D5.2: Report on supporting FMS and HMI technology research

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Lead beneficiary: Hu Haoliang (CARERI)
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E-mail:	Michael.Finke@dlr.de
Project website address:	www.project-great.eu

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	Name	Organisation	Date
Coordinator			
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EXECUTIVE SUMMARY

Addressing environmental challenges, especially global warming, is more than ever an issue for the community. This matter is becoming an increasing priority at regional and global level. Commitments have been made to reduce the aviation's environmental footprint. Global air traffic is contributing to climate change, influencing local air quality and, consequently, affecting the health and quality of life of all citizens. The air traffic is growing and is expected to continue growing significantly in the future to cope with the increasing demand for mobility and connectivity. A long-term effect on the environment from aviation sector, mainly caused by aircraft noise and exhaust gases (especially CO_2, nitrogen oxides NO_x and methane), make it a clear target for mitigation efforts. The future growth of aviation shall go hand in hand with environment sustainability policies. Therefore, studies and research are being conducted worldwide exploring possible optimization of the aircraft technologies as well as Air Traffic Management (ATM) operations. Given the close interdependency between several flight parameters, including the route of flight, and environmental impact, optimization in flight trajectory design and air traffic control (ATC) operations are an appropriate means to reduce the emissions in short- and medium-term time frames.

The international project "Greener Air Traffic Operations" (GreAT) has been launched in line with this objective. This Horizon 2020 project is conducted in cooperation between 6 Chinese and 7 European partners.

This document involves two parts: research on trajectory optimization of Flight Management System under multi-constraints and multiple optimization targets and research on human-machine interface of Avionics System supporting aircraft green cruise operation.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 875154 GreAT.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Acronym	Signification
ADS-B	Automatic Dependent Surveillance-Broadcast
AIRB	Airborne Situation Awareness
AMMD	Aerodrome Moving Map Display
ANSP	Air Navigation Service Provider
AP	Approach Configuration
ATAS	ADS-B Traffic Advisory System
ATC	Air Traffic Control
ATM	Air Traffic Management
ATSU	Air Traffic Service Unit
BADA	Base of Aircraft Data
CAAC	Civil Aviation Administration of China
CAVS	CDTI Assisted Visual Separation
CD	Control Display
CL-RRT	Closed-loop Rapidly-exploring Random Tree
CPDLC	Controller data link communication system
CR	cruise configuration
DOC	Direct Operating Cost
EASA	European Union Aviation Safety Agency
EHAM	Amsterdam Airport Schiphol
EVAcq	Enhanced Visual Acquisition
FAA	Federal Aviation Administration
FIM	Flight-deck Interval Management
IC	Initial climb configuration
ICAO	International Civil Aviation Organization
ITP	In-Trail Procedure

LD	landing configuration
MCT	Minimum Completion Time
ND	Navigation Display
RRT	Rapidly-exploring Random Tree
SURF	Surface Situation Awareness
TCAS	Traffic Alert and Collision Avoidance System
TO	take-off configuration
TSAA	Traffic Situation Awareness with Alerts
VSA	Visual Separation on Approach

1 INTRODUCTION

Due to population explosion and immoderate industrialization, the impacts of the greenhouse effect are gradually intensifying. Eventually, it is corroding the sustainable development of modern society. The fossil energy crisis is also rocketing the cost of transportation, which brings non-negligible pressures to the air traffic operation community.

In the face of the increasing demand for air transport in the future, ICAO, FAA, EASA and other major international research institutions believe that improving the efficiency of air transport in the future requires improving the level of air traffic management and airborne avionics systems simultaneously. In view of the demand for green traffic in the future, the research of avionics system mainly focuses on the following two aspects:

1) How can the avionics system participate in the organization and management of operation activities more effectively under the green traffic operation environment, and how to organize and apply the capabilities of the avionics system for green traffic;
2) How to improve the performance and capability of avionics equipment, and research on avionics capability.

Among them, the research on avionics capability is mainly focused on the research of avionics system architecture, sensor equipment and other technologies; The organization and application of avionics system capability for green traffic is mainly to use existing technical conditions, and establish corresponding flight environment perception ability, information comprehensive analysis and decision-making ability, which is one of the most effective means to improve aircraft operational efficiency.

Green air traffic operation refers to the realization of energy conservation, emission reduction and noise reduction at all stages of aircraft flight through the innovation of air traffic management technology and avionics technology.

1.1 PURPOSE OF THE DOCUMENT

This report involves two parts: research on trajectory optimization of Flight Management System under multi-constraints and multiple optimization targets and research on human-machine interface of Avionics System supporting aircraft green cruise operation.

Research on trajectory optimization of Flight Management System under multi-constraints and multiple optimization targets clarifies the constraints that affect the flight trajectory generation, the optimization target and its mechanism in the calculation process, and consider these factors in corresponding calculations in the flight trajectory construction and optimization, and make full use of the information provided by monitoring, communication and navigation equipment to ensure that the profile generated by the flight management system meets the requirements of airspace management, safety and economy. This part aims to develop a trajectory generation algorithm considering multiple constraints and multiple optimization targets to achieve the goal of green air traffic operation.

Research on human-machine interface of Avionics System supporting aircraft green cruise operation describes the application display requirements under different application scenarios of green flight path and the contents related to human-machine interface design. In response to the increasing flight density, the future civil aircraft avionics system will introduce new functions of green track display based on ADS-B and other applications, such as the pilot/air traffic controller data link communication system (CPDLC), for example, a large amount of flight environment information and data link information will be calculated and processed, and then sent to the cockpit display system to provide reasonable flight information and guidance information for the pilot, and improve the pilot's situational awareness Operational efficiency and aircraft operational efficiency.

1.2 SCOPE

In this document, two methods are proposed wherein the FMS collaborates with the surveillance system, the communication system and the navigation system to collect information of the weather, terrain, and surrounding air traffic. Based on this information, algorithms for conflict-free 4D trajectory generation and optimization are developed, which consider the meteorological conditions and movement of other aircraft in the vicinity. Multiple objectives are concerned in the trajectory optimization, including the minimization of flight time and gaseous emissions.

In addition, this document also describes the application display requirements of green trajectory in different application scenarios and the related human-machine interface design. In order to meet the demand of increasing flight density in the future airspace, the future avionics system of civil aircraft will introduce new functions such as green trajectory display based on ADS-B and Controller Pilot Data Link Communications (CPDLC), such as calculating and processing a large amount of flight environment information and data link information, and sending them to the cockpit display system to provide reasonable flight information and guidance information for pilots, so as to improve pilots' situation awareness, operational efficiency and aircraft operation efficiency.

1.3 INTENDED READERSHIP

This section describes the intended audience for this document. In general, readers of this document can be:

1) Readers internal to the project, using this document as input for their own activities;

2) Readers from the GreAT sister projects (ACACIA, CLIMOP and ALTERNATE), to follow latest developments and approaches, and to drive scientific exchange between the sister projects. This is for the purpose of aligning the activities of all four projects and to identify synergy effects. Finally, this document can also serve as reference for scientific publications.

3) Readers from the GreAT Advisory board, to provide input and to follow the developments from a stakeholder point of view.

4) Readers involved in current and future projects dealing with reducing the impact of aviation on climate change, especially to build upon the approaches described in this document; and to align other developments (e.g. modifications to aircraft propulsion and airframe) with it.

5) Readers from air navigation service providers (ANSPs) or other stakeholders not involved in the project but effected from its improvements (especially airports, airlines and air traffic control (ATC) equipment providers).

6) Standardization bodies and regulating authorities / organizations, such as ICAO, European Union Aviation Safety Agency (EASA), EUROCONTROL or Civil Aviation Administration of China (CAAC).

7) All other interested members of aviation community.

1.4 STRUCTURE OF THE DOCUMENT

This document contains the following sections:

Chapter 1 Introduction – describes the purpose and scope of the document, the intended audience and the document structure.

Chapter 2 FMS – proposes two methods wherein the FMS collaborates with the surveillance system, the communication system and the navigation system, considering multiple objectives including flight time and fuel consumption.

Chapter 3 HMI – analyzes the impact of the regulatory functions that may be authorized on the cockpit resources, as well as the impact on the operational safety and efficiency of the airspace under consideration of crew participation, and establishes a reasonable airborne interface used for evaluation and demonstration.

Chapter 4 Summary – concludes the document.

Chapter 5 References – contains the references.

2 FMS (Research on Trajectory Optimization of Flight Management System under Multi-constraints and Multiple Optimization Targets)

2.1 PROBLEM DEFINITION

2.1.1 Research objectives and tasks

To facilitate the operation of green air traffic, it needs to combine the comprehensive information of airborne systems such as monitoring, navigation and communication, break through the trajectory optimization technology under multiple constraints, and generate the optimized trajectory from takeoff to landing. The core issue is the construction and optimization of flight trajectory to find the optimal flight trajectory under various constraints and improve the economy and safety of aircraft.

Due to that there are many constraints and optimization targets that affect the optimization & calculation of performance prediction, it needs to clarify the influencing factors and their mechanism in the calculation process, and consider these factors for the corresponding calculation during the trajectory construction and optimization, so as to ensure that the predicted profile meets the requirements of airspace management, safety and economy. The factors to be considered can be divided into the following categories:

(a) Flight status and performance constraints of aircraft

Aircraft performance is the basis of flight trajectory construction and the primary factor to be considered, which mainly includes the ceiling, speed range at different altitudes, climbing performance, cruising performance, descending performance, voyage altitude, voyage distance, fuel consumption under different climbing modes, flight time, etc.

(b) Optimization indexes

The optimization indexes refer to the objectives concerned in the process of aircraft trajectory optimization, which are: minimum fuel, minimum cost, minimum time, maximum climb/descent track angle, maximum climb/descent rate, maximum endurance time, etc. The most typical optimization index is cost index. The cost index is the state of the aircraft at economic speed, which is the result of comprehensive consideration of time cost and fuel cost, and requires the company to accurately calculate the cost.

(c) Environmental information

Environmental information mainly includes the information of external temperature, wind speed, etc., which has a direct impact on the flight speed and flight performance of aircraft and needs to be considered in the process of trajectory optimization. An accurate wind temperature model should be built, and the flight instructions of aircraft should be corrected in real time according to the current information in the actual flight process, which is a critical influencing factor of dynamic planning.

(d) Flight plan and ATM requirements

Flight plan is a description of flight route (longitude, latitude and altitude) and RTA requirements, and it is the main constraint of flight trajectory optimization prediction. There are four types of altitude restrictions for waypoints in the flight plan: "AT", "AT or Above", "AT or Below" and "Between", and the aircraft must meet the altitude instructions to be reached at each waypoint along the route. The waypoint speed limit is usually regarded as a speed limit that can't be exceeded. If possible, fly at the specified speed, but if necessary, it is constrained by other control factors.

On the one hand, the requirements of ATM are reflected in the established flight plan; on the other hand, it is reflected in the emergency settings during the flight and the real-time control instructions of ATM. It must ensure that the optimized flight trajectory does not conflict with other aircraft in the airspace, which is also a critical factor in the dynamic optimization and prediction of flight trajectory. There is a need for interaction and balance between ATM instructions and the optimization and prediction of flight trajectory.

2.1.2 Technical issues to be solved

According to the flight plan, air traffic management, backup fuel rules and the performance limitation of the aircraft itself, the flight profile is optimized to achieve the minimum cost index, the optimal flight speed and altitude of the flight profile in each flight phase are calculated, and the fuel consumption of the aircraft is monitored, which provides data for the vertical guidance of the aircraft and the performance advisory of the pilot. These research items involve aircraft design performance, aerodynamics, engine characteristics, atmospheric conditions, airport conditions and airspace operation regulations, etc., which are interdisciplinary and comprehensive tasks, with difficulty in comprehensive design.

The main difficulty of this technology is the complexity of constraints and optimization targets. It needs to comprehensively consider multiple constraints such as control requirements, meteorological information, flight missions, aircraft performance restrictions, airline policies, planned fight segment speed, altitude and time restrictions, and calculate the optimal flight profile to meet the safety and economic requirements. The original forms of the constraint information are quite different, some are table-based parameters provided by aircraft manufacturers, and some are predicted temperatures and winds.

During the calculation and optimization of 3D flight profile, performance prediction and optimization need to calculate the altitude and speed profile that meets the minimum operating cost of the aircraft according to cost parameters, weather, performance constraints of the aircraft itself and other factors. During the 4D flight profile management, the performance prediction optimizes and corrects the airspeed of the flight plan, and generates the commanded airspeed to meet the requirements of the waypoint arrival time, thus improving the flight arrival time and turnaround period, reducing the waiting time and enhancing the flight safety.

2.1.3 Research methods and approaches

Clarify the constraints that affect the flight trajectory generation, the optimization target and its mechanism in the calculation process, and consider these factors in corresponding calculations in the flight trajectory construction and optimization, and make full use of the information provided by monitoring, communication and navigation equipment to ensure that the profile generated by the flight management system meets the requirements of airspace management, safety and economy.

2.1.4 Expected goal

The expected goal is to develop a trajectory generation algorithm considering multiple constraints and multiple optimization targets to achieve the objectives of green air traffic operation.

2.2 METHODS DESCRIPTION

2.2.1 Constraint model

As an important part of this study, constraints are of great significance to the authenticity and applicability of this study. This section mainly discusses the establishment of constraint model.

The constraints in this study are mainly divided into the following types: aircraft performance constraints, waypoint constraints of horizontal flight plan, speed altitude constraints, obstacles constraints, and restricted area constraints caused by meteorological effects.

2.2.1.1 Aircraft performance constraints

1) Minimum turn radius: Time and turn radius are required for the aircraft to change its heading. When the curvature radius of each turning point of the trajectory is less than the minimum turn radius of the aircraft, the trajectory cannot be flown, so the minimum turn radius should be considered in the course of trajectory planning, and the curvature radius of track point at the turning point should be greater than or equal to the minimum turn radius;

2) Maximum pitch angle: The factors that affect the pitch angle of an aircraft in 3D flight trajectory planning include its own maneuverability, flight altitude and climate conditions, etc. This constraint restricts the aircraft to pitch only in a specific angle, and requires that the pitch angle of an aircraft at a certain track point be less than the maximum pitch angle;

3) Minimum and maximum flight altitude: The minimum altitude of each reachable track point during track search is not less than a given safe altitude, and at the same time, since some aircraft controlled by the ground station need to contact the ground station, the flight altitude is also required to be no higher than the maximum pitch angle.

2.2.1.2 Obstacle constraints

Threat field constraint: During the flight, the aircraft needs to consider the location, threat radius and threat degree of various threats (bad weather, terrain obstacles, etc.), and must obtain threat information in time to ensure the safety of the aircraft.

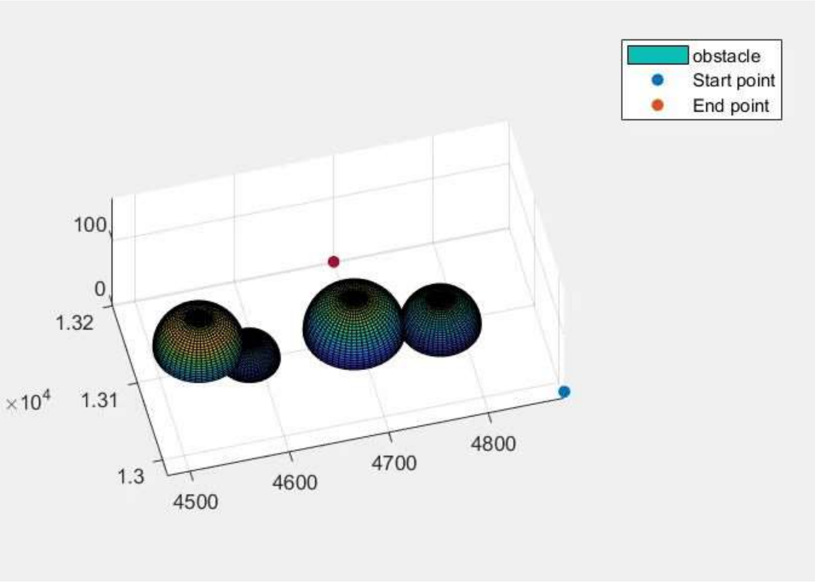

Figure 1: Diagram of static obstacles

2.2.1.3 Weather-induced restricted area constraints

In order to further approach the real flight conditions, this study will use real weather data, so it is inevitable to encounter some areas that cannot fly due to meteorological restrictions, such as nasty clouds, strong winds or thunderstorms, etc. At this time, the track points output by the trajectory optimization algorithm cannot enter these areas.

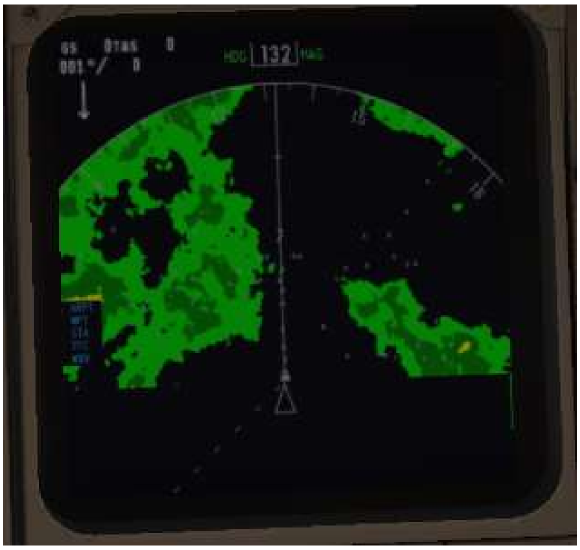

Figure 2: Diagram of extensive rain clouds

2.2.2 Evaluation model of trajectory optimization index

In this chapter, the advantage of CL-RRT algorithm and Hybrid-A* algorithm is determined by establishing the evaluation model of trajectory optimization index. The evaluation model of flight trajectory optimization index consists of optimization target function, aircraft flight dynamics model, flight configuration, thrust model, resistance model and fuel consumption model. The above models are established by referring to BADA, and these models will be introduced in this section.

2.2.2.1 Establishment of optimization target function

The optimization target function aims to determine the minimum cost of a single flight. By referring to BADA 3.8 and other relevant civil aviation flight data, the Direct Operating Cost (DOC) is introduced to calculate the minimum cost of a single flight. Generally speaking, DOC mainly includes:

1) Fixed costs (aircraft insurance and ground taxi costs, etc.).
2) Flight-related costs.
3) Fuel-related costs.

2.2.2.2 Flight configuration

There are five aircraft configurations based on flight altitude and speed, namely, take-off configuration (TO), initial climb configuration (IC), cruise configuration (CR), approach configuration (AP) and landing configuration (LD). Different flight configurations define different calculation forms of thrust and drag of aircraft.

2.2.3 Multi-constraint and Multi-objective Trajectory Optimization Algorithm

In view of the two algorithms mentioned in the project, compare their optimization effect in three specified routes: Beijing-Taiyuan, Guangzhou-Amsterdam. After preliminary investigation and comparison, two path planning algorithms, CL-RRT and Hybrid-A*, are proposed for this project. Here is a brief introduction to the general idea of these two algorithms.

2.2.3.1 Path planning algorithm based on CL-RRT

By extending the traditional RRT algorithm, CL-RRT samples the input of a stable closed-loop system composed of aircraft and controllers, which significantly improves the real-time performance and security of the algorithm, and can generate feasible flight trajectories online in an unknown and complex environment, and is usually close to the optimal flight trajectory. In this study, the fuel consumption, flight time and flight cost of a complete flight phase, including take-off, climb, cruise, descent, approach and landing, are taken as optimization targets.

The idea of the algorithm is as follows:

1) Setting of initialization conditions: Initialize the optimized objective and flight route, and plan the route under the constraints of the constraint model;

2) Design of collision detection algorithm: To ensure that the real-time planned route can avoid obstacles safely and effectively;

3) Expansion of random tree: Based on the idea of RRT expanded random tree to search a route from the starting point to the target point under the constraint model output;

4) Further route optimization: Further optimize the searched route to ensure that the final route can achieve the minimum flight time, fuel consumption and cost.

For (1), the settings of initial conditions can be roughly divided into: setting of starting point, setting of target point, setting of constraints and setting of working interval. The setting of the starting point includes the coordinates of the starting point and the initial entry angle of the starting point; The setting of the target point includes the coordinates of the target point and the final entry angle of the target point; Constraint setting includes aircraft performance constraints (minimum turn radius, flight altitude, minimum length of track section, climb rate, descent rate, etc.) and obstacles constraints (distribution of obstacles: centroid of obstacles, average geometric radius of obstacles, number of obstacles, etc.); Environmental constraints: As this project needs to consider the actual influence of wind power and temperature, the actual path planning needs to consider the actual constraints of aerodynamics and the actual influence of temperature on aircraft flight performance. This project mainly considers: horizontal flight plan with altitude constraint and speed constraint, cruising altitude, altitude limitation of climbing and descending speed, air temperature data of air route, boundary and entrance coordinates of western flexible airspace, meteorological restricted area boundary, aircraft gross weight, optimization mode, setting of starting point and setting of target point.

For (2), the collision detection algorithm is designed to ensure that the planned route can effectively avoid obstacles. The idea of collision detection algorithm is as follows: Firstly, the Euclidean coordinates of the centroid of each obstacle are obtained, and the coordinates of the own ship are analyzed; Then, calculate the distance between the own ship and the centroid of all obstacles; If the distance between the own ship and the centroid of any obstacle is less than the safety margin of the obstacle, it is determined that a collision has occurred. Where, the safety margin of obstacles is defined as the radius of obstacles plus the safety boundary distance or the height of obstacle crossing.

For (3), expansion of random tree: This step adds the starting point to the random tree and sets the expansion step size according to the idea of RRT. Generate random points in space, find the nearest node on the random tree, and set an expanded step size on the line between them to get new nodes. Determine whether the new node and adjacent nodes cross obstacles, and if not, add the new node to the random tree. Judge whether the distance between the latest node and the target point is less than or equal to the step, if not, repeat the previous steps, otherwise, find the leaf node closest to the target point in the random tree as the starting point, and search the parent node upward in turn, so as to get the trajectory from the starting point to the target point. However, the above processes need to meet the constraints in the constraint model.

For (4), due to that the trajectory searched in (3) is not necessarily the optimal, and the optimal trajectory is obtained via further optimization on the basis of the trajectory searched in (3). The specific steps are as follows: Take the track obtained in (3) as the center, extend the left and right sides to a certain length to obtain a "feasible airspace search range", and count the indicators of each effective trajectory obtained within the search azimuth of the feasible domain, including fuel consumption, flight time, cost, etc., and output the track points, optimized vertical flight trajectory, optimized horizontal flight trajectory, optimized speed profile and optimized fuel consumption profile of each effective flight path.

The schematic diagram of path planning algorithm for CL-RRT is as follows:

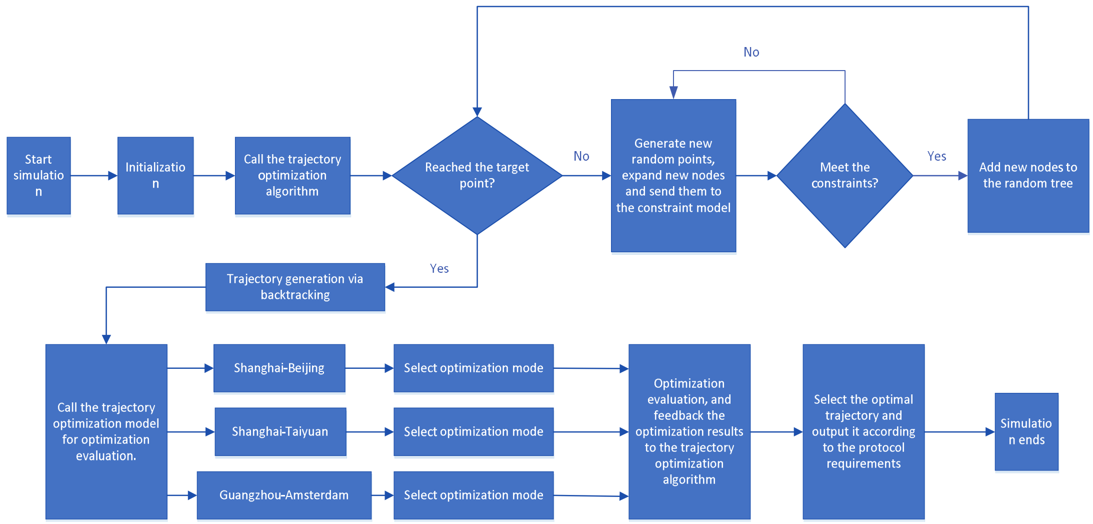

Figure 3: Workflow of trajectory algorithm program

2.2.3.1.1 CL-RRT-based path planning algorithm module

The CL-RRT-based path planning algorithm module is used to search the flight trajectories that meet the constraints from the starting point to the target point, which mainly consists of two parts: the track point search module and the track point connection module; The track point search module bases on the CL-RRT path planning algorithm to search for the track points from the starting point to the target point, and the track point connection module connects the track points searched by the track point search module in a constrained connection mode to obtain a feasible path.

2.2.3.1.1.1 Waypoint search module

The design idea of track point search is roughly as follows: Based on the expansion idea of CL-RRT random tree, the sub-nodes are continuously expanded to the target point with a certain expansion step size from the starting point. Each expanded sub-node must ensure that it does not collide with obstacles and meet the output constraints of the constraint module. If it does not meet the requirements, new sub-nodes are randomly generated again. When the generated sub-nodes reach the target point or are less than an expansion step, it is considered that the algorithm has found the target point, and then track back from the target point. The pseudo-code of the algorithm is as follows:

Table 1. Pseudo-code based on CL-RRT waypoint search algorithm

CL-RRT-based waypoint search algorithm

Input: Workspace, Start Point, End Point, Constraint. Output: The path from the starting point to the end point that satisfies the constraint. Initialization The number of iteration steps from 0 to the maximum. 1. Generate random points in the workspace q_{rand} 2. Find the nearest neighboring node q_{near} from the random point q_{rand} 3. Connect q_{rand} with the neighboring node in a certain step size to q_{near} generate the new node q_{new} 4. Perform collision detection on q_{near} and q_{new}: I: If no collision occurs, add q_{new} to the random tree II: If any collision occurs, return to step 1. 5. Check whether the target point has been reached. I: If yes, stop the growth of the random tree, and track back. II: If no, return to step 1.

2.2.3.1.1.2 Waypoint connection module

The waypoint connection module is used to connect the parent node and the child node in a connection mode that satisfies the constraints. This module will first introduce the connection mode of 2D paths satisfying kinematic and dynamic constraints. In order to meet the scenario requirements, it will introduce the transformation matrix required by the conversion approach No.2 for transforming 2D paths into 3D paths.

This part mainly explains the connection mode of 2D paths considering constraints and the method of transforming 2D paths into 3D paths. The pseudo-code of the algorithm is as follows:

Table 2. Pseudo-code of waypoint connection module

Waypoint connection
Input: Child node, parent node and turn radius Output: 3D waypoints between child nodes and parent nodes that satisfy constraints 1. Given the coordinates of parent node and child node 2. Calculate the transformation matrix T_{ag} 3. Take the child node as the coordinate origin o, and calculate the relative

coordinates of the parent node A

4. Connect oA with MCT to obtain 2D MCT trajectory
5. The 2D waypoints obtained in Step 4 is multiplied by the transformation matrix T_{ag} to obtain the 3D waypoints
6. The 3D waypoints obtained in Step 5 are added to the true coordinates of the child nodes

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2.2.3.2 Hybrid-A*-based path planning algorithm

Hybrid-A* algorithm replaces the nodes in A* algorithm with trajectories generated by the model that satisfy kinematic constraints, thus solving the problem that paths do not satisfy kinematic constraints. The main difference between Hybrid-A* algorithm and basic A* algorithm is that the steps of Hybrid-A* algorithm generate connecting nodes and target curves according to rules. In this study, the fuel consumption, flight time and flight cost of each phase during a complete flight process, including take-off, climb, cruise, descent, approach and landing, are taken as optimization targets.

1) Setting of initialization conditions: Location of initial point, location of end point, setting of constraints, setting of optimization targets, setting of cost function, setting of heuristic function and setting of working interval;

2) Design of collision detection algorithm: To ensure that the real-time planned route can avoid obstacles safely and effectively;

3) Design of heuristic search: Definition of openlist and closelist, design of heuristic function, design of cost function, selection of nodes, setting of node priority, search and update of parent nodes, etc.;

4) Count the indicators of each effective track: Fuel consumption, flight time and cost, and output the track points of each effective track.

For 1), the settings of initial conditions can be roughly divided into: setting of starting point, setting of target point, setting of constraints and setting of working interval. The setting of the starting point includes the coordinates of the starting point; The setting of the target point includes the coordinates of the target point; Constraint setting includes aircraft performance constraints (minimum turn radius, flight altitude, minimum length of track section, climb rate, descent rate, etc.) and obstacles constraints (distribution of obstacles: centroid of obstacles, average geometric radius of obstacles, number of obstacles, etc.); Environmental constraints: As this project needs to consider the actual influence of wind power and temperature, the actual path planning needs to consider the actual constraints of aerodynamics and the actual influence of temperature on aircraft flight performance. In addition, it needs to define an openlist and a closelist for finding and storing waypoints, and to design a heuristic function and a cost function. These two functions are selected according to the optimized objective. This project can consider selecting the next waypoint according to the fuel consumption and flight path of each step. This project mainly considers: horizontal flight plan with altitude constraint and speed constraint, cruising altitude, altitude limitation of climbing and descending speed, air temperature data of air route, boundary and entrance coordinates of western flexible airspace, meteorological restricted area boundary, aircraft gross weight, optimization mode, setting of starting point and setting of target point.

For 2), the collision detection algorithm is designed to ensure that the planned route can effectively avoid obstacles. The general idea of collision detection algorithm is as follows: Obtain the coordinates of the own ship and the Euclidean distance of the centroid of the obstacle in real time, and ensure that the coordinates of the next point obtained by the path planning algorithm meet this constraint in real time: The Euclidean distance between the own ship and the obstacle is always greater than the radius of the obstacle, but considering the need to leave a certain safety margin, the Euclidean distance between the own ship and the obstacle should be greater than the radius of the obstacle plus the safe boundary distance or the height of the obstacle crossing. Points that do not meet this constraint should not be used as intermediate points during path planning. In view of the simplification of obstacles, the establishment of the aforementioned constraint model has been described, so it will not be repeated here.

For 3), the general idea of the algorithm is as follows: Firstly, initialize the openlist and the closelist, add the starting point to the openlist, and give the starting point the highest priority. Next, generate the nodes. First, determine whether the openlist is empty. If not, select the node with the highest priority$n$, and delete the node n from the openlist and put it into the closelist. Next, look for the neighboring nodes of node. Select the optimal neighboring node m according to the cost function and the heuristic function. If the optimal neighboring node m is in the closelist, skip selecting the next node; If the optimal neighboring node is not in the closelist, set the parent node of node m as node n. Calculate the priority of the node m and put the node m in the openlist. Note that the above processes need to meet the constraints in the constraint model.

For 4), perform further optimization according to the searched path to find the optimal one. Count the indicators of each effective trajectory obtained within the search azimuth of the feasible domain are counted, including fuel consumption, flight time, cost, etc., and output the track points, optimized vertical flight trajectory, optimized horizontal flight trajectory, optimized speed profile and optimized fuel consumption profile of each effective flight path. The following figure shows the flow chart of the trajectory optimization algorithm based on Hybrid-A* algorithm:

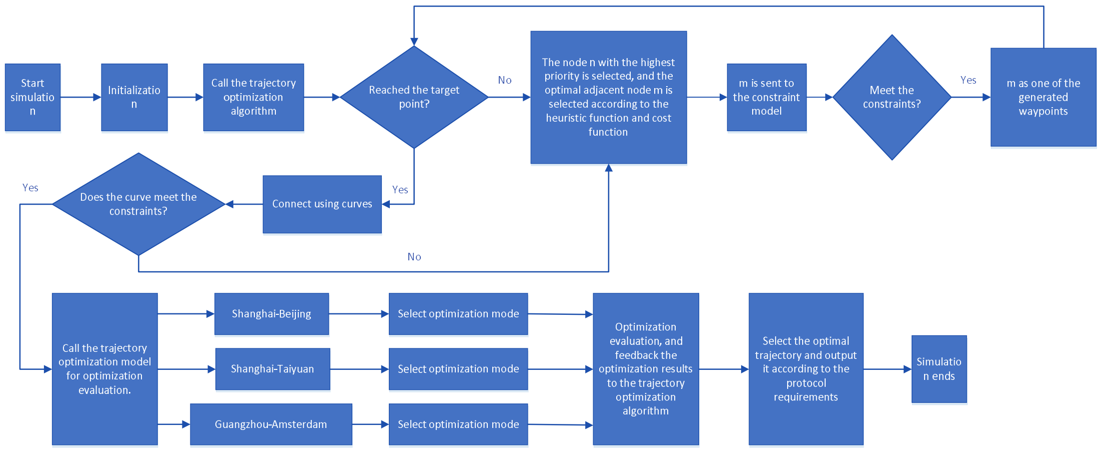


Figure 4: Flow chart of Hybrid-A* algorithm-based trajectory optimization algorithm

2.2.3.2.1 Implementation of Hybrid-A* algorithm

2.2.3.2.1.1 Constraint module

This module is used to establish the constraint model of the algorithm.

i. Establishment of waypoint constraints
ii. Establishment of obstacle constraints
iii. Establishment of aircraft performance limit constraints
iv. Establishment of speed altitude limit constraints
v. Establishment of restricted area constraints due to meteorological effects

2.2.3.2.2 Hybrid-A*-based path planning algorithm module

2.2.3.2.2.1 Waypoint search module

This module is used to search for the track points from the starting point to the target point.

The search idea of waypoints is roughly as follows: After initializing the openlist and the closelist, based on the node expansion idea of Hybrid-A*, starting from the node with the lowest path cost in the openlist, continuously expand the child nodes to the target point with the optimization target as the optimization condition with a specific expansion step size and discrete angle, obtaining the expanded node list. Traverse the expanded node list. When adding nodes to the openlist, ensure that the nodes meet the obstacle avoidance requirements and the output constraints of the constraint module. If it does not meet the requirements, skip it. If the node is already in the closelist, skip it. When the node reaches the target point or the distance between the node and the target point is less than or equal to the expansion step size, it will be judged as reaching the target point, then jump out of the expansion node cycle, and backtrack the parent node from the target point. The pseudo code of the algorithm is as follows:

Table 3. Hybrid-A* node expansion algorithm

Hybrid-A* node expansion algorithm
Input: Workspace, starting point, end point, constraints and expansion step size Output: The path from the starting point to the end point that satisfies the constraint. 1. Initialization: add the starting point to the openlist. Repeat the following steps: 2. Take the head node in the openlist as the current processing node. 3. If the current processing node reaches the vicinity of the target point Exit 4. Expand the current node to get an expanded node list. 5. Traverse the points in the expanded node list. 6. If the node does not meet the collision avoidance condition Skip 7. If the node is already in the closelist Skip 8. If the node is already in the openlist Judge whether the node needs to be updated. 9. If the node is not in the openlist Update the node into the openlist. 10. End traversal 11. Sort the nodes in the openlist according to the path cost, and return to step 1.

i. Select the current processing node.

Select the head node in the openlist as the current processing node.

ii. Expanded node list generation

According to the idea of Hybrid A*, each node contains information such as position, attitude angle, path cost function and parent node pointer, which is expressed as:

$$n = (x, y, yaw, G(n), F(n), {n_p}^*)$$

Where, (x, y) is the position information, yaw is the yaw angle information, $G(n)$ is the path cost from the starting point to the current node, $F(n)$ is the path cost from the starting point to the end point, which is used to prioritize the expanded nodes to guide the expansion direction of the nodes, and ${n_p}^*$ is the pointer to the parent node. The expression of cost function $F(n)$ is as follows:

$$F(n) = G(n) + H(n)$$

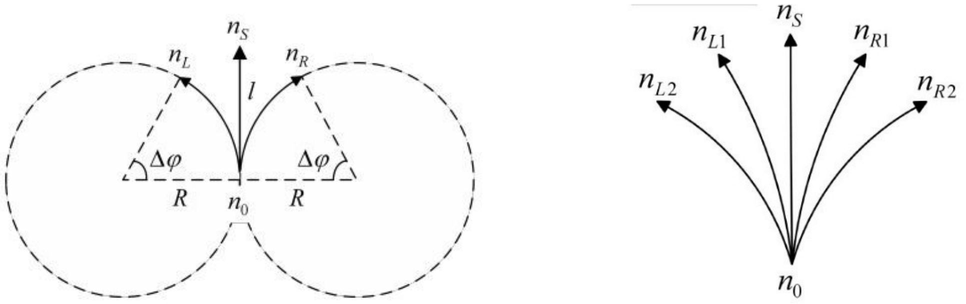
Where, $H(n)$ is a heuristic function. In general, in the Hybrid A* algorithm, the Dubins curve length, which ignores the environmental obstacle constraint and considers only the kinematic constraint, or the programming results of A* algorithm, which ignores the kinematic constraint and considers only the environmental obstacle constraint, can be selected as the heuristic function, or two heuristic parallel methods 5 can be adopted. The heuristic function selected in this project is Euclidean distance from the track point to the target point. If the track point is q_{new} and the target point is q_{goal}, the calculation of $H(n)$ is as follows:

$$H(n) = \sqrt{(x_{q_{goal}} - x_{q_{new}})^2 + (y_{q_{goal}} - y_{q_{new}})^2 + (z_{q_{goal}} - z_{q_{new}})^2}$$

Table 4. Interpretation of related parameters

$x_{q_{goal}}$	$y_{q_{goal}}$	$z_{q_{goal}}$
Target point abscissa	Target point ordinate	Target point altitude
$x_{q_{new}}$	$y_{q_{new}}$	$z_{q_{new}})$
Track point abscissa	Track point ordinate	Track point altitude

Therefore, the node expansion of Hybrid-A* algorithm adopts the node expansion mode of continuous space, and the schematic diagram of node expansion is as follows.



(a) Single expansion angle (b) Multi-expansion angle

Figure 5: Schematic diagram of node expansion

iii. Traverse the expanded node list

The list of expanded nodes obtained by traversal. If the point does not meet the constraint model, skip; If the node is already in the closelist, skip; If the node is already in the openlist, compare whether the new expansion mode makes the node have a smaller path cost, and if so, update the parent node and path cost of the point in the openlist; If the node is not in the openlist, add the node to the openlist.

iv. Sort the nodes in the openlist.

Sort the nodes in openlist according to the path cost.

v. Judge the end condition of node expansion

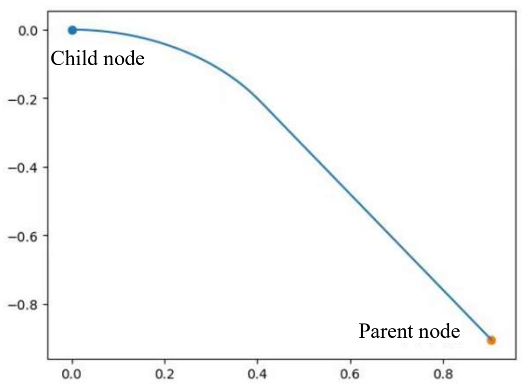
Judge whether that end point has been added into the openlist. If yes, the pathfinding ends, and sequentially backtracking the parent node from the end point to generate a complete planned path; If not, skip to step (a).

2.2.3.2.2.2 Waypoint connection module

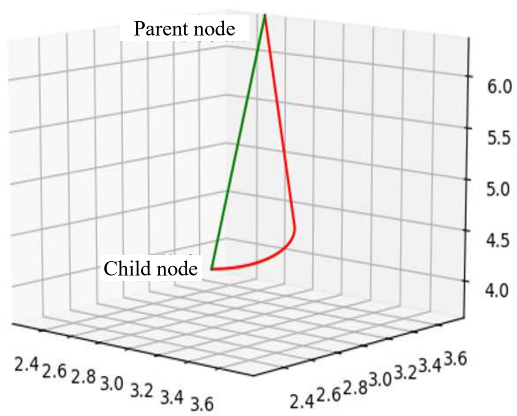
The module is used to connect the track points obtained by search to obtain a 2D path and convert the obtained 2D path. The pseudo-code of this module is as follows:

Table 5. Pseudo-code of waypoint connection module

Waypoint connection
Input: Child node, parent node and turn radius
Output: 3D waypoints between child nodes and parent nodes that satisfy constraints
1. Given the coordinates of parent node and child node
2. Calculate the transformation matrix T_{ag}
3. Take the child node as the coordinate origin o,and calculate the relative coordinates of the parent node A
4. Connect oA with MCT to obtain 2D MCT trajectory
5. The 2D waypoints obtained in Step 4 is multiplied by the transformation matrix T_{ag} to obtain the 3D waypoints
6. The 3D waypoints obtained in Step 5 are added to the true coordinates of the child nodes



(a) 2D MCT curve



(b) 3D MCT curve

Figure 6: 2D-3D MCT curve

2.3 EXPERIMENTS AND RESULTS

2.3.1 Simulation verification of CL-RRT-based trajectory optimization algorithm

2.3.1.1 Simulation verification of Beijing-Taiyuan route scenario

2.3.1.1.1 Simulation verification of flight time optimization of Beijing-Taiyuan route under waypoint constraints

Table 6. Simulation verification of flight time optimization of Beijing-Taiyuan route under waypoint constraints

Test module No.	CLRRTHJYHSF_TEST_01	Name of tested module/function	Simulation verification of flight time optimization of Beijing-Taiyuan route under waypoint constraints
Description of tested module/function	Specific function	Taking Beijing as the starting point and Taiyuan as the end point, the waypoints data in the "ZBAA-ZBYN Cross-point Data" file as the waypoint constraints, and the flight time as the optimization target, complete the search of the optimized trajectory, and output the flight time and algorithm running time after trajectory optimization.	
	Input parameters	Position information of Beijing (starting point) (coordinates of x, y and z axes in geodetic coordinate system), position information of Taiyuan (end point) (coordinates of x, y and z axes in geodetic coordinate system), aircraft speed, waypoint data of ZBAA-ZBYN route, flight speed at starting point, flight fuel consumption at starting point, temperature	

		at starting point, pressure at starting point, the mass of the aircraft and the wing area of the aircraft.
	Output parameters	The route between Beijing and Taiyuan that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan, and the flight time between Beijing and Taiyuan that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan.
	Main flow and algorithm	Obtain the waypoints between the starting point and the target point ➞ Obtain the constraints ➞ Search the route from the starting point to the end point under the condition of satisfying the constraints ➞ Calculate the thrust of each waypoint ➞ Calculate the drag of each waypoint ➞ Calculate the speed and acceleration of each waypoint ➞ Calculate the flight time between each route segment ➞ Calculate the fuel consumption of each waypoint ➞ Calculate the flight fuel consumption between each route segment.
Expected result	Criterion	1.Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Beijing-Taiyuan waypoint. 2.Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Beijing-Taiyuan waypoint speed. 3.The flight time of Beijing-Taiyuan is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target.
	Interpretation of results	1.Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained

		Beijing-Taiyuan waypoint, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Beijing-Taiyuan waypoint speed, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint speed. 3. The flight time of Beijing-Taiyuan is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the waypoint constraint of horizontal flight and the optimization target, and outputs the optimized time.

2.3.1.1.2 Simulation verification of fuel consumption optimization of Beijing-Taiyuan route under waypoint constraints

Table 7. Simulation verification of fuel consumption optimization of Beijing-Taiyuan route under waypoint constraints

Test module No.	CLRRTHJYHSF_TEST_02	Name of tested module/function	Simulation verification of fuel consumption optimization of Beijing-Taiyuan route under waypoint constraints
Description of tested module/function	Specific function	Taking Beijing as the starting point and Taiyuan as the end point, the waypoints data in the "ZBAA-ZBYN Cross-point Data" file as the waypoint constraints, and the fuel consumption as the optimization target,	

		complete the search of the optimized trajectory, and output the fuel consumption and algorithm running time after trajectory optimization.
	Input parameters	Position information of Beijing (starting point) (coordinates of x, y and z axes in geodetic coordinate system), position information of Taiyuan (end point) (coordinates of x, y and z axes in geodetic coordinate system), aircraft speed, waypoint data of ZBAA-ZBYN route, flight speed at starting point, flight fuel consumption at starting point, temperature at starting point, pressure at starting point, the mass of the aircraft and the wing area of the aircraft.
	Output parameters	The route between Beijing and Taiyuan that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan, and the fuel consumption between Beijing and Taiyuan that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan.
	Main flow and algorithm	Obtain the waypoints between the starting point and the target point → Obtain the constraints → Search the route from the starting point to the end point under the condition of satisfying the constraints → Calculate the thrust of each waypoint → Calculate the drag of each waypoint → Calculate the speed and acceleration of each waypoint → Calculate the flight time between each route segment → Calculate the fuel consumption of each waypoint → Calculate the fuel consumption between each route segment.

Expected result	Criterion	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Beijing-Taiyuan waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Beijing-Taiyuan waypoint speed. 3. The fuel consumption of Beijing-Taiyuan is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target.
	Interpretation of results	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Beijing-Taiyuan waypoint, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Beijing-Taiyuan waypoint speed, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint speed. 3. The fuel consumption of Beijing-Taiyuan is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the waypoint constraint of horizontal flight and the optimization target, and outputs the optimized fuel consumption.

2.3.1.2 Simulation verification of Guangzhou-Amsterdam route scenario

2.3.1.2.1 Simulation verification of flight time optimization of Guangzhou-Amsterdam route under waypoint constraints

Table 8. Simulation verification of flight time optimization of Guangzhou-Amsterdam route under waypoint constraints

Test module No.	CLRRTHJYHSF_TEST_11	Name of tested module/function	Simulation verification of flight time optimization of Guangzhou-Amsterdam route under waypoint constraints
Description of tested module/function	Specific function	Taking Guangzhou as the starting point and Amsterdam as the end point, the waypoints data in the "ZGGG-EHAM Cross-point Data" file as the waypoint constraints, and the flight time as the optimization target, complete the search of the optimized trajectory, and output the flight time and algorithm running time after trajectory optimization.	
	Input parameters	Position information of Guangzhou (starting point) (coordinates of x, y and z axes in geodetic coordinate system), position information of Amsterdam (ending point) (coordinates of x, y and z axes in geodetic coordinate system), aircraft speed, waypoint data of ZGGG-EHAM route, flight speed at starting point, flight fuel consumption at starting point, temperature at starting point, pressure at starting point, the mass of the aircraft and the wing area of the aircraft.	
	Output parameters	The route between Guangzhou and Amsterdam that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan, and the flight time between Guangzhou and Amsterdam that meets the waypoint	

		constraints (altitude constraints and speed constraints) of the horizontal flight plan.
	Main flow and algorithm	Obtain the waypoints between the starting point and the target point → Obtain the constraints → Search the route from the starting point to the end point under the condition of satisfying the constraints → Calculate the thrust of each waypoint → Calculate the drag of each waypoint → Calculate the speed and acceleration of each waypoint → Calculate the flight time between each route segment → Calculate the fuel consumption of each waypoint → Calculate the flight fuel consumption between each route segment.
Expected result	Criterion	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 3. The flight time of Guangzhou-Amsterdam is searched and output under the constraint of the waypoint of horizontal flight and taking the flight cost as the optimization target.
	Interpretation of results	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Guangzhou-Amsterdam

		waypoint speed, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint speed. 3. The flight time of Guangzhou-Amsterdam is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the waypoint constraint of horizontal flight and the optimization target, and outputs the optimized flight time.

2.3.1.2.2 Simulation verification of fuel consumption optimization of Guangzhou-Amsterdam route under waypoint constraints

Table 9. Simulation verification of fuel consumption optimization of Guangzhou-Amsterdam route under waypoint constraints

Test module No.	CLRRTHJYHSF_TEST_12	Name of tested module/function	Simulation verification of fuel consumption optimization of Guangzhou-Amsterdam route under waypoint constraints
Description of tested module/function	Specific function	Taking Guangzhou as the starting point and Amsterdam as the end point, the waypoints data in the "ZGGG-EHAM Cross-point Data" file as the waypoint constraints, and the fuel consumption as the optimization target, complete the search of the optimized trajectory, and output the fuel consumption and algorithm running time after trajectory optimization.	
	Input parameters	Position information of Guangzhou (starting point) (coordinates of x, y and z axes in geodetic coordinate system), position information of Amsterdam (end point) (coordinates of x, y and z axes in geodetic	

		coordinate system), aircraft speed, waypoint data of ZBAA-ZBYN route, flight speed at starting point, flight fuel consumption at starting point, temperature at starting point, pressure at starting point, the mass of the aircraft and the wing area of the aircraft.
	Output parameters	The route between Guangzhou and Amsterdam that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan, and the flight time between Guangzhou and Amsterdam that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan.
	Main flow and algorithm	Obtain the waypoints between the starting point and the target point → Obtain the constraints → Search the route from the starting point to the end point under the condition of satisfying the constraints → Calculate the thrust of each waypoint → Calculate the drag of each waypoint → Calculate the speed and acceleration of each waypoint → Calculate the flight time between each route segment → Calculate the fuel consumption of each waypoint → Calculate the fuel consumption between each route segment.
Expected result	Criterion	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 3. The fuel consumption of Guangzhou-Amsterdam is searched and output under the constraint of the waypoint of horizontal

		flight and taking the flight time as the optimization target.
	Interpretation of results	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint speed, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint speed. 3. The fuel consumption of Guangzhou-Amsterdam is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the waypoint constraint of horizontal flight and the optimization target, and outputs the optimized fuel consumption.

2.3.1.3 Simulation and verification of flight time optimization of Guangzhou-Amsterdam route under the constraints of waypoint, obstacle and restricted area caused by meteorological effects

Table 10. Simulation and verification of flight time optimization of Guangzhou-Amsterdam route under the constraints of waypoint, obstacle and restricted area caused by meteorological effects

Test module No.	CLRRTHJYHSF_TEST_15	Name of tested module/function	Simulation and verification of flight time optimization of Guangzhou-Amsterdam route under the constraints of waypoint, obstacle and restricted area caused by meteorological effects
Description of tested module/function	Specific function	Taking Guangzhou as the starting point and Amsterdam as the end point, the waypoints data in the "ZGGG-EHAM Cross-point Data" file as the waypoint constraints, the obstacle areas set between Guangzhou and Amsterdam (the searched waypoints cannot enter these areas) as the obstacle constraint, the bad weather areas set between Guangzhou and Amsterdam as the restricted areas caused by meteorological effects (the searched waypoints cannot enter these areas), and the flight time as the optimization target, complete the search of the optimized trajectory, and output the flight time and algorithm running time after trajectory optimization.	
	Input parameters	Position information of Guangzhou (starting point) (coordinates of x, y and z axes in geodetic coordinate system), position information of Amsterdam (end point) (coordinates of x, y and z axes in geodetic coordinate system), aircraft speed, waypoint data of ZGGG-EHAM route; Set the geometric center and radius of the obstacle area, set the geometric center and radius of the restricted area caused by meteorological effects; flight speed at starting point, flight fuel consumption at	

		starting point, temperature at starting point, pressure at starting point, the mass of the aircraft and the wing area of the aircraft.
	Output parameters	The route between Guangzhou and Amsterdam that meets the waypoint constraints (altitude constraints, speed constraints), obstacle constraints and restricted area constraints caused by meteorological effects of horizontal flight plan, and the flight cost between Guangzhou and Amsterdam that meets the waypoint constraints (altitude constraints, speed constraints), obstacle constraints and restricted area constraints caused by meteorological effects of horizontal flight plan.
	Main flow and algorithm	Obtain the waypoints between the starting point and the target point → Obtain the constraints → Search the route from the starting point to the end point under the condition of satisfying the constraints → Calculate the thrust of each waypoint → Calculate the drag of each waypoint → Calculate the speed and acceleration of each waypoint → Calculate the flight time between each route segment.
Expected result	Criterion	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 3. Under the constraint of obstacles, the searched waypoints cannot be within the range of obstacles. 4. Under the restricted area constraint caused by weather, the speed at the waypoint obtained by search cannot be

		within the restricted area constraint caused by weather. 5. The flight time of Guangzhou-Amsterdam is searched and output under the constraints of waypoints, obstacles and restricted areas caused by weather in horizontal flight and taking flight time as the optimization target.
	Interpretation of results	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint speed, which indicates that the CL-RRT-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint speed. 3. Under the constraint of obstacles, the searched waypoints cannot be within the range of obstacles, which indicates that the CL-RRT trajectory optimization algorithm was used to search and obtain the optimized trajectory under the obstacle constraints. 4. Under the restricted area constraint caused by weather, the speed at the waypoint obtained by search cannot be within the restricted area constraint caused by weather, which indicates that the CL-RRT-based trajectory optimization algorithm has obtained the optimized trajectory under the weather-induced restricted area constraint. 5. The flight time of Guangzhou-Amsterdam is searched and output under the constraint of the waypoint of horizontal flight and

		taking the flight time as the optimization target, which indicates that the CL-RRT-based trajectory optimization algorithm takes the flight time as the optimization target under the constraint of the waypoints of horizontal flight, the obstacle constraint and the restricted area caused by weather, and outputs the optimized flight time.

2.3.2 Simulation verification of Hybrid-A*-based trajectory optimization algorithm

2.3.2.1 Simulation verification of Beijing-Taiyuan route scenario

2.3.2.1.1 Simulation verification of flight time optimization of Beijing-Taiyuan route under waypoint constraints

Table 11. Simulation verification of flight time optimization of Beijing-Taiyuan route under waypoint constraints

Test module No.	HYBRIDHJYHSF_TEST_01	Name of tested module/function	Simulation verification of flight time optimization of Beijing-Taiyuan route under waypoint constraints
Description of tested module/function	Specific function	Taking Beijing as the starting point and Taiyuan as the end point, the waypoints data in the "ZBAA-ZBYN Cross-point Data" file as the waypoint constraints, and the flight time as the optimization target, complete the search of the optimized trajectory, and output the flight time and algorithm running time after trajectory optimization.	
	Input parameters	Position information of Beijing (starting point) (coordinates of x, y and z axes in geodetic coordinate system), position information of Taiyuan (end point) (coordinates of x, y and z axes in geodetic coordinate system), aircraft speed,	

		waypoint data of ZBAA-ZBYN route, flight speed at starting point, flight fuel consumption at starting point, temperature at starting point, pressure at starting point, the mass of the aircraft and the wing area of the aircraft.
	Output parameters	The route between Beijing and Taiyuan that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan, and the flight time between Beijing and Taiyuan that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan.
	Main flow and algorithm	Obtain the waypoints between the starting point and the target point → Obtain the constraints → Search the route from the starting point to the end point under the condition of satisfying the constraints → Calculate the thrust of each waypoint → Calculate the drag of each waypoint → Calculate the speed and acceleration of each waypoint → Calculate the flight time between each route segment → Calculate the fuel consumption of each waypoint → Calculate the flight fuel consumption between each route segment.
Expected result	Criterion	4. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Beijing-Taiyuan waypoint. 5. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Beijing-Taiyuan waypoint speed. 6. The flight time of Beijing-Taiyuan is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target.

	Interpretation of results	4. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Beijing-Taiyuan waypoint, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint. 5. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Beijing-Taiyuan waypoint speed, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint speed. 6. The flight time of Beijing-Taiyuan is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the waypoint constraint of horizontal flight and the optimization target, and outputs the optimized time.

2.3.2.1.2 Simulation verification of fuel consumption optimization of Beijing-Taiyuan route under waypoint constraints

Table 12. Simulation verification of fuel consumption optimization of Beijing-Taiyuan route under waypoint constraints

Test module No.	HYBRIDHJYHSF_TEST_02	Name of tested module/function	Simulation verification of fuel consumption optimization of Beijing-Taiyuan route under waypoint constraints
Description of tested module/functio	Specific function	Taking Beijing as the starting point and Taiyuan as the end point, the waypoints data in the "ZBAA-ZBYN Cross-point Data"	

n		file as the waypoint constraints, and the fuel consumption as the optimization target, complete the search of the optimized trajectory, and output the fuel consumption and algorithm running time after trajectory optimization.
	Input parameters	Position information of Beijing (starting point) (coordinates of x, y and z axes in geodetic coordinate system), position information of Taiyuan (end point) (coordinates of x, y and z axes in geodetic coordinate system), aircraft speed, waypoint data of ZBAA-ZBYN route, flight speed at starting point, flight fuel consumption at starting point, temperature at starting point, pressure at starting point, the mass of the aircraft and the wing area of the aircraft.
	Output parameters	The route between Beijing and Taiyuan that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan, and the fuel consumption between Beijing and Taiyuan that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan.
	Main flow and algorithm	Obtain the waypoints between the starting point and the target point ➞ Obtain the constraints ➞ Search the route from the starting point to the end point under the condition of satisfying the constraints ➞ Calculate the thrust of each waypoint ➞ Calculate the drag of each waypoint ➞ Calculate the speed and acceleration of each waypoint ➞ Calculate the flight time between each route segment ➞ Calculate the fuel consumption of each waypoint ➞ Calculate the fuel consumption between each route segment.

Expected result	Criterion	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Beijing-Taiyuan waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Beijing-Taiyuan waypoint speed. 3. The fuel consumption of Beijing-Taiyuan is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target.
	Interpretation of results	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Beijing-Taiyuan waypoint, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Beijing-Taiyuan waypoint speed, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint speed. 3. The fuel consumption of Beijing-Taiyuan is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the waypoint constraint of horizontal flight and

		the optimization target, and outputs the optimized fuel consumption.

2.3.2.2 Simulation verification of Guangzhou-Amsterdam route scenario

2.3.2.2.1 Simulation verification of flight time optimization of Guangzhou-Amsterdam route under waypoint constraints

Table 13. Simulation verification of flight time optimization of Guangzhou-Amsterdam route under waypoint constraints

Test module No.	HYBRIDHJYHSF_ TEST_11	Name of tested module/function	Simulation verification of flight time optimization of Guangzhou-Amsterdam route under waypoint constraints
Description of tested module/function	Specific function	Taking Guangzhou as the starting point and Amsterdam as the end point, the waypoints data in the "ZGGG-EHAM Cross-point Data" file as the waypoint constraints, and the flight time as the optimization target, complete the search of the optimized trajectory, and output the flight time and algorithm running time after trajectory optimization.	
	Input parameters	Position information of Guangzhou (starting point) (coordinates of x, y and z axes in geodetic coordinate system), position information of Amsterdam (ending point) (coordinates of x, y and z axes in geodetic coordinate system), aircraft speed, waypoint data of ZGGG-EHAM route, flight speed at starting point, flight fuel consumption at starting point,	

		temperature at starting point, pressure at starting point, the mass of the aircraft and the wing area of the aircraft.
	Output parameters	The route between Guangzhou and Amsterdam that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan, and the flight time between Guangzhou and Amsterdam that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan.
	Main flow and algorithm	Obtain the waypoints between the starting point and the target point ➞ Obtain the constraints ➞ Search the route from the starting point to the end point under the condition of satisfying the constraints ➞ Calculate the thrust of each waypoint ➞ Calculate the drag of each waypoint ➞ Calculate the speed and acceleration of each waypoint ➞ Calculate the flight time between each route segment ➞ Calculate the fuel consumption of each waypoint ➞ Calculate the flight fuel consumption between each route segment.
Expected result	Criterion	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 3. The flight time of Guangzhou-Amsterdam is searched and output under the constraint of the waypoint of horizontal flight and taking the flight cost as the optimization target.

	Interpretation of results	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint speed, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint speed. 3. The flight time of Guangzhou-Amsterdam is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the waypoint constraint of horizontal flight and the optimization target, and outputs the optimized flight time.

2.3.2.2.2 Simulation verification of fuel consumption optimization of Guangzhou-Amsterdam route under waypoint constraints

Table 14. Simulation verification of fuel consumption optimization of Guangzhou-Amsterdam route under waypoint constraints

Test module No.	HYBRIDHJYHSF_TEST_12	Name of tested module/function	Simulation verification of fuel consumption optimization of Guangzhou-Amsterdam route

			under waypoint constraints
Description of tested module/function	Specific function	Taking Guangzhou as the starting point and Amsterdam as the end point, the waypoints data in the "ZGGG-EHAM Cross-point Data" file as the waypoint constraints, and the fuel consumption as the optimization target, complete the search of the optimized trajectory, and output the fuel consumption and algorithm running time after trajectory optimization.	
	Input parameters	Position information of Guangzhou (starting point) (coordinates of x, y and z axes in geodetic coordinate system), position information of Amsterdam (end point) (coordinates of x, y and z axes in geodetic coordinate system), aircraft speed, waypoint data of ZBAA-ZBYN route, flight speed at starting point, flight fuel consumption at starting point, temperature at starting point, pressure at starting point, the mass of the aircraft and the wing area of the aircraft.	
	Output parameters	The route between Guangzhou and Amsterdam that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan, and the flight time between Guangzhou and Amsterdam that meets the waypoint constraints (altitude constraints and speed constraints) of the horizontal flight plan.	
	Main flow and algorithm	Obtain the waypoints between the starting point and the target point → Obtain the constraints → Search the route from the starting point to the end point under the condition of satisfying the constraints → Calculate the thrust of each waypoint → Calculate the drag of each waypoint → Calculate the speed and acceleration of each waypoint → Calculate the flight time between each route segment → Calculate	

		the fuel consumption of each waypoint ➡ Calculate the fuel consumption between each route segment.
Expected result	Criterion	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 3. The fuel consumption of Guangzhou-Amsterdam is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target.
	Interpretation of results	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint speed, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint speed. 3. The fuel consumption of Guangzhou-Amsterdam is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and

		obtains the optimized trajectory under the waypoint constraint of horizontal flight and the optimization target, and outputs the optimized fuel consumption.

2.3.2.3 Simulation and verification of flight time optimization of Guangzhou-Amsterdam route under the constraints of waypoint, obstacle and restricted area caused by meteorological effects

Table 15. Simulation and verification of flight time optimization of Guangzhou-Amsterdam route under the constraints of waypoint, obstacle and restricted area caused by meteorological effects

Test module No.	HYBRIDHJYHSF_TEST_20	Name of tested module/function	Simulation and verification of flight time optimization of Guangzhou-Amsterdam route under the constraints of waypoint, obstacle and restricted area caused by meteorological effects
Description of tested module/function	Specific function	Taking Guangzhou as the starting point and Amsterdam as the end point, the waypoints data in the "ZGGG-EHAM Cross-point Data" file as the waypoint constraints, the obstacle areas set between Guangzhou and Amsterdam (the searched waypoints cannot enter these areas) as the obstacle constraint, the bad weather areas set between Guangzhou and Amsterdam as the restricted areas caused by meteorological effects (the searched waypoints cannot enter these	

		areas), and the flight time as the optimization target, complete the search of the optimized trajectory, and output the flight time and algorithm running time after trajectory optimization.
	Input parameters	Position information of Guangzhou (starting point) (coordinates of x, y and z axes in geodetic coordinate system), position information of Amsterdam (end point) (coordinates of x, y and z axes in geodetic coordinate system), aircraft speed, waypoint data of ZGGG-EHAM route; Set the geometric center and radius of the obstacle area, set the geometric center and radius of the restricted area caused by meteorological effects; flight speed at starting point, flight fuel consumption at starting point, temperature at starting point, pressure at starting point, the mass of the aircraft and the wing area of the aircraft.
	Output parameters	The route between Guangzhou and Amsterdam that meets the waypoint constraints (altitude constraints, speed constraints), obstacle constraints and restricted area constraints caused by meteorological effects of horizontal flight plan, and the flight cost between Guangzhou and Amsterdam that meets the waypoint constraints (altitude constraints, speed constraints), obstacle constraints and restricted area constraints caused by meteorological effects of horizontal flight plan.
	Main flow and algorithm	Obtain the waypoints between the starting point and the target point → Obtain the constraints → Search the route from the starting point to the end point under the condition of satisfying the constraints → Calculate the thrust of each waypoint → Calculate the drag of each waypoint →

		Calculate the speed and acceleration of each waypoint ➞ Calculate the flight time between each route segment.
Expected result	Criterion	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint. 3. Under the constraint of obstacles, the searched waypoints cannot be within the range of obstacles. 4. Under the restricted area constraint caused by weather, the speed at the waypoint obtained by search cannot be within the restricted area constraint caused by weather. 5. The flight time of Guangzhou-Amsterdam is searched and output under the constraints of waypoints, obstacles and restricted areas caused by weather in horizontal flight and taking flight time as the optimization target.
	Interpretation of results	1. Under the constraint of the horizontal flight waypoints, the waypoint obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint, which indicates that the Hybrid-A*-based trajectory optimization algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint. 2. Under the constraint of the horizontal flight waypoints, the waypoint speed obtained by the search is close to the constrained Guangzhou-Amsterdam waypoint speed, which indicates that the Hybrid-A*-based trajectory optimization

		algorithm searches and obtains the optimized trajectory under the constraint of the horizontal flight waypoint speed. 3. Under the constraint of obstacles, the searched waypoints cannot be within the range of obstacles, which indicates that the Hybrid-A* trajectory optimization algorithm was used to search and obtain the optimized trajectory under the obstacle constraints. 4. Under the restricted area constraint caused by weather, the speed at the waypoint obtained by search cannot be within the restricted area constraint caused by weather, which indicates that the Hybrid-A*-based trajectory optimization algorithm has obtained the optimized trajectory under the weather-induced restricted area constraint. 5. The flight time of Guangzhou-Amsterdam is searched and output under the constraint of the waypoint of horizontal flight and taking the flight time as the optimization target, which indicates that the Hybrid-A*-based trajectory optimization algorithm takes the flight time as the optimization target under the constraint of the waypoints of horizontal flight, the obstacle constraint and the restricted area caused by weather, and outputs the optimized flight time.

3 HMI (Research on Human-machine Interface of Avionics System Supporting Aircraft Green Cruise Operation)

3.1 INTRODUCTION

Systems related to human-machine interface design mainly involve two parts: green trajectory display based on ADS-B and Controller Pilot Data Link Communications (CPDLC), interface layout and operation logic.

The green trajectory display mainly provides the pilot with information about the aircraft in the surrounding airspace, including flight number, model, relative distance, relative speed and heading, so as to improve the pilot's airspace awareness. Controller Pilot Data Link Communications (CPDLC) is a new air traffic control method introduced in recent years. It is more convenient for air traffic controllers and pilots to record/process communication data and automatically handle related work by using data communication instead of traditional voice communication, which greatly reduces the workload of air traffic controllers and pilots and reduces the risk of communication errors.

3.2 SCENARIO DEFINITION

3.2.1 Overview of scenario definition

A scenario is a combination of related events. Scenario analysis is a common technology of requirements capture, which refers to the method of place the product to be developed in its operating scenario and analyzing its expected behaviors in the scenario to obtain the requirements.

Operational scenario refers to the combination of personnel behavior, flight phase, internal and external environment (fire, atmosphere, terrain, electromagnetism, etc.) and internal state (failure) of aircraft.

3.2.2 Levels of flight scenarios

The operating environment, operations and products of aircraft are extremely complicated. Corresponding to the level of requirements, flight scenarios can be divided into aircraft-level scenarios, system-level scenarios and equipment-level scenarios, while the aircraft-level scenario takes the aircraft as the object, considering the operation and maintenance of the aircraft, including the use of products by all stakeholders such as pilots, flight attendants and maintenance personnel, and even air traffic controllers and passengers, as well as the operating environment of the aircraft. The system-level scenario takes the system as the research object, considering the operation and maintenance environment of the system. Different from the aircraft-level scenario, the system-level scenario also needs to consider the influence of the state of the cross-linked system, that is, the state of other systems with electrical interfaces and mechanical interfaces with the object system, which is similar to the equipment-level scenario.

3.2.3 Definitions of typical flight phases

Based on the actual operation of the aircraft, this document further refines the various phases of the time dimension, including taxi-out, takeoff, climb, cruise, descent, approach, landing and taxi-in, etc.

3.2.4 Specific flight scenario requirements for green trajectory operation

DO-289 defines 8 applications of cockpit traffic situation awareness. With the development of technology, the objectives and names of the applications have changed greatly. In recent years, there are 8 mainstream applications: Enhanced Visual Acquisition (EVAcq), Airborne Situation Awareness (AIRB); Surface Situation Awareness (SURF); Visual Separation on Approach (VSA); In-Trail Procedure (ITP); Traffic Situation Awareness with Alerts (TSAA), also known as ADS-B Traffic Advisory System (ATAS); CDTI Assisted Visual Separation (CAVS); Flight-deck Interval Management (FIM).

3.2.5 Application of airborne situation awareness (AIRB)

The application of airborne situation awareness (AIRB) aims to help the flight crew to establish their own situation awareness of traffic by providing appropriate on-board display of surrounding traffic in all air flight phases, thus improving flight safety and flight operation. It is expected that the flight crew will perform current tasks more efficiently, including both decision-making and subsequent actions, so flight safety and flight operation should be able to be strengthened. The actual benefits will vary with airspace and flight rules. AIRB enables pilots to obtain the traffic situation information of the whole airspace during the flight, helping them to understand the surrounding traffic conditions for higher flight safety. This application is the minimum requirement for installing devices that implement other applications (such as VSA or ITP). This application improves the safety and efficiency by providing pilots with enhanced awareness of traffic scenarios. AIRB can use ADS-B technology to graphically display the surrounding traffic situation to pilots and provide traffic information.

CDTI can be used to provide enhanced traffic awareness to the crew, assist the crew to visually obtain traffic outside the cockpit window and provide situation perception of over-the-horizon traffic. CDTI should provide the crew with enhanced route traffic information (aircraft identification code, azimuth, altitude and heading) and detection functions that can improve any potential route traffic risks: display the ADS-B traffic situation relative to the aircraft on the plan (aerial view), specifically display the position, heading and altitude information of each aircraft and additional information such as identity; Pilots can check the corresponding identification number, ground speed and other additional information by selecting an aircraft icon; Remind the pilot that there may be aircraft that may cause potential route traffic risks. In addition to traffic conditions, it can also provide in-flight mobile map display devices. The devices shall meet the requirements of Electronic Map Display for Graphic Description of Aircraft Position (TSO-C165a).

3.3 FUNCTIONAL DESIGN

With the rapid development of civil aviation, the number of aerial vehicles is increasing, and the airspace density is increasing sharply. Air traffic management only relies on ICI control on the ground, which can no longer meet the needs of flight safety. The development and application of ADS-B and TCAS technology provide a solid foundation for air-to-air surveillance. Through the system equipped with green trajectory display, pilots can obtain data such as traffic situation, topography and geography in the airspace around the aircraft, as well as relevant prompts based on the function of airborne equipment (such as flight conflict, images of near-ground warning, voice prompt, etc.). From this information, pilots can find and understand the surrounding information in time, realize air-to-air surveillance and improve the safety level.

The display with green trajectory display function is an important means for pilots to monitor the traffic situation information around the aircraft and the state of aircraft in the vicinity. The green trajectory display function can provide pilots with a certain range of terrain and geo-electronic map data centered on the aircraft and with the interface display radius as the maximum distance, comprehensive track data of surrounding aircraft, and enhanced functional information such as the aircraft state, conflict detection, and near-ground warning. However, due to the limitation of screen size, resolution and display accuracy, too much information such as map data, various prompts, aircraft icons and signs on the interface will interfere with each other, and the screen will look too messy, so the pilot cannot get the information he wants to know through the display.

The main function of the green trajectory display is to present the traffic information of the surrounding aircraft to the pilot. The green trajectory display function receives and processes the message information sent by the ADS-B airborne host, and displays the traffic information provided in the ADS-B message on the display, which can provide a friendly human-machine interface for the flight crew and facilitate the pilot to more intuitively understand the traffic situation around the local airspace. The own ship traffic information provided by the display includes own ship symbol, identification code, position, ground speed, altitude, heading or track angle, etc. The information about adjacent aircraft situation provided includes the symbol, identification code of the adjacent aircraft, position information of the adjacent aircraft relative to the own ship, such as azimuth and distance, altitude, speed, track angle, trajectory, crossing trend, motion intention, etc.; The navigation information provided includes route information, airport information, navigation station information, general waypoint information, airspace information, next waypoint, waiting time and waiting distance to the next waypoint.

Realize typical application scenarios, including follow-climbing scenario, leading descent scenario and leading-follow combined climbing scenario.

3.3.1 Whole flight decomposition of green trajectory display

The flight process is divided into the following eight phases according to the definition of flight scenario:

Table 16. Green trajectory function items of whole flight process

Flight phase	**Sub-flight phase**	**Green trajectory display function items**
Ground roll-out (G1)	Ground waiting (G11)	Provide support for the decision-making of the crew in the taxiing phase (ASSA); Runway occupancy warning (FAROA); Enhanced visual perception in low visibility (EVAcq);
	Passenger greeting phase (G12)	
	Lounge bridge roll-out (G13)	
	Short stay (G14)	
	Taxi to the takeoff line (G15)	
Take-off (T1)	Take-off and accelerate to V1 (T11)	Provide support for the decision-making of the crew in the takeoff phase (ASSA); Enhanced visual perception in low visibility (EVAcq); Provide departure trajectory optimization (FMS, ND)
	Accelerate from V1 to off-the-ground (T12)	
	Climb from off-the-ground to 35ft (T13)	
Climb (F1)	Climb from 35ft to 400ft (F11)	Enhanced visual perception in low visibility (EVAcq); Provide the location and conflict alarm of adjacent aircraft (CD);
	Climb from 400ft to 1500ft (F12)	
	1500ft level flight acceleration (F13)	
	Climb from 1500ft to 10000ft (F14)	
	10000ft level flight acceleration	

	(F15)	
	Climb to cruise altitude (F16)	
Cruise (F2)	Manual cruise (F21)	Provide the location and conflict alarm of adjacent aircraft (CD); Provide green trajectory optimization function (FMS, ND)
	Automatic cruise (F22)	
	Decelerate before descending (F23)	
Descent (F3)	Descend to 10000ft (F31)	Enhanced visual perception in low visibility (EVAcq);
	10000ft level flight deceleration (F32)	
	Descend from 10000 to 1500ft (F33)	
Approach (F4)	Standby (F41)	Enhanced visual perception in low visibility (EVAcq); Final approach phase runway acquisition (FAROA) Provide approach trajectory optimization (FMS, ND)
	Approach (F42)	
Landing and taxiing (L1)	Leveling (L11)	Provide support for the decision-making of the crew in the landing phase (ASSA);
	Touchdown (L12)	
	Slow down to less than 20 knots (L13)	
Ground taxiing and stop (G2)	Taxi into the parking position (G21)	Enhanced visual perception in low visibility (EVAcq); Provide the location and conflict alarm of adjacent aircraft (CD);

The most basic application of green trajectory display function is to enhance traffic situation awareness.

3.3.2 Overall design of green trajectory display

3.3.2.1 Functional design

The green trajectory display is mainly responsible for the navigation information display of the own ship and the situation information display of the adjacent aircraft, and realizes the functions of Day/Night mode switching, brightness level display, screen range selection, target highlight selection and so on in response to the pilot's operation. It can start the manual self-test of the receiver and green trajectory display and display the fault information of the receiver and green trajectory display, and meanwhile reserve the function of navigation database injection, trajectory display function and automatic sensor brightness acquisition function.

3.3.2.2 Logic design

The green trajectory display module performs logical operations related to navigation information display, alarm information display, traffic information display and map control through the received external input data, calculates the position and state of interface elements, and updates the interface display. When applying for ITP, the data information of adjacent aircraft will be displayed. After the pilot selects the target aircraft, the detailed data of the aircraft will be displayed and the ITP criteria will be calculated. After the selection is completed, the ITP application will be sent.

The green trajectory display displays the traffic information in the ADS-B message information received by the airborne host by receiving and processing the message sent by the airborne host, and then displays the traffic information in the form of graphics and text on the display, thus providing a friendly human-machine interface for the flight crew and facilitating the pilot to intuitively understand the traffic situation in the airspace around the aircraft.

The green trajectory display provided by the display includes own ship traffic information, own ship symbol, identification code, position, ground speed, altitude, heading or track angle, etc. The information about adjacent aircraft situation provided includes the symbol, identification code of the adjacent aircraft, position information of the adjacent aircraft relative to the own ship, such as azimuth and distance, altitude, speed, track angle, trajectory, crossing trend, motion intention, etc.; The navigation information provided includes route information, airport information, navigation station information, general waypoint information, airspace information, next waypoint, waiting time and waiting distance to the next waypoint.

3.4 DISPLAY SYSTEM DESIGN

Green trajectory display mainly includes navigation map MAP/PLAN display, traffic situation information display, 4D trajectory display and other display items. The green trajectory display is displayed on the interface of ND, so the interface design of ND is analyzed first, and then the traffic information module of green trajectory display is designed.

3.4.1 ND interface design

ND mainly provides pilots with information such as own ship position, own ship heading, surrounding state, navigation alarm, etc. It is mainly displayed in three modes: MAP/PLAN mode, display with traffic information and full screen display.

The ND interface displayed in normal format in MAP/PLAN mode is shown in the following figure, the ND interface with traffic information display is shown in the following figure, and the ND interface displayed in full screen is shown in the following figure.

(a) Standard screen (b) With traffic information (c) Full screen

Figure 7: MAP mode

MAP/PLAN navigation map display mainly displays the following information:

1) Atmospheric data, velocity information and wind indication
2) Range reading
3) Heading/route indication
4) Selected heading reading
5) Waypoint information
6) MAP information
7) Warning notice
8) Navigation information
9) Horizontal navigation information
10) Meteorological radar notice
11) Vertical guidance display

3.4.2 Related design of green trajectory display interface

The green trajectory display mainly provides the pilot with information about the aircraft in the surrounding airspace, including flight number, model, relative distance, relative speed and heading, so as to improve the pilot's airspace awareness. Integrated in ND page, it can be used to assist pilots to complete ITP procedure. When ITP is applied to transoceanic flight, the flight crew can choose one or two reference planes with the same track, and keep a specified distance in front of or behind the reference planes to ascend or descend to reach a new altitude. The flight crew selects the appropriate reference aircraft via the ITP interface, sends an ITP application to the air traffic control, and keeps a specified distance from the reference aircraft. Monitor the ITP process after the application is approved, so that the pilot can realize the ITP process smoothly and efficiently. It is mainly used to indicate adjacent aircraft in the air. When relevant valid adjacent aircraft data are received and ADS-B display is turned on, adjacent aircraft indication should be displayed in all flight phases.

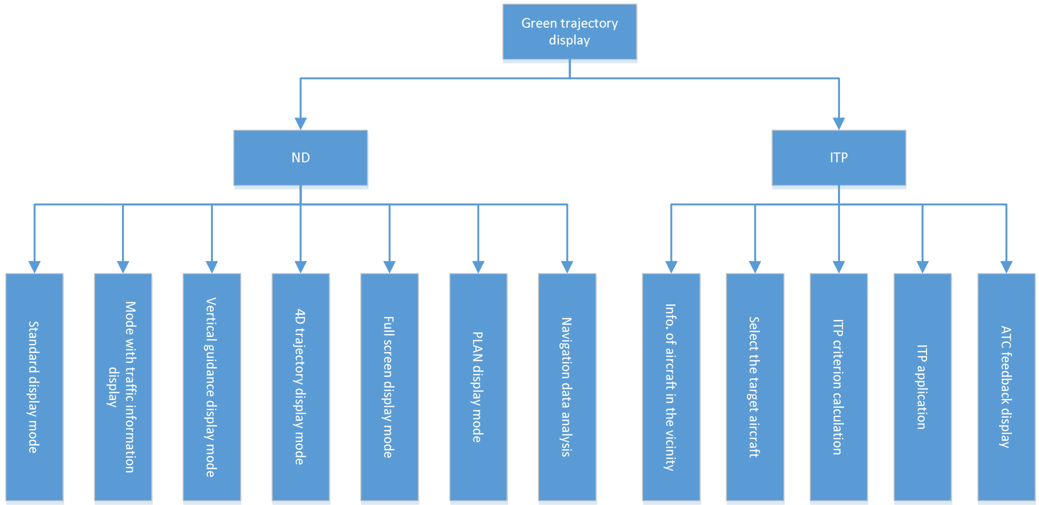


Figure 8: Function module structure of green trajectory display

The input data of green trajectory display function includes own ship flight data, other traffic data, own ship flight plan data, ITP uplink and downlink data, etc. ITP uplink instructions come from CPDLC module. The green trajectory display function module needs to analyze the navigation database to obtain navigation data such as waypoints and the position of navigation stations to support the display of flight plans and navigation information on ND.

The air traffic symbol style is only displayed on the MAP mode, while the traffic symbol style is not displayed in the PLAN mode. The traffic symbol is displayed as shown in the following figure:

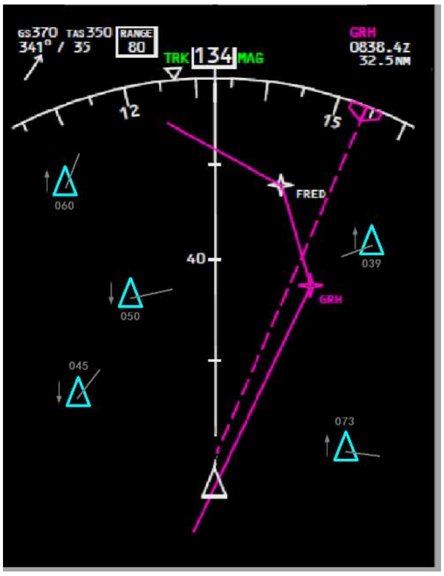


Figure 9: Design of green trajectory display

As shown in the above figure, air traffic information mainly includes traffic symbols, altitude relative to own ship, vertical speed, real-time heading and other information, where:

(a) Traffic symbol

The style of the traffic symbol is consistent with that of the own ship symbol, which is a triangle, the color is cyan, and the sharp angle is upward, showing the position relative to the own ship symbol on the map.

(b) Altitude relative to own ship

The relative altitude is displayed above/below the traffic symbol, with three digits, displayed in units of 100ft, and the color is light gray. If the target aircraft is above the own ship, the traffic symbol of altitude is displayed above the symbol, and vice versa.

(c) Vertical velocity

There is an indicator of vertical movement trend on the left side of the traffic symbol. If the position of the aircraft changes in the vertical direction, the corresponding change trend direction will be displayed.

(d) Real-time heading

Traffic symbols have short lines to indicate the heading, and the color is light gray.

There are two display modes for green trajectory display: display in MAP mode and display in ITP mode. The interface is shown in the following figure for display in MAP mode.

The display partition and display information include:

1) List of surrounding aircraft
2) Information of selected aircraft

3) Adjacent aircraft indication

Figure 10: Green trajectory display window in MAP mode

The interface displayed in ITP mode is shown in the following figure: The display information of ITP includes: altitude zone, surrounding aircraft information, own ship symbol, map range, selected aircraft information, ITP application, etc., and its interface is shown in the following figure.

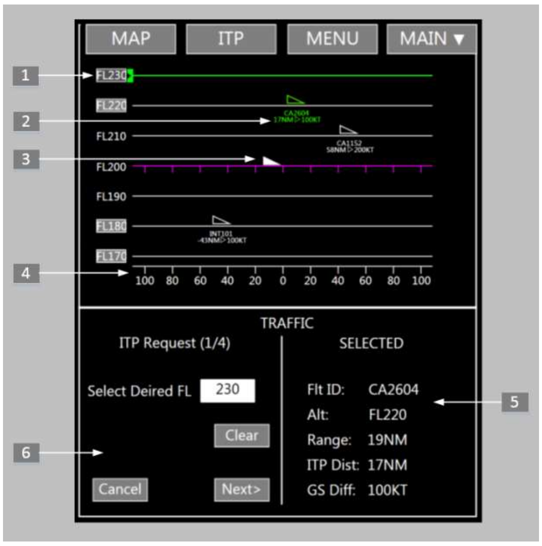


Figure 11: ITP mode interface on MAP page

ITP display mainly helps pilots to realize the ITP process. By displaying the vertical traffic information of the surrounding airspace, it helps pilots to select ITP reference aircraft and apply for the ITP process. After the application is approved, it monitors the progress of the ITP process, so that pilots can realize the ITP process smoothly and efficiently. The display items of ITP interface is shown in the following figure. ITP display information includes:

1) Altitude zone
2) Adjacent aircraft information
3) Own ship symbol
4) Map range
5) Information of selected aircraft
6) ITP application

3.4.3 Communication display of pilot/air traffic controller data link

The interaction between external data sources and internal modules of CPDLC is shown in the following figure:

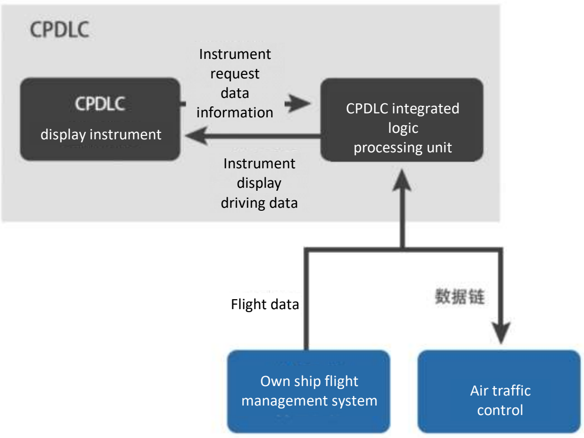


Figure 12: CPDLC external data source and internal module interaction diagram

CPDLC receives flight data from local flight management system and monitoring and control data from air traffic control at the same time, and interacts with the display interface via the integrated logic processing unit. The interactive data includes driving data displayed by the instrument and data requested by the instrument.

CPDLC provides air-ground data communication for ATC service. This includes a series of basic data, such as instruction permission, related information and request, taken by ATC procedure. It can provide controllers with the functions of issuing altitude command, crossing restriction command, horizontal spacing command, route changing command, velocity command, radio frequency command and information request; It can provide pilots with the ability to answer, inquire information, announce or cancel an emergency; It also provides pilots with the ability to request conditional permission (downstream) and information from ATSU; The function of "free text" makes the information exchange between the two not need to follow the formal format; Another auxiliary function is to enable a ground system to transmit CPDLC to another ground system via a data link. The specific application is as follows:

(a) Controllers and pilots will combine CPDLC with existing voice communication. This form is expected to be used for daily or complex matters. Although the current procedures are initially implemented, with the development of systems and procedures, the degree of functional automation of aircraft and ground systems will be greatly improved.

(b) The application of CPDLC does not affect the principle that the designated aircraft only receives one control command source at a specified time. The ability of pilots to apply for downstream clearance does not affect this principle.

(c) CPDLC message transmission includes three steps: selecting the receiver, selecting the appropriate message from the display directory or other methods and executing message transmission. The received message can be displayed and/or printed. Messages sent by downstream ATSU are distinguished from CPDLC messages sent by current ATS.

(d) CPDLC can make up for some disadvantages of voice communication, such as crowded voice channels, misunderstanding caused by poor sound quality or mistranslation, and interference caused by simultaneous speech.

The design adopts a display based on ARINC 661 bus, and the display format style of the display system based on ARINC 661 bus can be completely customized, which can provide more and more complete information to pilots on one page. Nowadays, the display system of civil aircraft tends to have large-screen, and the number of display items is increasing. The communication between pilots and air traffic controllers (ATC) is becoming more frequent, and the amount of information transmitted is also increasing. Therefore, it becomes more important to improve the efficiency of receiving and processing information and reduce the workload of pilots. The interface optimization message of CPDLC shows that the introduction of graphical symbols can make it more intuitive, concise and friendly. This design avoids the rigid and lengthy text, lightens the burden on pilots, and makes the time requirements of all waypoints in the flight process clear at a glance, thus improving their situation awareness. In addition, some simple icons are used instead of text to improve the efficiency of receiving and processing information with the same meaning for pilots. According to ICAO DOC9694, the human-machine interaction functions of the airborne terminal of CPDLC mainly include:

1) Information exchange between pilots and current data managers;
2) Data transfer between the current data manager and the next data manager;
3) Transmission of offshore license information with offshore data managers.

Therefore, the human-machine interaction interface of CPDLC is designed, including the display of waypoints and their arrival time, and the operation of Agree/Reject ATC instructions (about arrival time). In addition, the function of "input check" is added.

During the taxiing and take-off phase, the interaction between the pilot and the air traffic controller mainly includes departure clearance request, engine start clearance request, taxiing clearance request and take-off clearance request. The pilot sends out requests for pushback, engine start, taxi clearance and take-off clearance to the air traffic controller in turn, waiting for the air traffic controller's reply until all the requests are approved, and the pilot executes pushback, engine start, taxi clearance and take-off in turn. During the whole flight phase, including take-off, climb, cruise and descent, the main operations between the pilot and the air traffic controller are offshore clearance request, altitude clearance request, velocity clearance request, route selection request, free text reception and information feedback, voice clearance request. In addition, the transfer and control of control authority, data link information and status query update are required. The pilot sends out requests for offshore clearance, altitude clearance, velocity clearance and route to the air traffic controller according to the situation, and the air traffic controller responds in turn according to the situation until all the requests are approved, and the pilot makes offshore clearance, altitude change, velocity change, route selection and other operations according to the actual situation. During approach and taxiing, the pilot sends out the requests for approach clearance and landing clearance to the air traffic controller in turn, and the air traffic controller responds in turn according to the actual situation, until all requests are approved, and the pilot operates the aircraft to taxi out of the runway and park on the apron.

3.4.4 CPDLC Operation Flow Definition and HMI Design

3.4.4.1 CPDLC operation flow

3.4.4.1.1 Normal take-off process based on surface guidance

The normal takeoff process based on surface guidance is shown in the following figure:

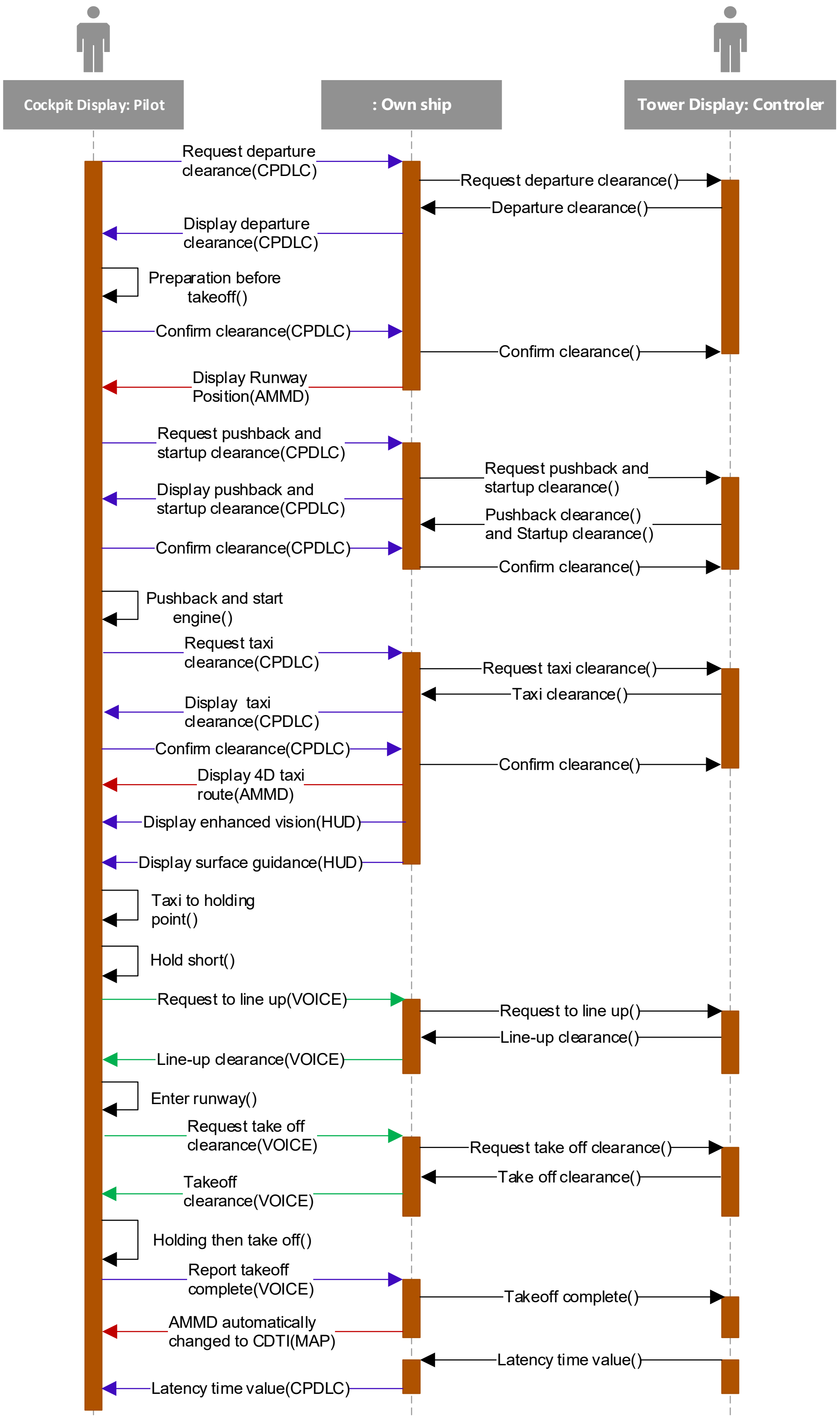


Figure 13: Normal take-off process based on surface guidance

3.4.4.1.2 Normal landing process based on surface guidance

The normal landing process based on surface guidance is shown in the following figure:

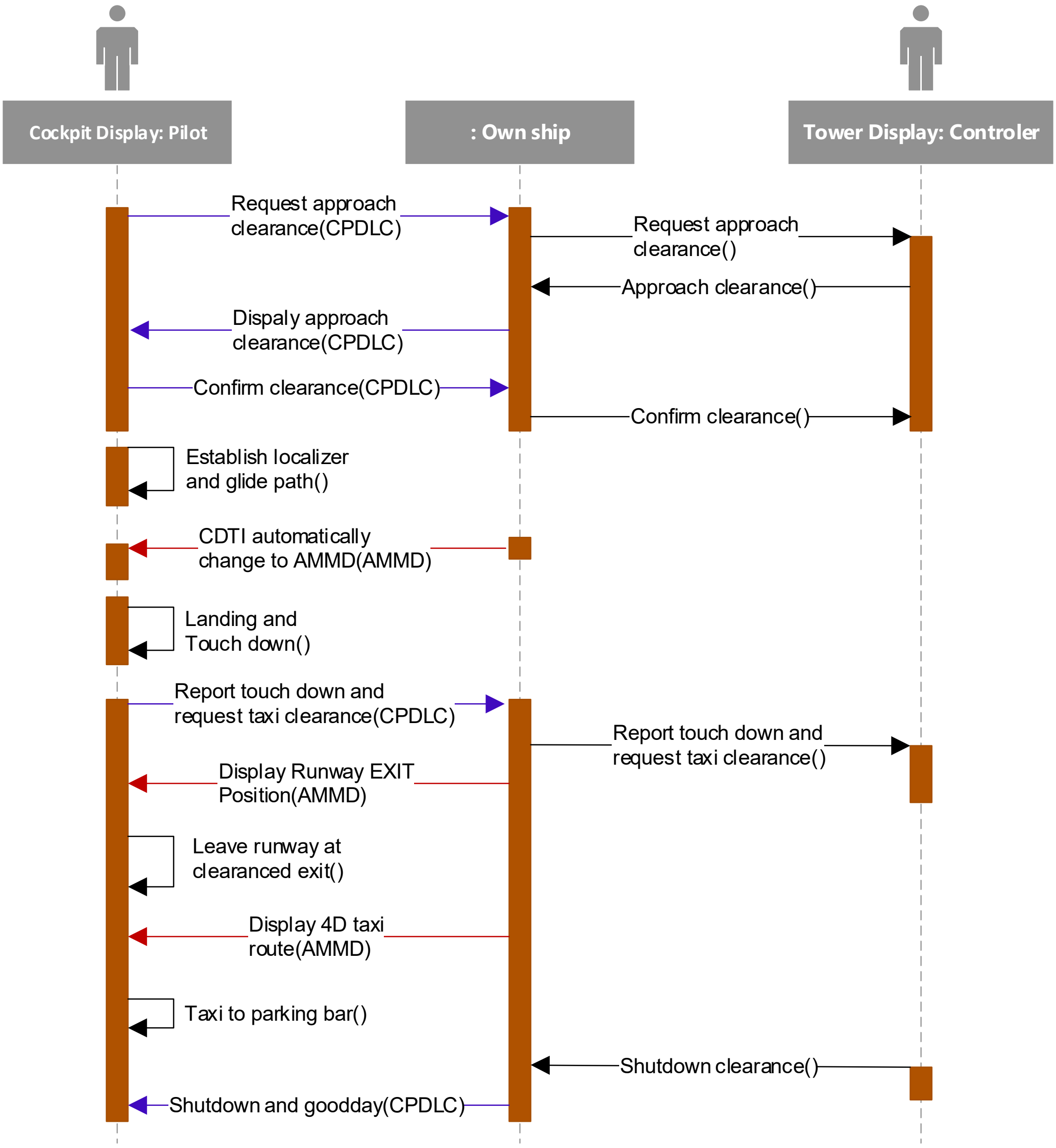


Figure 14: Normal landing process based on surface guidance

3.4.4.1.3 Operation flow of RSI triggered scenarios

The operation flow of RSI triggered scenarios is shown in the following figure:

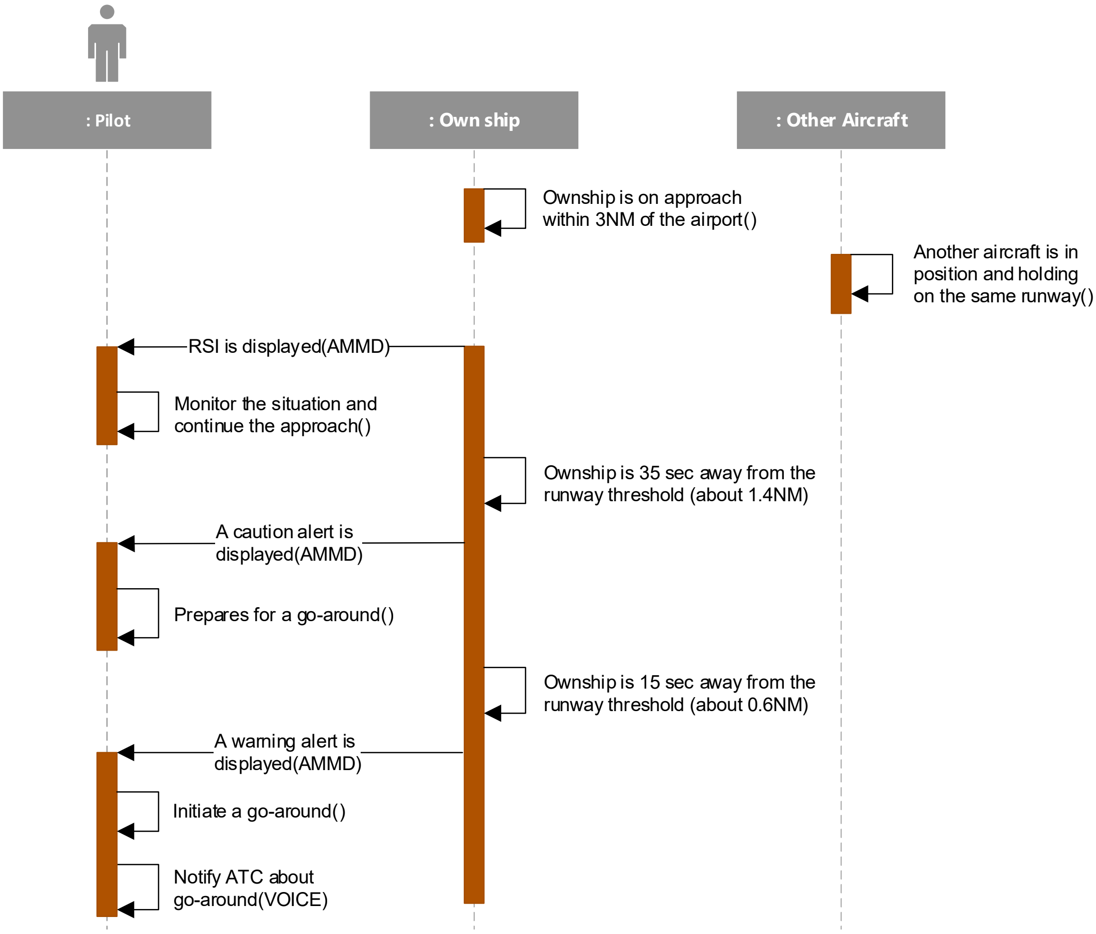


Figure 15: Operation flow of typical RSI triggered scenarios

3.4.4.1.4 Operation flow of TI triggered scenarios

The operation flow of TI triggered scenarios is shown in the following figure:

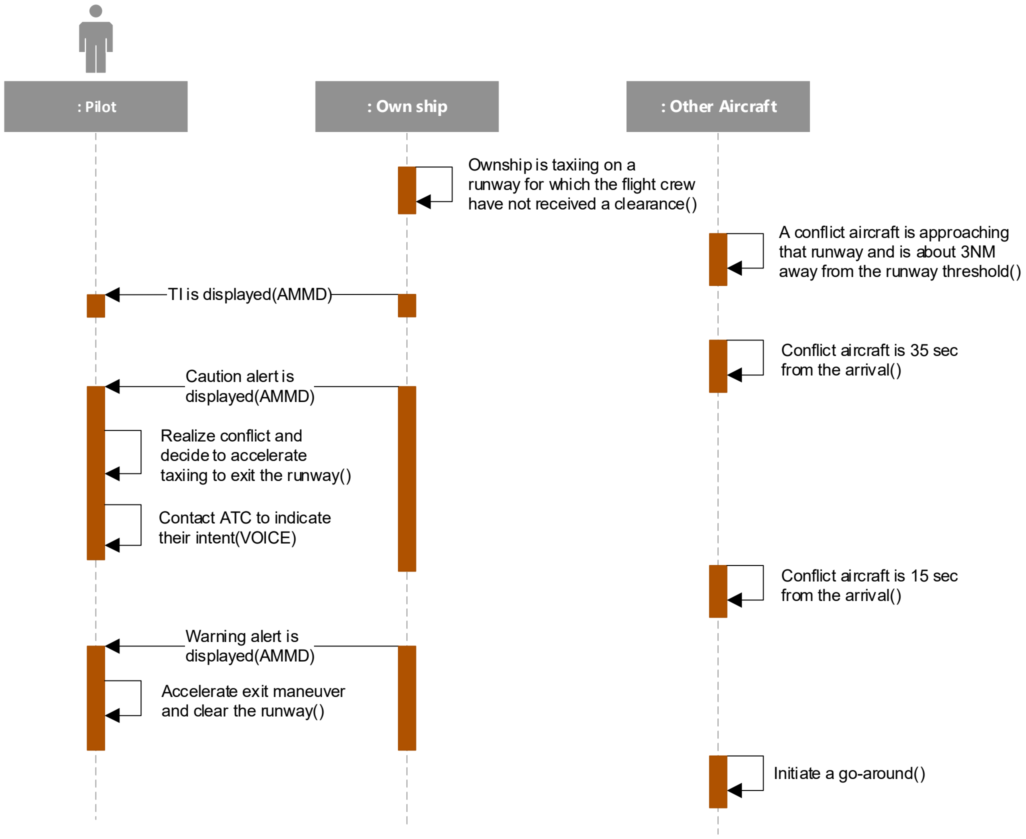


Figure 16: Operation flow of typical TI triggered scenarios

3.4.4.1.5 Operation flow of ITP application scenarios

The operation flow of ITP application scenarios is shown in the following figure:

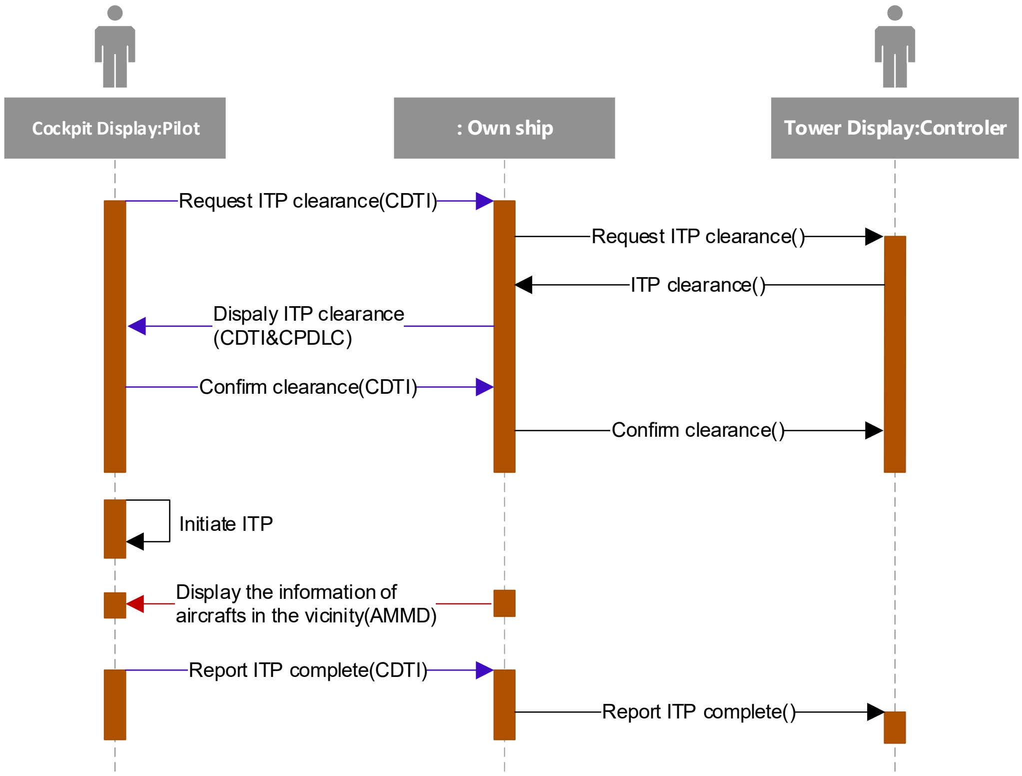


Figure 17: Operation flow of ITP application scenarios

3.4.4.2 Process logic

This module is used for communication with ATC, including the application of various clearances, the display of ATC instructions, the response to ATC clearances (Accept/Reject) and the communication of other information. The software mainly includes basic information management, clearance application and message management.

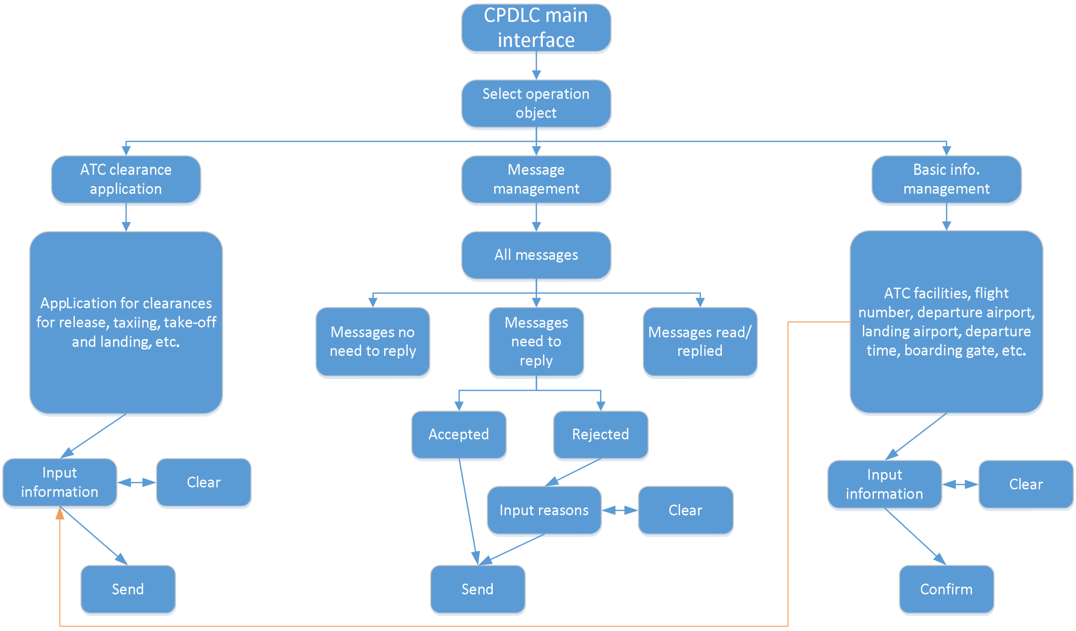


Figure 18: CPDLC operation logic

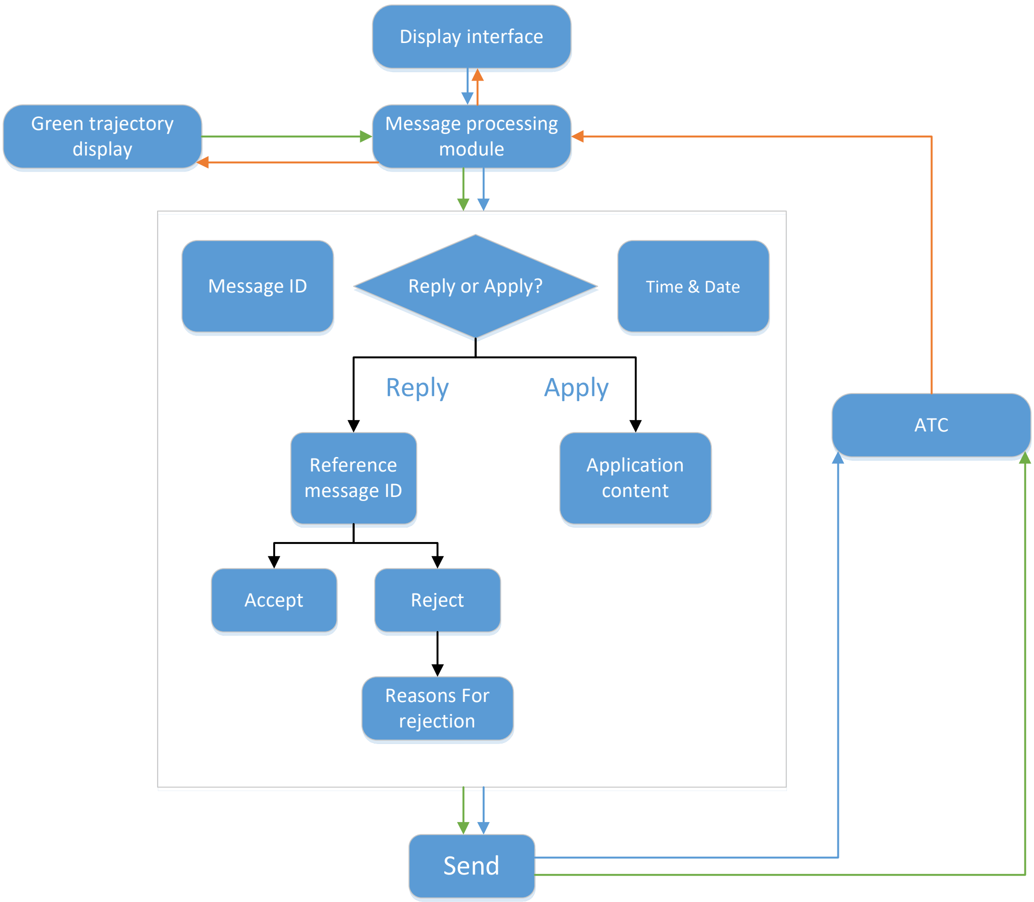


Figure 19: CPDLC background data processing logic

4 SUMMARY

In recent years, population explosion and immoderate industrialization have been aggravating both the energy crisis and greenhouse impacts. These facts potentially corrode the sustainable development of modern society. Moreover, the rapid development of aviation has further exacerbated the problem of air pollution and energy stress. The fossil energy shortage is rocketing the cost of transportation, which brings nonnegligible pressures to the air traffic operation community.

In this report, two methods are proposed wherein the FMS collaborates with the surveillance system, the communication system and the navigation system to collect information of the weather, terrain, and surrounding air traffic. Based on this information, algorithms for conflict-free 4D trajectory generation and optimization are developed, which consider the meteorological conditions and movement of other aircraft in the vicinity. Multiple objectives are concerned in the trajectory optimization, including the minimization of light time and gaseous emissions.

In addition, we analyze the impact of the regulatory functions that may be authorized on the cockpit resources, as well as the impact on the operational safety and efficiency of the airspace under consideration of crew participation, determine the collaborative operations of the air-ground coordination of the licensable functions, information flow, etc., and establish a reasonable airborne interface used for evaluation and demonstration. The focus is put on the cockpit human factor study and high-efficiency air-ground coordination which is beneficial to enhance situational awareness of flight crew and assist the decision making to implement greener flight procedures.

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