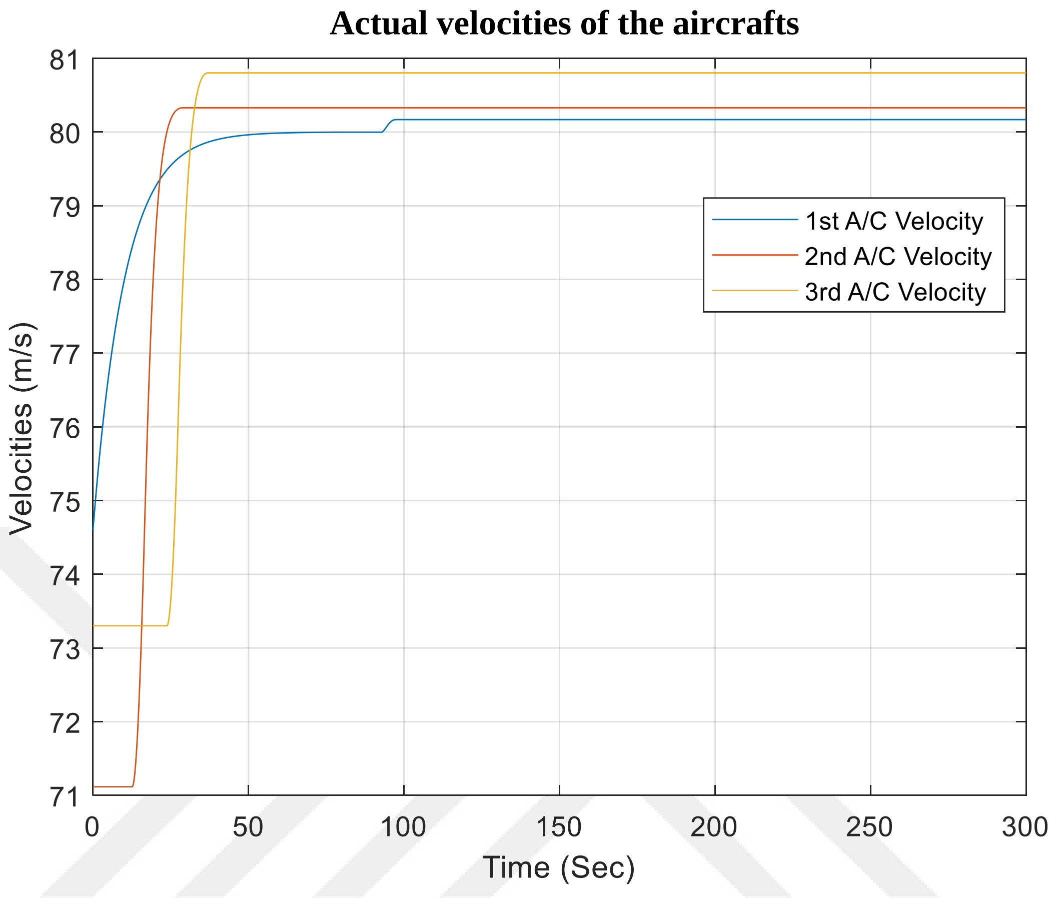

Figure 5.3: Velocity time graph for three different aircrafts (A/Cs)

Fig 5.3 shows how all three aircraft start with different initial velocities. The 1st A/C starts around 75 m/s, the 2nd A/C starts around 71 m/s, and the 3rd A/C starts around 73 m/s.

The graph shows the actual velocity profiles of three aircraft over time, highlighting their initial acceleration and eventual stabilization at a common velocity of around 80 m/s. The differences in their initial velocities and rates of acceleration can be observed clearly in the early part of the graph.

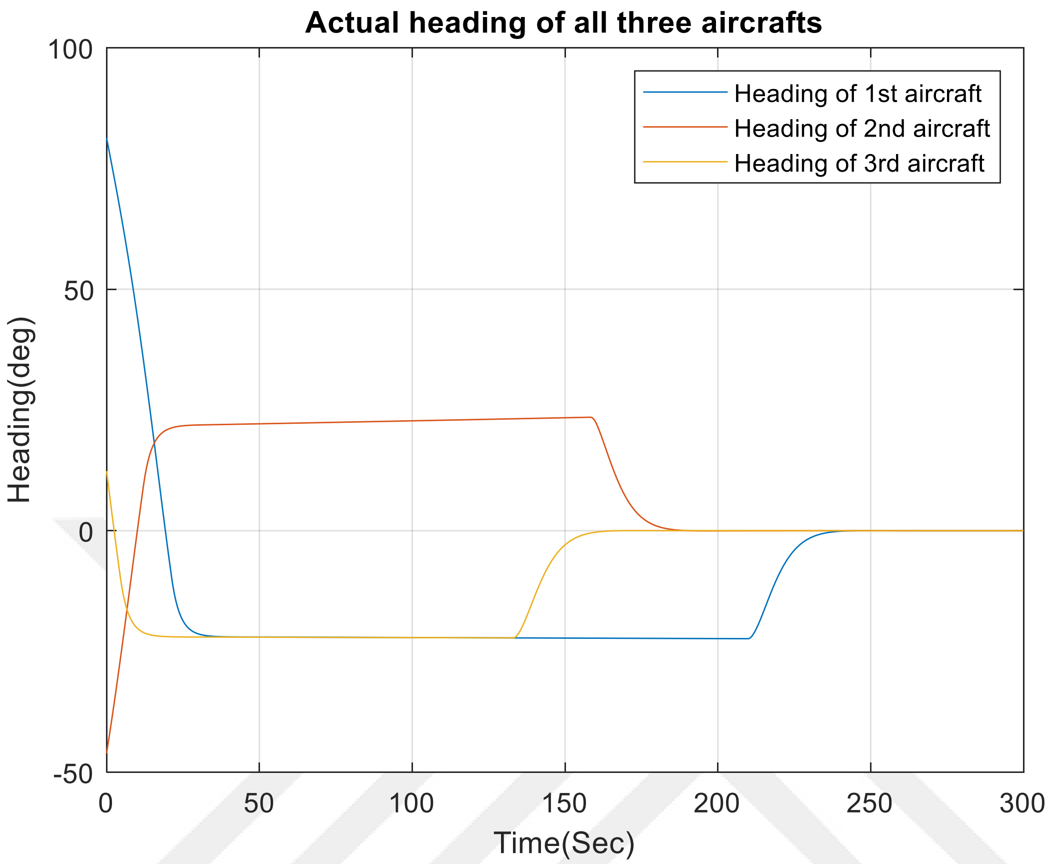

Figure 5.4: Actual headings of three different aircrafts (A/Cs) over time.

Fig 5.4 shows how all three aircraft undergo significant heading changes within the first 50 seconds. After the initial adjustment period, the headings of the aircraft stabilize to a lesser degree of change and finally converge to approximately 0 degrees or close to it by the end of the simulation time period.

The graph represents actual tracking of aircraft headings over time, illustrating how each aircraft adjusts its heading to achieve a specific flight path or to avoid potential conflicts in their trajectories.

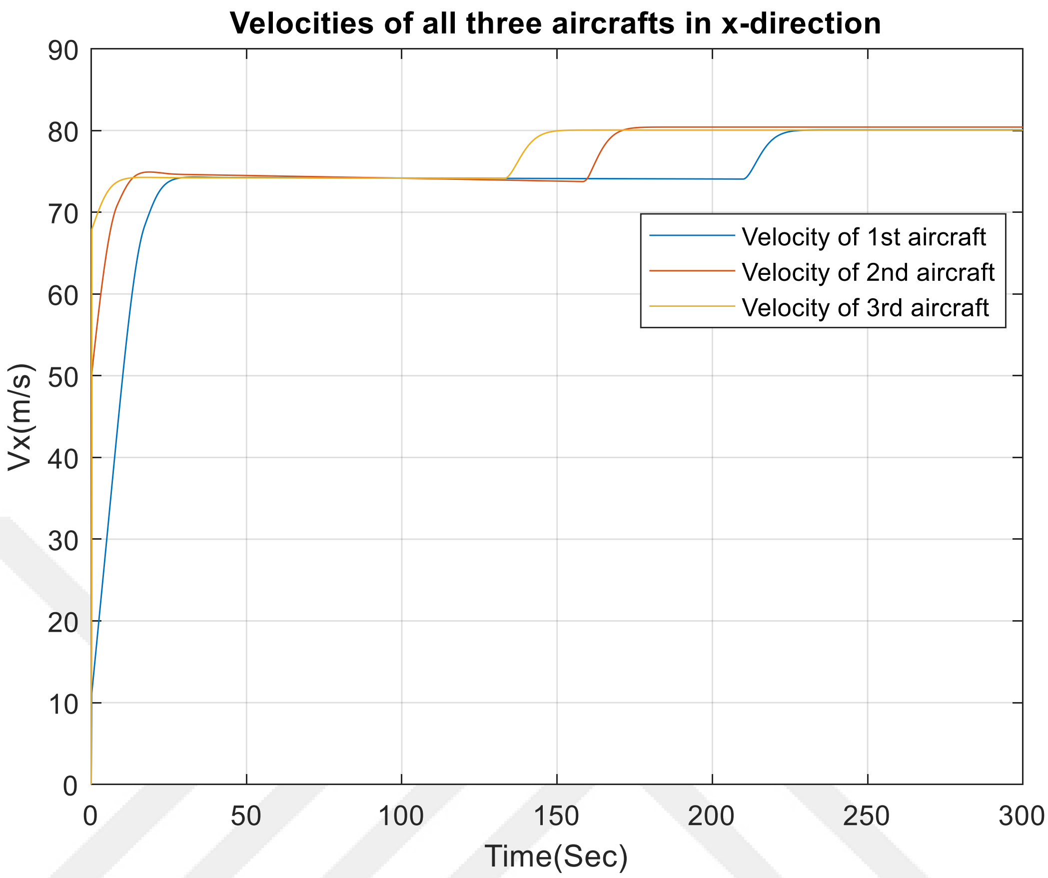

Figure 5.5: Velocities in the x- direction (Vx) of three different aircrafts (A/C) over time.

Fig 5.5 shows how the velocities of the three aircrafts change over a period of 300 seconds, highlighting their acceleration phases and eventual stabilization at different speeds. The differences in their profiles depends on the initial conditions, control inputs, or environmental factors affecting each aircraft differently.

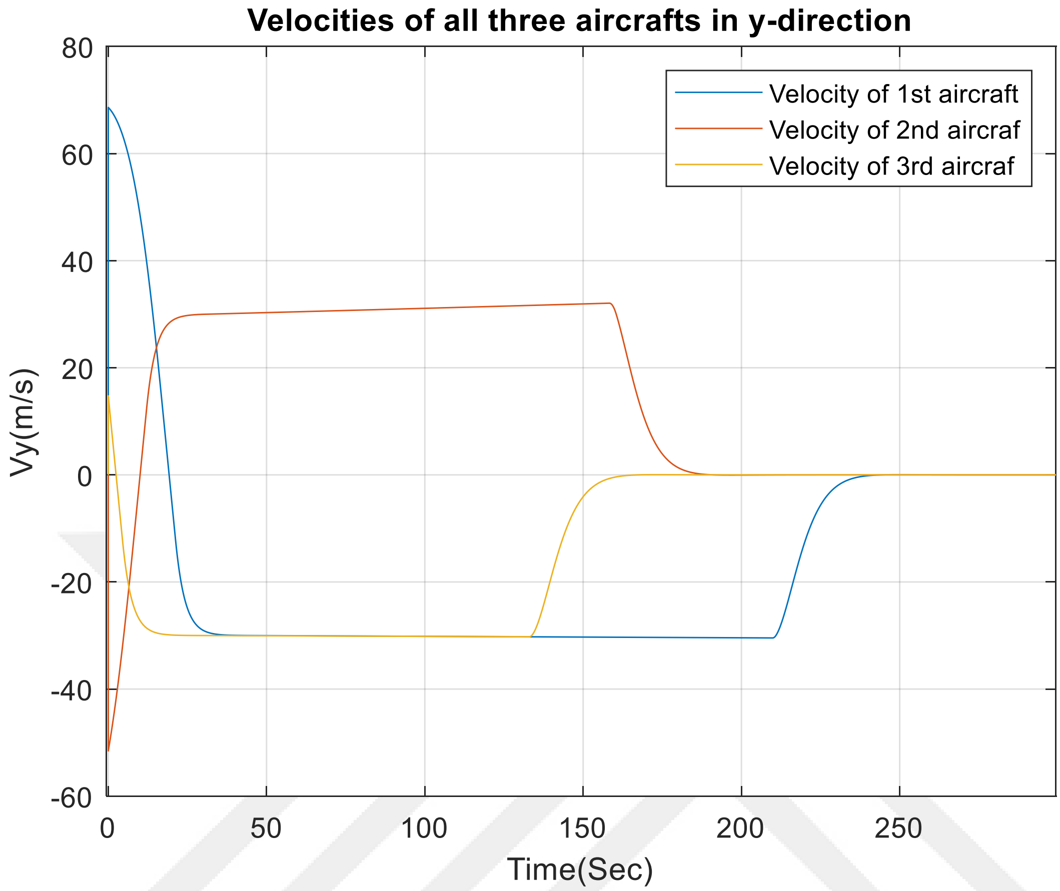

Figure 5.6: Velocities in the y- direction (Vy) of three different aircrafts (A/C) over time.

Fig 5.6 shows how dynamic changes in Y-velocities for three aircraft over time of 300 seconds. The velocities indicate different initial conditions and subsequent maneuvers or control inputs affecting the aircraft. The stabilization of velocities around 0 m/s towards the end suggests that all three aircraft eventually reach a steady state with no movement in the Y-direction.

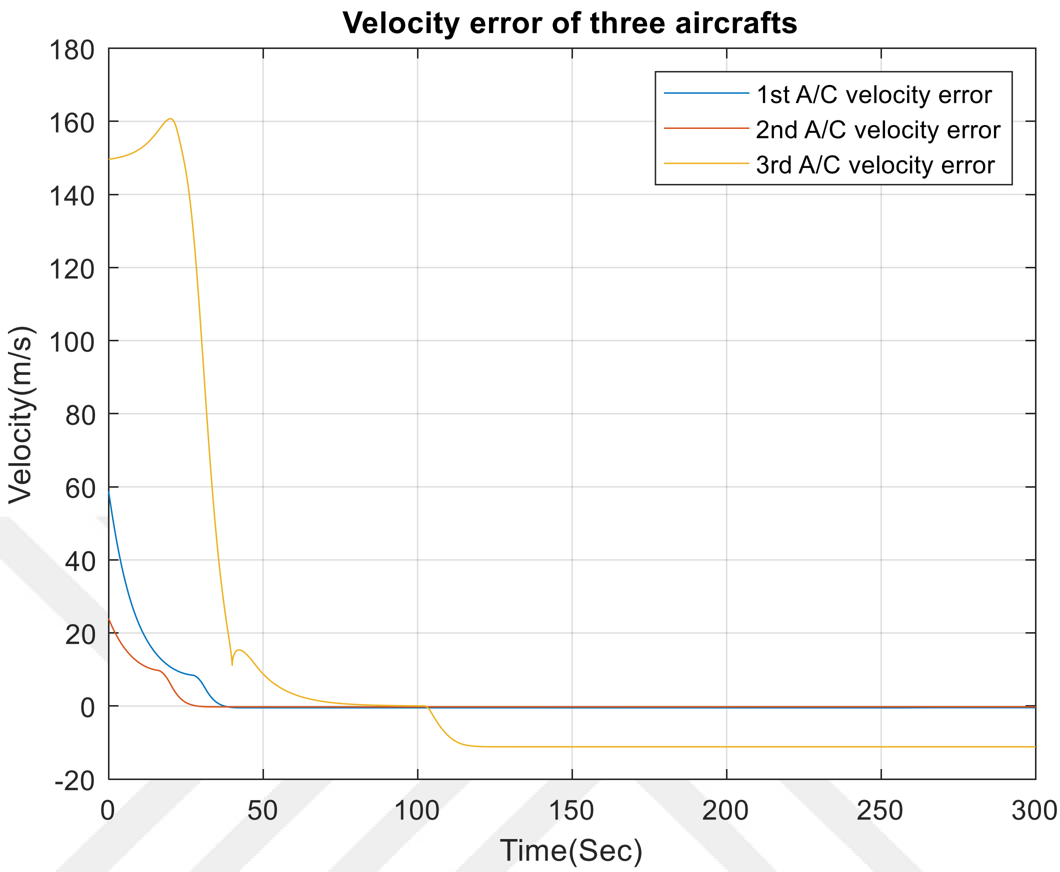

Figure 5.7: Velocity errors of the three aircrafts over time.

Fig 5.7 shows how at time 0, the initial velocity errors for the three aircraft differ. The third aircraft has a significantly higher initial error compared to the first and second aircrafts. All three aircrafts show a decrease in velocity error over time which indicates that the control systems are effectively reducing the velocity error.

The first aircraft's error decreases gradually and stabilizes around zero after approximately 50 seconds. The second aircraft's error also decreases and stabilizes at zero, showing an effective correction mechanism. The third aircraft has a large initial error but quickly reduces the error to zero around 50 seconds, then stabilizes at zero.

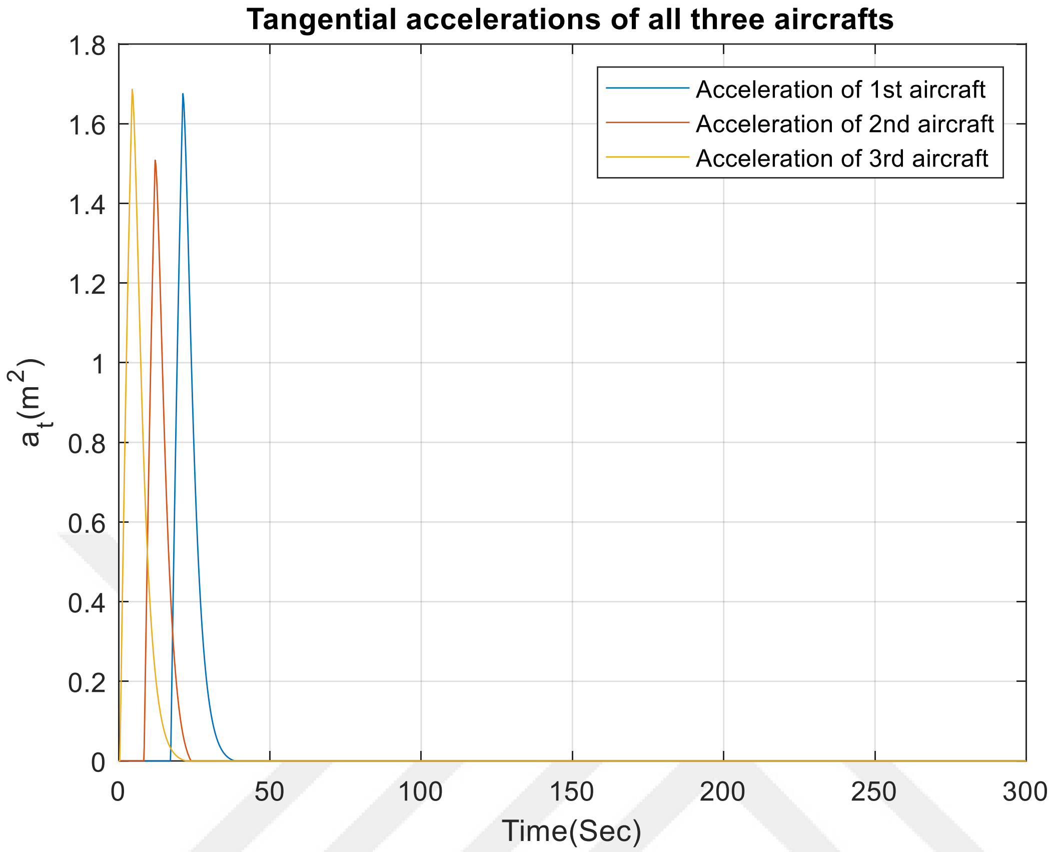

Figure 5.8: Tangential accelerations (a_t) of three different aircrafts over time.

Fig 5.8 shows how all three A/C systems show a rapid increase in acceleration at the beginning, followed by a sharp decline to near zero. This indicates a high initial burst of acceleration which quickly diminishes. The third A/C system has the highest peak acceleration, followed by the first, and then the second. However, all systems stabilize to near-zero acceleration within a similar timeframe. The significant activity for each system occurs within the first 100 seconds, suggesting that the major dynamic changes in acceleration are concentrated in this period. The initial peaks and subsequent rapid decreases provides insights into the efficiency and performance characteristics of each A/C system, with the second A/C system being the most aggressive in terms of acceleration.

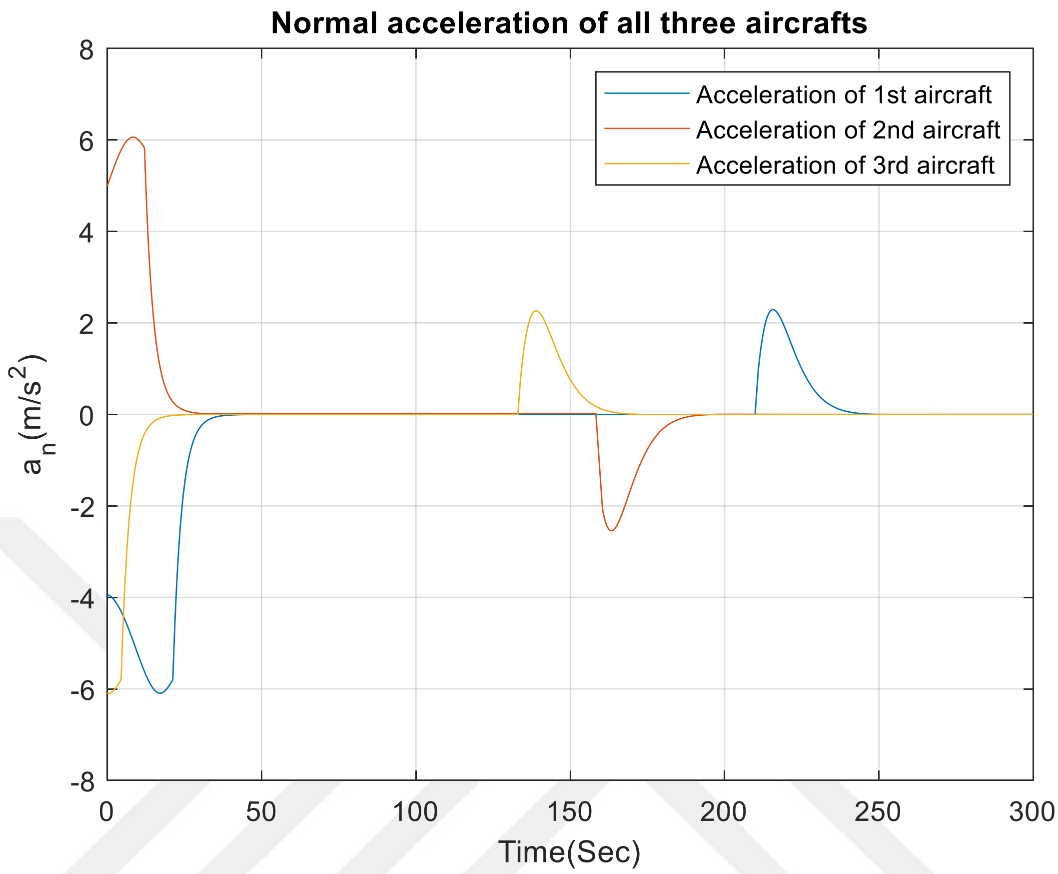

Figure 5.9: Normal accelerations (a_n) of three different aircrafts over time.

Fig 5.9 shows how the first and third aircraft experience significant positive and negative accelerations, indicating dynamic changes in their motion. The second aircraft shows a more stable acceleration pattern with smaller variations.

The accelerations of the first and second aircraft stabilize near zero with occasional spikes, indicating relatively steady motion with periodic changes. The third aircraft shows a distinct peak around 100 seconds and a dip around 150 seconds.

The first aircraft shows a significant acceleration spike around 250 seconds while the second and third aircraft maintain relatively stable accelerations with minor fluctuations. Ths graph analyzes and compare the normal accelerations of three different aircraft over a specific time period.

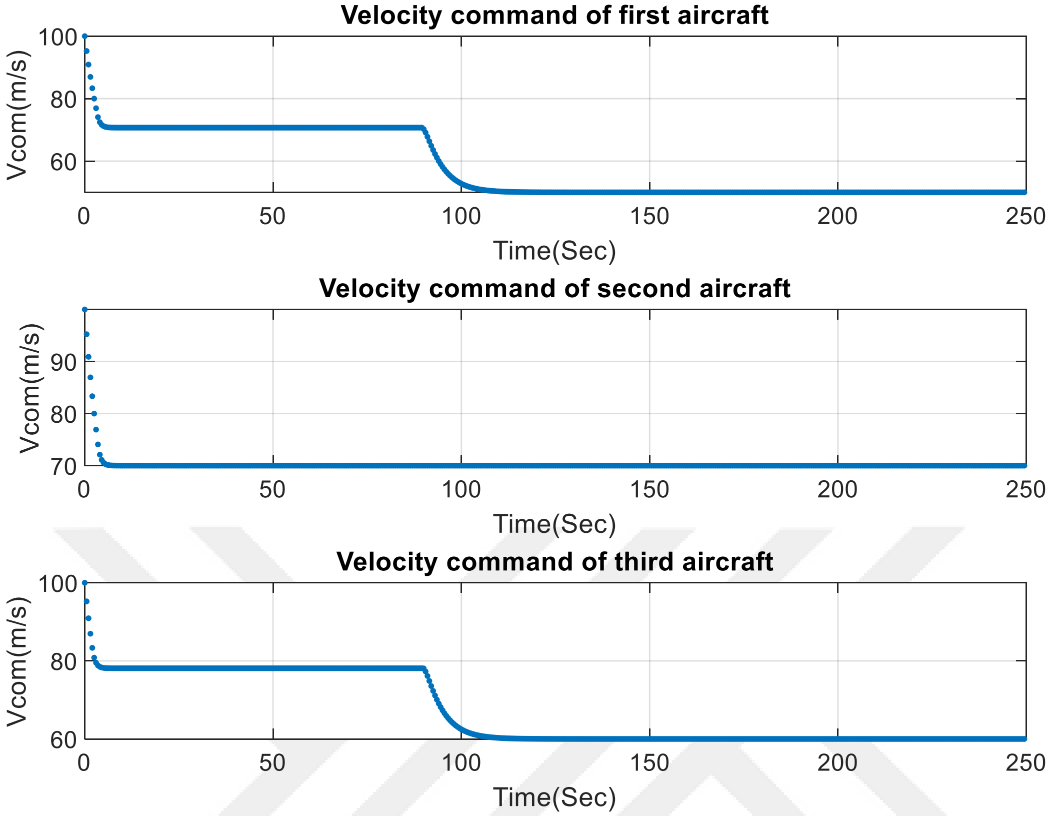

Figure 5.10: Velocity commands or desired velocity of the three aircrafts over time.

The figure 5.10 shows how the velocity commands for three different aircraft change over time with the purpose of analyzing and compares the velocity profiles of multiple aircraft to ensure they follow desired paths.

The velocity command for the first aircraft starts high, around 100 m/s, and then drops sharply at around the 100-second mark, stabilizing at around 70 m/s.

The velocity command for the second aircraft starts at around 100 m/s and drops at around 70 m/s and remains constant throughout the time period, indicating no change in the velocity command.

And then, the velocity command for the third aircraft starts high, around 100 m/s, similar to the 1st aircraft, and then drops sharply at around the 100-second mark, stabilizing at around 80 m/s for the rest of the time period.

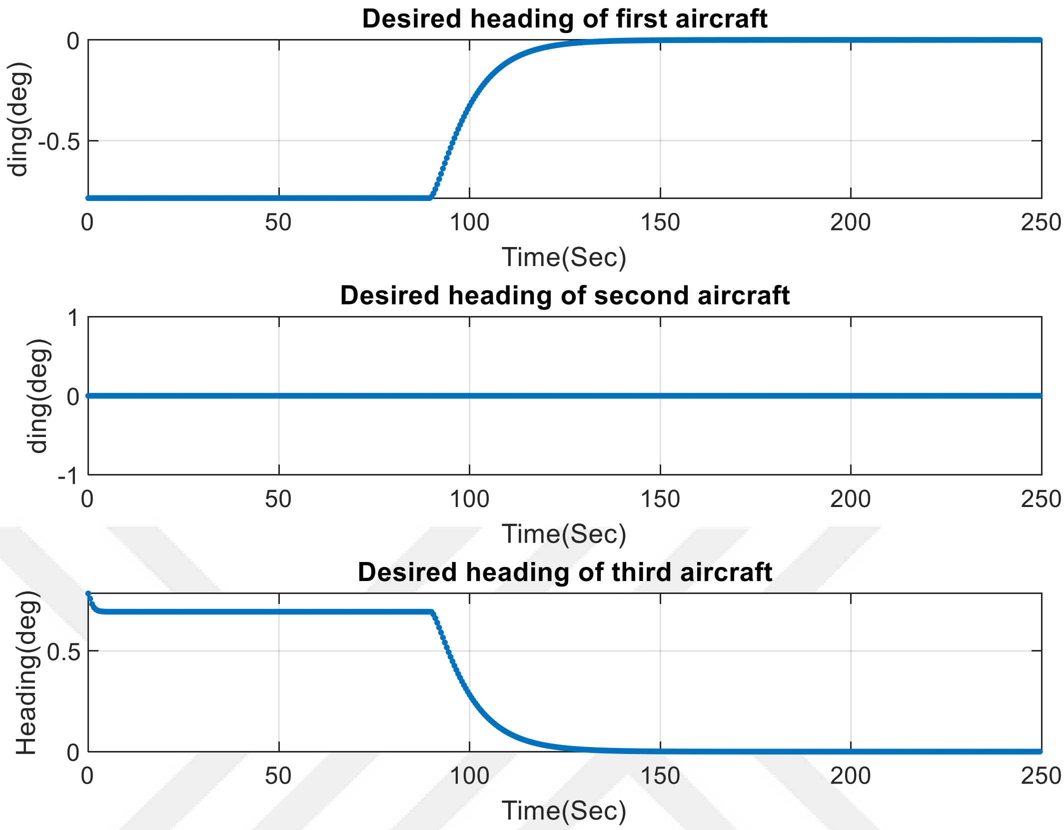

Figure 5.11: Desired headings of the three aircrafts over time.

The figure 5.11 shows how different aircrafts respond to heading commands in order to visualize their state trajectories and control inputs over time.

First aircraft changes its heading from 0 to 1 degree between 100 and 150 seconds, second aircraft maintains a constant heading of 0 degrees, and third aircraft changes its heading from 1 to 0 degrees between 100 and 150 seconds.

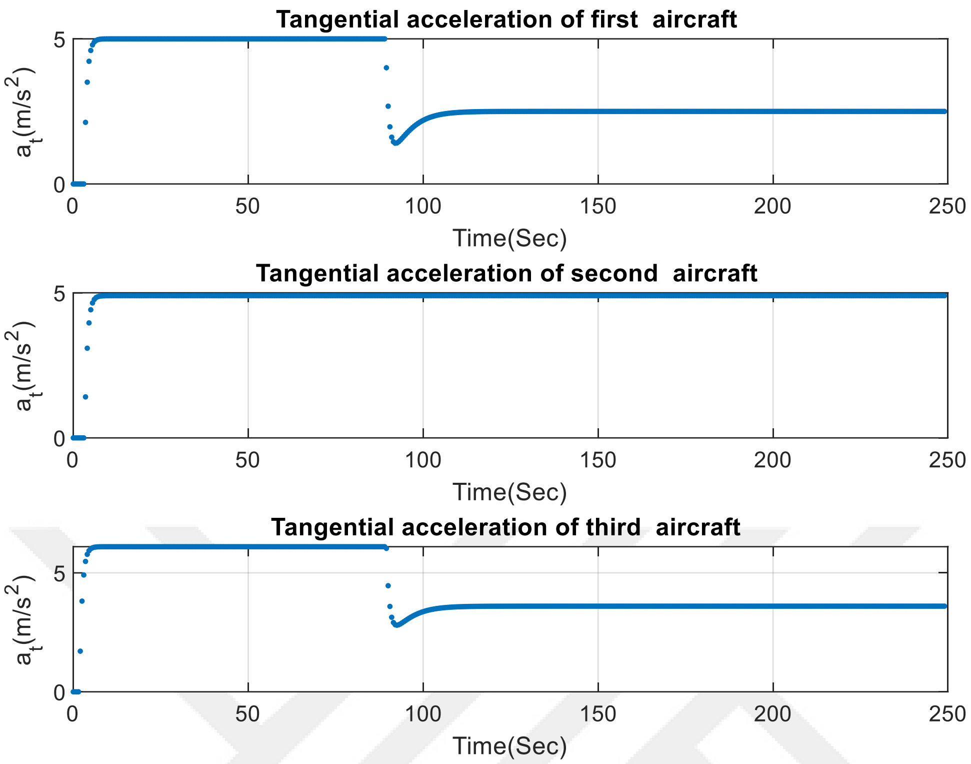

Figure 5.12: Tangential accelerations of the three aircrafts over time.

Fig 5.12 shows how the tangential acceleration profiles shown in the figure 5.11 are critical for understanding the dynamics and control of each aircraft during path tracking. These profiles help in adjusting the tangential acceleration to achieve desired speed and position. The feedback control loop is used to adjust the tangential acceleration dynamically based on real-time data, ensuring the aircraft stays on its optimal path.

The plot of first aircraft shows that the tangential acceleration starts at a high value around 5 $m/s^2$and then drops sharply, stabilizing at a lower value after approximately 100 seconds. The second aircraft's acceleration profile follows a similar pattern to the first, with an initial high acceleration that drops and stabilizes at a lower value after around 100 seconds and the third aircraft's acceleration shows the same trend, with a high initial acceleration followed by a drop and stabilization at a lower value after about 100 seconds.

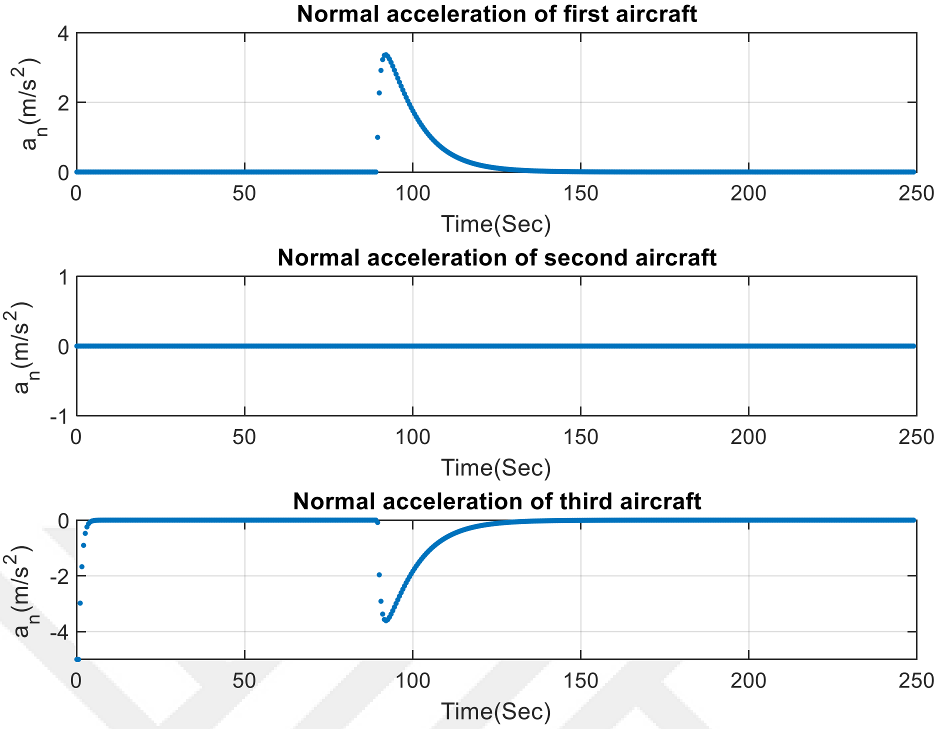

Figure 5.13: Normal accelerations of the three aircrafts over time.

The figure 5.13 shows the normal acceleration of different aircraft over time, by examining these plots, we can understand the dynamic behavior of each aircraft during flight or landing period.

The graph of first aircraft indicates a significant spike in normal acceleration around the 90-100 seconds, reaching approximately 3.5 m/s^2, after this spike, the normal acceleration rapidly decreases and stabilizes close to zero. This indicates that the first aircraft experienced a sudden maneuver or external force causing a sharp increase in acceleration before quickly returning to a stable state.

The graph of second aircraft shows a constant normal acceleration close to zero throughout the entire 250 seconds duration. This indicates that the aircraft maintained a steady flight without significant maneuvers or disturbances affecting its normal acceleration.

The third aircraft shows a sharp decrease in normal acceleration around the 90-100 seconds, reaching approximately $-4\ m/s^2$, then the acceleration increases and stabilizes close to zero. This indicates that the third aircraft experienced a sudden maneuver or external force causing a sharp decrease in acceleration before quickly returning to a stable state.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusions

The rapid growth of air traffic globally has heightened the need for advanced systems capable of ensuring safety, efficiency, and punctuality in air travel. Despite numerous studies on optimal path planning, there is a lack of comprehensive research on optimal path planning in air traffic as the density of air traffic continue to increase, hence, the complexity of managing multiple aircraft within shared airspace becomes more prominent. This necessitates sophisticated techniques for path planning and tracking to mitigate risks of collision and optimize flight operations.

The main significance of this research is to design automatic air traffic control (ATC) algorithm that could significantly reduce the work load on the human air traffic operators in order to enhance overall safety and efficiency of air traffic operations with the goal of balancing and optimizing air traffic flow, reduce congestion and delays, avoid collision between aircrafts, improve fuel efficiency and overall system performance, and also used in control guidance of landing swarm of drones in a confined area without collision between them.

The research demonstrates a comprehensive framework for understanding the motion of an aircraft along a defined path using both the longitudinal and lateral dynamics, allowing for the prediction of the aircraft's speed, orientation, and position over time.

The model defined by the differential equations of the aircraft, implemented and analyzed using MATLAB simulations which provides a framework for understanding and optimizing the control of an aircraft's trajectory. The simulations demonstrated the trajectory progression of three different initial conditions with varying control gains. The results illustrated the impact of these gains on the velocity, heading changes, and positional accuracy of the system over time and how it affects aircraft's path. The cost function serves as an objective measure for optimization, aiming to minimize the deviation in the x-coordinate between specific scenarios. This approach highlights the importance of precise control in achieving desired flight outcomes, and the ability to tune control parameters to meet specific mission objectives. The visualization of the trajectories benefits in understanding the dynamic response of the aircraft to different control inputs, providing valuable insights for further optimization and refinement of control strategies.

6.2 Future Work

While this study has provided significant insights into optimal path planning in air traffic control, there are several areas that deserve further investigation. One of the main limitations of this research was dynamic environment like weather which causes sudden changes such as storms, turbulence, or wind patterns, can necessitate real-time route adjustments. On this we research, we used point-mass model of the aircraft that controls the actual velocity and heading angle of the aircraft to the desired velocity and heading angle using tangential and normal accelerations to control the aircraft. We also, used MATLAB optimization algorithms to minimize the cost function with the objective optimizing risk of collision between aircrafts and reducing destination time to reach to the final position. Our model automatically controls and guides three aircrafts to the desired destination successfully, which was the main goal of the research. The problem in our model, we were not able to control n number of aircrafts, which is why I recommend the future work to be focused on conducting the research that uses more advanced algorithms like swarm intelligence algorithms that can control multiple aircrafts or any other space vehicles.

REFERENCES

Baruh, H. (1999). Analytical dynamics. *(No Title)*.

BENADDY, M., & KRIT, S. (2018). OPTIMIZATION AND AUTOMATION OF AIR TRAFFIC CONTROL SYSTEMS: AN OVERVIEW.

Bicchi, A., & Pallottino, L. (2000). On optimal cooperative conflict resolution for air traffic management systems. *IEEE Transactions on Intelligent Transportation Systems*, *1*(4), 221-231.

Bilimoria, K. D., Sridhar, B., Grabbe, S. R., Chatterji, G. B., & Sheth, K. S. (2001). FACET: Future ATM concepts evaluation tool. *Air Traffic Control Quarterly*, *9*(1), 1-20.

Bolczak, R., Gonda III, J. C., Saumsiegle, W. J., & Tornese, R. A. (2004). Controller-pilot data link communications (CPDLC) Build 1 value-added services. The 23rd Digital Avionics Systems Conference (IEEE Cat. No. 04CH37576),

Bolić, T., & Ravenhill, P. (2021). SESAR: The past, present, and future of European air traffic management research. *Engineering*, *7*(4), 448-451.

Bollino, K., & Lewis, L. R. (2008). Collision-free multi-UAV optimal path planning and cooperative control for tactical applications. AIAA Guidance, Navigation and Control Conference and Exhibit,

Breitler, A., Lesko, M., & Kirk, M. (1996). Effects of sector complexity and controller experience on probability of operational errors in air route traffic. *Federal Aviation Association, Report DTFA01-95-C-00002*.

Cantone, J., Gray, J., Loechle, J., & Swanson, G. (2011). A Benefit-Cost Framework for Evaluating Alternative Real Time Control Strategies in Louisville, Kentucky. WEFTEC 2011,

CHEN, C.-H. (1993). *VHF AIR/GROUND COMMUNICATIONS FOR AIR TRAFFIC CONTROL A DECISION TREE APPROACH TO SYSTEM INNOVATIONS*.

Clements, J. C. (1999). The optimal control of collision avoidance trajectories in air traffic management. *Transportation Research Part B: Methodological*, *33*(4), 265-280.

Couluris, G., Hunter, C., Blake, M., Roth, K., Sweet, D., Stassart, P., Phillips, J., & Huang, A. (2003). National airspace system simulation capturing the interactions of air traffic management and flight trajectories. AIAA Modeling and Simulation Technologies Conference and Exhibit,

d'Aspremont, A., Sohier, D., Nilim, A., El Ghaoui, L., & Duong, V. (2006). Optimal path planning for air traffic flow management under stochastic weather and capacity constraints. 2006 International Conference onResearch, Innovation and Vision for the Future,

Di Vito, V., Bucchignani, E., Montaquila, R. V., Cerasuolo, G., Montesarchio, M., Zollo, A. L., & Cinquegrana, D. (2022). Analysis of vulnerability of ATM to weather phenomena. IOP Conference Series: Materials Science and Engineering,

Doc, I. (1992). 9426: Air Traffic Services Planning Manual. *Montreal, Canada: The International Civil Aviation Organization (ICAO)*.

Ehrmanntraut, D.-I. R. (2010). Full automation of air traffic management in high complexity airspace.

Elenkov, M. P., Beriša, H. A., & Barišić, I. I. (2019). Challenges of the Implementation of the Concept of Flexible Use of Airspace in the Republic of Serbia. *Vojnotehnicki glasnik/Military Technical Courier*, *67*(2), 374-402.

Elfatih, N. M., Ali, E. S., & Saeed, R. A. (2023). Navigation and Trajectory Planning Techniques for Unmanned Aerial Vehicles Swarm. In *Artificial Intelligence for Robotics and Autonomous Systems Applications* (pp. 369-404). Springer.

Eltahier, M. M. A., & Hamid, K. (2017). Review of instrument landing system. *IOSR Journal of Electronics and Communication Engineering*, *12*(1), 106-113.

Frezza, L., Marzioli, P., Santoni, F., & Piergentili, F. (2021). Vhf omnidirectional range (VOR) experimental positioning for stratospheric vehicles. *Aerospace*, *8*(9), 263.

Friedman, M. F. (1988). Decision analysis and optimality in air traffic control conflict resolution I. optimal timing of speed control in a linear planar configuration. *Transportation Research Part B: Methodological*, *22*(3), 207-216.

Frolow, I., & Sinnott, J. H. (1989). National airspace system demand and capacity modeling. *Proceedings of the IEEE*, *77*(11), 1618-1624.

Galotti, V. P. (2019). *The Future Air Navigation System (FANS): Communications, Navigation, Surveillance–Air Traffic Management (CNS/ATM)*. Routledge.

Gardi, A., Sabatini, R., Marino, M., & Kistan, T. (2016). Multi-objective 4d trajectory optimization for online strategic and tactical air traffic management. *Sustainable aviation: Energy and environmental issues*, 185-200.

Garza, K., Goble, C., Brooke, J., & Jay, C. (2015). Framing the community data system interface. Proceedings of the 2015 British HCI Conference,

Giannatto, C., & Markowsky, G. (2014). Potential vulnerabilities of the nextgen air traffic control system. Proceedings of the International Conference on Security and Management (SAM),

Gilbert, G. (1973). Historical development of the air traffic control system. *IEEE Transactions on Communications*, *21*(5), 364-375.

Gopalakrishnan, K., & Balakrishnan, H. (2021). Control and optimization of air traffic networks. *Annual Review of Control, Robotics, and Autonomous Systems*, *4*(1), 397-424.

Groves, P. D. (2015). Principles of GNSS, inertial, and multisensor integrated navigation systems, [Book review]. *IEEE Aerospace and Electronic Systems Magazine*, *30*(2), 26-27.

Hill, J., Archibald, J., Stirling, W., & Frost, R. (2005). A multi-agent system architecture for distributed air traffic control. AIAA guidance, navigation, and control conference and exhibit,

Holland, F., Rucker, R., & Horowitz, B. (1973). Structure of the airspace. *IEEE Transactions on Communications*, *21*(5), 382-398.

Inoue, S., Furuta, K., Nakata, K., Kanno, T., Aoyama, H., & Brown, M. (2012). Cognitive process modelling of controllers in en route air traffic control. *Ergonomics*, *55*(4), 450-464.

Jiang, Y., Xu, X., Zhang, H., & Luo, Y. (2015). Taxiing route scheduling between taxiway and runway in hub airport. *Mathematical Problems in Engineering*, *2015*(1), 925139.

Jiménez, Y. M. (2012). A generic multi-agent reinforcement learning approach for scheduling problems. *PhD, Vrije Universiteit Brussel*, *128*, 11.

Kearney, P., Li, W. C., Zhang, J., Braithwaite, G., & Wang, L. (2020). Human performance assessment of a single air traffic controller conducting multiple remote tower operations. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *30*(2), 114-123.

Lovato, A. V., Fontes, C. H., Embiruçu, M., & Kalid, R. (2018). A fuzzy modeling approach to optimize control and decision making in conflict management in air traffic control. *Computers & Industrial Engineering*, *115*, 167-189.

Mackenzie, D. (2010). *ICAO: A history of the international civil aviation organization*. University of Toronto Press.

Mahapatra, P. (1999). *Aviation Weather Surveillance Systems: Advanced Radar and Surface Sensors for Flight Safety and Air Traffic Management* (Vol. 8). Iet.

Mahmoud, T., & Trilaksono, B. R. (2018). Integrated INS/GPS navigation system. *International Journal on Electrical Engineering and Informatics*, *10*(3), 491-512.

Menon, P. K., & Park, S. (2016). Dynamics and control technologies in air traffic management. *Annual Reviews in Control*, *42*, 271-284.

Mihetec, T., Jakšić, Z., & Steiner, S. (2011). Air Space Management Procedures in Europe. 14th International Conference on Transport Science ICTS,

Moon, S., Oh, E., & Shim, D. H. (2013). An integral framework of task assignment and path planning for multiple unmanned aerial vehicles in dynamic environments. *Journal of Intelligent & Robotic Systems*, *70*(1), 303-313.

Munoz, C., Narkawicz, A., & Chamberlain, J. (2013). A TCAS-II resolution advisory detection algorithm. AIAA Guidance, Navigation, and Control (GNC) Conference,

Ostroumov, I., Kharchenko, V., & Kuzmenko, N. (2018). Optimization task of navigational aids ground network. *Proceedings of the National aviation university*(3), 16-22.

Ostroumov, I., Kuzmenko, N., & Kyzymchuk, O. (2022). Automatic Dependent Surveillance-Broadcast Trajectory Data Processing. 2022 IEEE 16th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET),

Özgür, M., & Cavcar, A. (2008). A knowledge-based conflict resolution tool for en-route air traffic controllers. *Aircraft Engineering and Aerospace Technology*, *80*(6), 649-656.

Philipp, W. Future European Harmonised ATM System. 1st AIAA, Aircraft, Technology Integration, and Operations Forum,

Pistelli, M., D'Ariano, A., & Pacciarelli, D. (2011). *Optimization models and algorithms for air traffic control in the airspace of busy airports*.

Pitor, J., Škultéty, F., & Götz, K. (2014). Non directional beacons checking.

Ramée, C., Kim, J., Deguignet, M., Justin, C., Briceno, S., & Mavris, D. (2020). Aircraft flight plan optimization with dynamic weather and airspace constraints. Proc. Int. Conf. Res. Air Transp., Ribeiro, V. F., Weigang, L., Milea, V., Yamashita, Y., & Uden, L. (2015). Collaborative decision making in departure sequencing with an adapted rubinstein protocol. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *46*(2), 248-259.

Rosenow, J., Fricke, H., Luchkova, T., & Schultz, M. (2019). Impact of optimised trajectories on air traffic flow management. *The Aeronautical Journal*, *123*(1260), 157-173.

Sabatini, R., Moore, T., & Ramasamy, S. (2017). Global navigation satellite systems performance analysis and augmentation strategies in aviation. *Progress in Aerospace Sciences*, *95*, 45-98.

Saeed, R. A., Omri, M., Abdel-Khalek, S., Ali, E. S., & Alotaibi, M. F. (2022). Optimal path planning for drones based on swarm intelligence algorithm. *Neural Computing and Applications*, *34*(12), 10133-10155.

Salvendy, G., & Karwowski, W. (2021). *Handbook of human factors and ergonomics*. John Wiley & Sons.

Scovel, C. L., & General, I. (2013). FAA's progress and challenges in advancing the next generation air transportation system. *Statement of the Honorable Calvin L Scovel III, Inspector General, US Department of Transportation before the Committee on Transportation and Infrastructure Subcommittee on Aviation United States House of Representatives, Washington DC*, *17*.

Shneydor, N. A. (1998). *Missile guidance and pursuit: kinematics, dynamics and control*. Elsevier.

Sikirda, Y., Shmelova, T., Kharchenko, V., & Kasatkin, M. (2021). Intelligent System for Supporting Collaborative Decision Making by the Pilot/Air Traffic Controller in Flight Emergencies. IntelITSIS,

Smith, T. (2010). Automatic dependent surveillance broadcast (ADS-B) out performance requirements to support air traffic control (ATC) service final rules. *FAA, Federal Aviation Admin., Washington, DC, USA, Tech. Rep., FAA, Rule*, *14*.

Sridhar, B., Grabbe, S. R., & Mukherjee, A. (2008). Modeling and optimization in traffic flow management. *Proceedings of the IEEE*, *96*(12), 2060-2080.

Srisaeng, P., Baxter, G., & Sampaothong, P. (2022). Estimating a Regional Airport Air Passenger Demand Using an Artificial Neural Network Approach: The Case of Huahin Airport, Thailand. *International Journal for Traffic and Transport Engineering*, *12*(2).

Uzun, M., Başpınar, B., Koyuncu, E., & İnalhan, G. (2017). Takeoff weight error recovery for tactical trajectory prediction automaton of air traffic control operator. 2017 IEEE/AIAA 36th Digital Avionics Systems Conference (DASC),

Vail, S., Churchill, A., Karlsson, J., McInerney, T., Domitrovich, J., & Phillips, T. (2015). *Guidebook for advancing collaborative decision making (CDM) at Airports*. Transportation Research Board Washington, DC.

Wang, H. (2015). ADS-B used in improvement of air traffic control.

Williamson, T., & Spencer, N. A. (1989). Development and operation of the traffic alert and collision avoidance system (TCAS). *Proceedings of the IEEE, 77*(11), 1735-1744.

Woo, J. W., An, J.-Y., Cho, M. G., & Kim, C.-J. (2021). Integration of path planning, trajectory generation and trajectory tracking control for aircraft mission autonomy. *Aerospace Science and Technology*, *118*, 107014.