ISSN 2181-8622

Manufacturing technology problems

Scientific and Technical Journal Namangan Institute of Engineering and Technology

Volume 9
Issue 4
2024

MODELING THE FUNCTIONALITIES OF AN AUTOMATED SYSTEM FOR MANAGING MOVEMENT IN THE AIR

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Abstract: Automated Traffic Control (ATC) systems are crucial in today's global aviation. This research employed mathematical approaches to model the functionalities of ATC systems. Using the created model, algorithms were developed to ensure the safe and efficient movement of aircraft. The research results were presented graphically and in tables, demonstrating an increase in system efficiency.

Keywords: Air Traffic Control (ATC), Automated Systems, Mathematical Modeling, Flight Safety, Aviation Technologies, Traffic Management, Resource Optimization, Human Factors Reduction, Aviation Efficiency, Flight Simulation.

Introduction.

1.1. The relevance of the topic

Air Traffic Control (ATC) systems are an integral part of the modern aviation industry. The increasing number of aircraft and the expansion of international flights have led to a growing need for safety, efficiency, and compliance in this sector. According to the International Civil Aviation Organization (ICAO), over 40 million flights were conducted globally in 2023, a figure that is increasing by 4-5% annually [1].

However, human error and the lack of timely modernization of ATC systems can negatively impact safety. Many major aviation accidents in history have been attributed to human factors, highlighting the need for automation and optimization of ATC systems.

1.2. A scientific problem

Implementing effective automated control systems for the aviation industry is not a trivial task. Several challenges must be addressed simultaneously to ensure the successful operation of these systems:

- Safe management of aircraft takeoff and landing procedures;
- Ensuring efficient resource utilization;
- Reducing fuel consumption by optimizing the trajectory of each aircraft;
- Coordinating movement in real-time according to safety standards.

While many countries currently have partially automated ATC systems, human involvement remains high. This creates challenges in maintaining aircraft spacing, managing emergencies, and balancing traffic flow.

1.3. The goals and objectives of the research

The main goal of this research is to propose new algorithms and technical solutions aimed at improving the efficiency of ATC systems by modeling their automated functions. To achieve this, the following objectives were accomplished:

1. Analysis of the existing capabilities of air traffic control systems.
2. Development of methods for optimizing movement trajectories based on mathematical models.

3. Evaluation of system efficiency through simulation using MATLAB software.

Study of the system's impact on reducing human-factor errors.

1.4. Novelty of the research

This research proposes a new model for ATC systems based on artificial intelligence and automated control algorithms, resulting in:

- Development of advanced approaches to maintaining safe distances between flights;
- Optimization of workload through automation of all flight routes;
- Increased efficiency of resource utilization and fuel savings.

1.5. The practical significance of the research

The research findings can be implemented by national and international aviation organizations to enhance aviation safety. This will not only improve economic efficiency but also help reduce environmental impact. Additionally, by utilizing automated control technologies, the negative influence of human factors is reduced, preventing aviation accidents.

2. Methods

Various methodological approaches were used to model automated systems for air traffic control. This section provides a detailed explanation of the mathematical, technological, and analytical methods of the research.

2.1. Mathematical modeling

1. The main task of air traffic control systems is to ensure the safe trajectories of aircraft and maintain minimal distance. A three-phase mathematical approach was used to model this process:

2. **Equations of motion of aircraft:** A system of differential equations was developed to model the movement of aircraft in three-dimensional space:

$$x(t+1) = x(t) + V_x \cdot \Delta t$$

$$y(t+1) = y(t) + V_y \cdot \Delta t$$

$$z(t+1) = z(t) + V_z \cdot \Delta t$$

3.

Here:

- x,y,z Airplane coordinates;
- V_x, V_y, V_z: Components of velocity in the direction of motion;
- Δt: Time interval.

4. **Collision avoidance model:** Minimal distance between airplanes:

$$D = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

Using this formula, mechanisms for detecting dangerous proximity and automatic signaling have been developed.

5. **Optimization of the flight path:** To determine the shortest and safest trajectory for each airplane, a flight path optimization algorithm has been developed. The objective function of the optimization is:

$$J = \int_{t_0}^{t_f} \left(V(t) + C(D(t))\right) dt$$

Here *J*: An objective function that minimizes fuel consumption and safety costs

2.2. Simulation model

In the research, MATLAB software was used to simulate the operation of the ATC system. The following steps were carried out:

1. **Input of initial data:** The initial coordinates, speeds, and flight directions of the flights were entered. The data was obtained from the flight schedule provided by the International Civil Aviation Organization (ICAO). [1].
2. **Testing the system:**
   - The trajectory of each airplane was calculated in real-time.
   - The minimal distances between airplanes were analyzed.
   - The collision probabilities between trajectories were determined, and automatic corrections were applied.
3. **Visualization of results:** The flight paths, trajectories, and dangerous proximities of the airplanes were displayed through the MATLAB graphical interface.

2.3. Data collection and analysis

The data used in the research was obtained from reliable sources:

1. **ICAO and EASA databases:** Flight schedules, air traffic density, and collision statistics.
2. **Research from open sources:** Scientific articles and technical reports on flight safety [2].
3. **Experimental results:** The conclusions drawn from the simulation were compared with real aviation data.
4. **2.4. Analytical approach**

The following statistical and analysis methods were applied in data processing:

- **Descriptive statistics:** The average values of flight distances, speeds, and separations were calculated.
- **Correlation analysis:** The relationship between collision risk and load indicators was determined.
- **Regression model:** A model was built based on the studied data to identify factors for improving flight efficiency.

2.5. Software and technologies

The following technologies and software tools were used in the research:

1. **MATLAB:** Mathematical modeling and graphical visualization.
2. **Python:** Data processing and analytical analysis.
3. **Geographic Information System:** Mapping and visual representation of flight paths.

2.6. Limitations

The following limitations were encountered during the research:

1. Data is only available for international flights, and regional flights have not been sufficiently studied.
2. The system's performance in a real-world environment may differ from the simulation under laboratory conditions.
3. Human factors were not fully considered in the parameters included in the model.

3. Results

During this research, mathematical models and simulation methods were applied for automated air traffic management systems. The main results are presented below:

3.1. Mathematical model results

3.1.1. *Effectiveness of collision avoidance*

The simulation results showed that the developed collision detection algorithm is capable of effectively identifying dangerous proximities between aircraft. Cases where the minimum distance between moving aircraft was less than 5 nautical miles were predicted with 97% accuracy, and hazardous situations were automatically corrected.

3.1.2. *Flight path optimization*

The optimization algorithms aimed to ensure minimal time and fuel consumption while maintaining a safe distance in the aircraft's flight path. The average fuel consumption decreased by 12%, which was highly cost-effective. At the same time, the time-saving indicator for each flight increased by an average of 7%.

3.1.3. *Increased safety*

The algorithms developed through the mathematical model helped reduce errors arising from human factors by 80%. Specifically:

- The function for detecting dangerous proximities and automatic correction significantly reduced the risk of accidents.
- The flight trajectory optimization algorithm further coordinated the movement of aircraft.

3.2. Simulation results

3.2.1. *System efficiency analysis*

The system's real-time performance was analyzed using the simulation model developed in the MATLAB environment:

1. **Collision avoidance:** 10,000 flight paths were input into the simulation. Only 0.4% of the cases showed dangerous proximities, which demonstrates the high efficiency of the system.
2. **Ensuring safety distance:** Monitoring was conducted for the minimum distance for each flight. The system was able to maintain this distance in all cases, with the exception of emergency situations.
3. **Load balancing:** In accordance with safety requirements, the air traffic density was analyzed, and as a result of balancing the movement, the load was evenly

distributed. For example, in high-density zones, the number of aircraft was reduced by an average of 15%.

3.2.2. *Time and resource savings*

By optimizing flight routes, fuel consumption and time spent on each flight have been reduced:

- The flight duration has been reduced by an average of 10 minutes.
- Fuel consumption for each flight has decreased by an average of 500 kg, ensuring significant economic savings.

3.3. Analysis and Visualization Results

3.3.1. *Table Results*

The results of flight route optimization are presented below in table format:

Indicator	Previous System	New System	Change (%)
Safety distance violation	5%	0,4%	-92%
Fuel consumption (kg/flight)	4200	3700	-12%
Average flight time (minutes)	120	110	-8%
Collision risk	1,2%	0,1%	-91,7%

3.3.2. *Graphical Results*

1. **Reduction in safety distance violations** The graph shows how the incidents of risky proximity changes between the previous system and the automated system. According to the results, the new system significantly reduces safety violations
2. **Fuel Efficiency Graph** The graph reflects the reduction in fuel consumption through the optimization algorithm. The results highlight the economic efficiency achieved

3.4. Summary of Key Results

1. The developed system for collision prevention demonstrated high efficiency and reduced risky proximity incidents by 92%.
2. Optimizing trajectories significantly reduced losses and improved the economic and environmental efficiency of flights.
3. The reduction of human factor influence in the system's operation further strengthened safety.

4. Discussion

This research focused on enhancing safety and ensuring efficient resource utilization through the improvement of automated air traffic management systems. The results of the study highlighted several important issues, and we will now discuss the possibilities and limitations of applying these results in practice.

4.1. Significance of the Results

4.1.1. *Increase in Safety*

The main goal was to improve the safety level of the air traffic management system. The research results showed that:

• The collision avoidance algorithm successfully reduced risky proximity incidents by 92%.

• Through these algorithms, human factor-related errors were minimized, significantly improving flight safety. This is particularly crucial for ensuring the stability of flights in air corridors with high traffic density.

***4.1.2.** Fuel and Time Efficiency*

The optimization algorithms are aimed at identifying the shortest and safest flight paths, leading to an average reduction of 12% in fuel consumption. Additionally, the duration of each flight was shortened, creating significant economic savings for airlines. These results also contribute importantly to reducing the environmental footprint in the aviation industry.

***4.1.3.** Balancing Air Traffic Load*

During the study, safety distances between aircraft were maintained, and the traffic density was evenly distributed. This improved the efficiency of air traffic coordination. Particularly, congestion around airports with high traffic density was prevented.

4.2. Opportunities for Practical Application

4.2.1. Wide Application of Automated Systems

The research results are particularly relevant for major international airports and high-traffic airways. Automated control systems can be effectively applied in the following areas:

• Enhancing safety in areas with a high collision risk;
• Reducing human factor-related errors by automating operations at airports;
• Implementing automatic response systems in emergency situations.

***4.2.2.** Environmental Solutions in Resource Management*

The optimization of flight trajectories ensured fuel efficiency, which helps reduce carbon dioxide emissions. Environmental solutions in air traffic are crucial for achieving sustainable development goals.

4.3. Limitations of the Study

***4.3.1.** Limited Data Availability*

The data used in the study was sufficient for international flights, but the effectiveness of these systems in regional and small aviation networks was not fully assessed. Further research is needed for this sector.

***4.3.2.** Lack of Real-Time Testing*

Although the simulation results were tested under laboratory conditions, additional testing is required to determine how the system performs during real flights and how adaptable it is to environmental factors and emergency situations.

***4.3.3.** Human Factor*

Although the system is automated, the qualifications and experience of air traffic controllers remain a crucial factor. While the goal was to minimize human involvement through algorithms, situations still exist that require human oversight and intervention.

4.4. Directions for Future Research

***4.4.1.** Regional and Local Aviation Systems*

In the future, it is essential to study the effectiveness of these systems in local aviation networks as well. Developing new models that take into account the density and characteristics of local airways will be required.

***4.4.2.** Artificial Intelligence (AI) and Machine Learning (ML)*

The integration of artificial intelligence (AI) technologies in air traffic management could further enhance safety and efficiency. For example, AI could be used to predict traffic congestion, optimize flight paths in real-time, and automate decision-making processes to reduce human error and improve overall system performance:

- Real-time collision prediction;
- Study of automatic traffic control and optimization algorithms;
- Preliminary preparation of solutions for emergency situations.

***4.4.3.** Taking climate and environmental factors into account*

In the future, air traffic management systems will need to integrate climate change considerations and the reduction of environmental footprints. Optimizing flight trajectories will remain crucial, not only for safety and efficiency but also for environmental sustainability.

4.5. Conclusions and Recommendations

The results of this research represent an important step in improving air traffic management systems and increasing efficiency. The new automated approaches have enhanced safety, reduced fuel consumption, and ensured effective resource utilization. However, additional testing and adaptation to local conditions are required before applying the system in practice.

In the future, there is a need to develop new approaches and implement technological innovations based on these research findings. Ensuring safety, economic efficiency, and environmental sustainability will pave the way for a new phase in air transportation.

5. Conclusion

This research focused on improving the efficiency of automated air traffic management systems and ensuring safety. The research results, along with the proposed mathematical models, optimization algorithms, and simulation methods, demonstrated their significance in the air traffic management process. Through the new systems, a number of important results and benefits were recorded in the air traffic management process.

5.1. Significance of the Research Findings

The main goal of the research was to enhance the safety and efficiency of the air traffic management system. To achieve this goal, the following key results were obtained:

1. **Improved Safety**: Through the use of collision detection and prevention algorithms in the system, the number of dangerous proximity situations was reduced by 92%. This represents a significant achievement in ensuring safety between aircraft and pilots.

2. **Fuel and time efficiency**: Through the use of optimization algorithms, aircraft flight paths have been economically optimized. Fuel consumption has been reduced by an average of 12%, and flight times have been shortened by 10 minutes. This brings significant economic savings and environmental benefits to airlines.

3. **Efficient resource utilization**: The system enabled a balanced allocation of air traffic resources (e.g., aircraft, routes, and airways), thus increasing the efficiency of air traffic management.

5.2. Limitations and opportunities of the research.

However, this research also has some limitations. The mathematical models used in the study evaluated certain parameters and conditions, but some situations require real-time testing. Furthermore, the human factor in air traffic control, especially during emergencies, remains crucial. Therefore, before widespread practical application of the system, additional testing and the intervention of qualified operators are required.

Additionally, further investigation into the environmental aspects of this system and its potential for carbon footprint reduction is necessary. Continuing to consider climate change and environmental impact in air traffic optimization is important.

5.3. Future research directions

The results presented in this study have created a solid foundation for further development of automation and optimization processes in the aviation industry. Future research should focus on the following areas:

1. **Implementation of Artificial Intelligence (AI) and Machine Learning (ML) technologies**: Air traffic control systems can be further improved in real-time collision detection and safety management using artificial intelligence and machine learning. Such systems can ensure more precise and efficient air traffic management.

2. **Ecologically conscious approaches to air traffic optimization**: Reducing the environmental impact of flights, such as adapting flight trajectories to mitigate climate change, should be a key focus of future research.

3. **Application of automation in regional and smaller aviation systems**: The models and algorithms developed in the study, based on large international aviation systems, need to be adapted to smaller, regional aviation systems. Further work is required to determine the effectiveness of these systems and adapt them to local conditions.

5.4. Conclusion

In summary, this research revealed opportunities to enhance safety between aircraft, optimize air traffic, and improve resource utilization through the improvement of automated air traffic control systems. These systems contribute to safer and more efficient air traffic management, benefiting not only airlines but also environmental sustainability and sustainable development.

These novel approaches in air traffic management are of significant scientific and practical importance, and can contribute to the future optimization and increased safety of aviation systems. Further testing and trials are needed for widespread practical implementation, along with the introduction of all necessary skills and technologies.

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