The Collaborative Architecture Design of Unmanned Aerial Vehicle Flight Control Systems and Multimodal Information Networks in Low-Altitude Economy

Weihang Yan
Shanghai High School of BANZ, Shanghai, China

Abstract: This article focuses on the low-altitude economy field and delves deeply into the collaborative architecture design of unmanned aerial vehicle (UAV) flight control systems and multimodal information networks. This paper expounds the concept, current development status and application scenarios of low-altitude economy, analyzes the key components, working principles and technical challenges of unmanned aerial vehicle (UAV) flight control systems, and dissects the connotation, architecture and integration mechanism of multimodal information networks. On this basis, the design principles and goals of the collaborative architecture are proposed, the collaborative architecture is designed in detail, and its application scenarios and advantages are discussed. It seeks to offer theoretical backing and technical guidelines for the effective utilization of unmanned aerial vehicles (UAVs) within the low-altitude economy, thereby fostering its sustainable progress.

Keywords: Low-Altitude Economy; Unmanned Aerial Vehicle Flight Control System; Multimodal Information Network; Collaborative Architecture Design

1. Introduction

1.1 Research Background and Significance

As an emerging and all-encompassing economic model, the low-altitude economy is unveiling immense potential and vibrant energy for growth. Centered around low-altitude flight operations as its primary driving impetus, it extensively extends and spurs the thorough integrated advancement of associated sectors. The low-altitude economy encompasses several pivotal facets, including low-altitude manufacturing, low-altitude aviation, low-altitude support services, and comprehensive service offerings. Its application contexts are abundant and varied, spanning numerous domains such as municipal administration, consumer activities among residents, and industrial uses [1]. As technology keeps progressing, the low-altitude economy is ushering in development opportunities that are unparalleled. Based on pertinent forecasts, it's anticipated that by 2035, the industrial scale of China's low-altitude economy will surpass 6 trillion yuan [2].

As a crucial part of the low-altitude economy, unmanned aerial vehicles (UAVs) are assuming an ever-more prominent role across various sectors. In the realm of logistics and delivery, drones have the capability to overcome geographical barriers, swiftly transport goods to far-flung regions, enhance logistics efficiency, and cut down on expenses[3]. In terms of agricultural plant protection, agricultural drones can precisely spray pesticides and monitor crops, enhancing agricultural production efficiency, reducing pesticide usage, and protecting the ecological environment [4]. In disaster relief scenarios, drones can quickly reach the disaster-stricken area to carry out disaster reconnaissance and material distribution, etc., providing crucial support for rescue operations [5]. In the field of environmental monitoring, drones equipped with various sensors can obtain real-time data on environmental elements such as the atmosphere, water quality, and soil, providing a scientific basis for environmental protection and governance [6].

As the core control system of unmanned aerial vehicles (UAVs), the performance of the UAV flight control system directly determines the flight stability and mission execution capability of the UAV. An excellent flight control system can ensure the stable flight of unmanned aerial vehicles in complex environments and the accurate completion of various tasks [7]. At the same time, multimodal information networks are capable of amalgamating diverse forms of information, including text, images, audio, and video, thereby offering unmanned aerial vehicles (UAVs) a more thorough and precise perception of their environment along with decision-making support. Through the fusion of information from varied modalities, drones can gain a superior understanding of their surroundings and make more rational choices [8]. Hence, delving into the collaborative architecture design that combines unmanned aerial vehicle (UAV) flight control systems with multimodal information networks holds immense importance in boosting the application effectiveness of UAVs within the low-altitude economy and can serve to further advance the growth of this economic sector.

1.2 Current Research Status at Home and Abroad

Currently, notable research progress has been achieved both domestically and internationally in the areas of unmanned aerial vehicle (UAV) flight control systems and multimodal information networks. In the realm of UAV flight control systems, researchers are persistently investigating innovative control algorithms and sensor technologies aimed at improving the flight capabilities and stability of UAVs. The traditional PID control approach has found extensive use in UAV flight control systems owing to its benefits, including a straightforward structure and ease of application [9]. Decoupling control is capable of efficiently managing the intertwined relationships among the multiple variables of unmanned aerial vehicles (UAVs), thereby enhancing control precision [10]. Robust control techniques are able to boost the stability of unmanned aerial vehicles (UAVs) when confronted with uncertainties and disturbances [11].

With the rapid development of artificial intelligence technology, new control strategies based on machine learning and artificial intelligence have gradually emerged. These methods can automatically adjust control parameters by learning a large amount of flight data, achieving more intelligent and adaptive control. In the field of multimodal information networks, multimodal information fusion technology has become a research hotspot. By fusing information from different modalities, the completeness and accuracy of the information can be enhanced, providing more powerful support for intelligent decision-making.

2. Overview of Low-Altitude Economy

2.1 The Concept and Characteristics of Low-Altitude Economy

The low-altitude economy denotes an all-encompassing economic model that primarily hinges on civil manned and unmanned aircraft, and is propelled by low-altitude flight undertakings in various scenarios, including passenger and cargo transport, among other operations. This model extends and fosters the integrated advancement of associated sectors. It typically pertains to the airspace within a vertical span of 1,000 meters directly above the ground surface.

The low-altitude economy is characterized by its extensive reach, lengthy industrial supply chain, robust growth potential, and driving force. It traverses the primary, secondary, and tertiary sectors, encompassing multiple facets such as low-altitude manufacturing, low-altitude aviation, low-altitude support services, and comprehensive service offerings. It holds vast potential in spurring effective investment, generating consumer demand, and elevating the level of innovation.

2.2 The Development History and Current Situation of Low-Altitude Economy

The notion of the low-altitude economy was first incorporated into the national agenda in 2021. By 2023, it had been upgraded to a strategic emerging sector. During the 2024 Meeting, the term "low-altitude economy" was, for the first time, included in the government work report, signaling its emergence as a fresh catalyst for local economic growth.

Take Shenzhen as a case in point. Its burgeoning low-altitude industry encompasses low-altitude manufacturing, aviation, support services, comprehensive offerings, and a variety of low-altitude applications such as tourism, logistics, and inspection, thereby forging a lengthy and far-reaching low-altitude industrial ecosystem. In 2023, Shenzhen's low-altitude economy generated an annual output value exceeding 90 billion yuan, marking a 20% year-on-year increase. Consumer-grade drones from Shenzhen command a 70% share of the global market, while industrial-grade drones hold a 50% share. The city is also far ahead in terms of the flight volume and scale of cargo drones and helicopters.

2.3 Application Scenarios of Low-Altitude Economy

The application scenarios of low-altitude economy are very extensive, mainly including the development of new urban low-altitude transportation forms mainly based on various types of aircraft such as eVTOL and helicopters in the field of transportation to alleviate urban traffic congestion. In terms of logistics and distribution, drones are used for express delivery to enhance logistics efficiency and reduce logistics costs, especially in remote and poorly accessible areas, where the advantages are more obvious. In terms of agricultural plant protection, agricultural drones are used for pesticide spraying, crop monitoring and other operations to enhance agricultural production efficiency, reduce pesticide usage and protect the environment. In terms of disaster relief, when natural disasters such as earthquakes and floods occur, drones can quickly reach the disaster area to conduct disaster reconnaissance, material distribution and other rescue work, providing strong support. In terms of environmental monitoring, drones equipped with various sensors are utilized to monitor environmental elements such as the atmosphere, water quality, and soil, in order to promptly grasp environmental changes and provide data support for environmental protection and governance.

3. Analysis of Unmanned Aerial Vehicle Flight Control System

3.1 Key Components of the Unmanned Aerial Vehicle Flight Control System

The unmanned aerial vehicle (UAV) flight control system mainly consists of three key components: sensors, controllers, and actuators. Among them, the sensors include accelerometers, gyroscopes, compasses, barometers, GPS, etc. The accelerometer is used to detect the acceleration and tilt angle of the UAV to help the system understand its dynamic status. The gyroscope detects angular velocity and angle to provide rotation direction information. The compass determines the direction to ensure flying along the predetermined route, the barometer measures atmospheric pressure to estimate altitude, and GPS provides precise position and speed information, which are the keys to navigation and positioning. The controller is the "brain" of the flight control system, responsible for processing the data collected by sensors and generating control signals based on the preset flight plan or operation instructions. Common controllers include the flight controller responsible for flight attitude control and the navigation controller responsible for route planning. The actuator mainly consists of a motor, an electric speed controller and a servo. The motor controls the flight power, the electric speed controller regulates the motor speed, and the servo controls the steering of the unmanned aerial vehicle.

3.2 Working Principle of the Unmanned Aerial Vehicle Flight Control System

The working principle of the unmanned aerial vehicle flight control system involves signal transmission and control strategies. The signal transmission between the unmanned aerial vehicle (UAV) and the remote control or ground control station is mainly carried out through radio waves. Users send command signals through the control lever, buttons or touchscreen on the remote control, and these signals are transmitted to the receiver on the unmanned aerial vehicle via radio waves. After receiving the signal, the receiver transmits it to the flight controller, which adjusts the flight status of the unmanned aerial vehicle according to the instructions. Meanwhile, the sensors on the drone will constantly collect flight data and feed it back to the remote control or ground control station via radio waves, allowing users to monitor the status of the drone.

In terms of control strategies, the unmanned aerial vehicle (UAV) flight control system adopts multiple control methods. PID control is a classic control method that regulates the flight attitude and position of unmanned aerial vehicles (UAVs) through three links: proportional (P), integral (I), and differential (D). Decoupling control is used to address the mutual influence among multiple degrees of freedom of unmanned aerial vehicles (UAVs). By separating the roll, pitch and yaw control of UAVs, the accuracy and stability of control are enhanced. Robust control enhances the stability and performance of unmanned aerial vehicles (UAVs) in the presence of external disturbances or parameter variations, such as $H\infty$ control and μ -composite control, etc. In addition, methods such as fuzzy control and neural network control are applicable to handling control problems in uncertain and complex environments.

3.3 Technical Challenges Faced by Unmanned Aerial Vehicle Flight Control Systems

The flight control system of unmanned aerial vehicles (UAVs) faces many technical challenges in practical applications. Dynamic environmental adaptation is a significant issue. During flight, unmanned aerial vehicles (UAVs) encounter various complex meteorological conditions and geographical environments, such as strong winds, heavy rain, and mountainous areas. These factors can affect the flight stability of UAVs. Communication delay is also a problem that cannot be ignored. The communication delay between the unmanned aerial vehicle (UAV) and the ground control station may lead to untimely instruction transmission, affecting the real-time control of the UAV. In addition, the risk of single-machine failure and the optimization of task allocation are also difficult problems that need to be solved. During long-term flight, drones may experience hardware failures. How to ensure the overall stability of the cluster in the event of a single machine failure is a key issue. Meanwhile, when multiple drones are working collaboratively, how to rationally allocate tasks and improve the efficiency of task execution is also an urgent problem to be solved.

4. Analysis of Multimodal Information Networks

4.1 Definition and Connotation of Multimodal Information

Multimodal refers to the technologies and concepts involving the processing, integration and interaction of multiple modal information. Here, "modality" can be understood as different forms or sources of information, such as text, images, audio, video, gestures, touch, etc. Humans integrate information from different senses in the brain to form a comprehensive understanding of the surrounding environment and things. The goal of multimodal technology is to enable computers to process and understand information from various forms just like humans do, breaking the limitations of single-modal information processing and making computer systems more intelligent and powerful.

4.2 Architecture and Composition of Multimodal Information Networks

The multimodal information network consists of the data acquisition layer, the data fusion layer, the decision-making layer and the application layer. The data acquisition layer is responsible for collecting various modal information, such as image information through cameras, audio information through microphones, and text information through sensors, etc. The data fusion layer fuses the collected information of different modalities to extract useful feature information. Common fusion methods include data-level fusion, feature-level fusion and target-level fusion. The decision-making level makes decisions based on the integrated information and generates corresponding control instructions. The application layer applies the decision-making results to actual scenarios, such as intelligent customer service, autonomous driving, security monitoring and other fields.

4.3 Mechanisms and Methods of Multimodal Information Fusion

The mechanisms of multimodal information fusion mainly include alignment, fusion and transformation. Alignment focuses on how to establish corresponding relationships among different modalities. For instance, in the fusion of images and text, it is necessary to match the objects in the image with the descriptions in the text. Fusion is about how to effectively combine these multimodal information to improve the performance of the model. Common fusion methods include early fusion, mid-stage fusion and late fusion. Transformation is the process of converting information from one mode to another, such as converting a text description to an image or an image to a text description.

In terms of specific methods, multimodal joint representation is a representation method that maps the information of multiple modalities together into a unified multimodal vector space. It leverages technologies such as neural networks and probabilistic graphical models to integrate data from different modalities, generating a unified representation that contains multi-modal information. This not only retains key information from each modality but also establishes connections between modalities, supporting cross-modal tasks. Multimodal collaborative representation is a method that maps the information of multiple modalities to their respective representation spaces respectively, but the mapped vectors or representations need to meet certain correlation or constraint conditions. The core of this method lies in ensuring that the information among different modalities can collaborate with each other within the collaborative space to jointly optimize the performance of the model.

5. Collaborative Architecture Design of Unmanned Aerial Vehicle Flight Control Systems and Multimodal Information Networks in Low-Altitude Economy

5.1 Principles and Objectives of Collaborative Architecture Design

The collaborative architecture design adheres to the principles of real-time performance, scalability, robustness and intelligence. Real-time performance requires low-latency communication and computing in the system to ensure that the unmanned aerial vehicle (UAV) swarm can respond quickly to dynamic environments. Scalability supports clusters of different scales and ADAPTS to task changes. Robustness features strong fault tolerance, maintaining cluster stability in the event of single-machine failure or communication interruption. Intelligent integration of advanced algorithms enables autonomous decision-making and collaborative operations. The objective is to provide comprehensive and accurate environmental perception and decision support, enhance the application efficiency of unmanned aerial vehicles (UAVs) in low-altitude economies, and enable them to adapt to complex environments to complete tasks.

5.2 Overall Design of the Collaborative Architecture

It adopts a hierarchical architecture, which is divided into the perception layer, the decision-making layer and the execution layer. The perception layer collects data from the unmanned aerial vehicle's own sensors as well as multi-modal information such as external images and audio. After integration and preprocessing, it provides data support for the decision-making layer. The decision-making level uses multimodal information fusion algorithms to extract useful features and combines intelligent decision-making algorithms to generate task allocation and path planning strategies. The execution layer converts the strategy into flight control instructions, controls the flight of the unmanned aerial vehicle and feeds back the status information, so that the decision-making layer can adjust the strategy.

5.3 Detailed Design of Each Floor

The perception layer uses a variety of sensors to collect information. Besides the accelerometer and gyroscope of the unmanned aerial vehicle itself, it is also equipped with cameras, microphones, etc. The multimodal information collection module integrates and preprocesses information, such as data cleaning and feature extraction, to improve data quality. The decision-making level adopts multimodal information fusion algorithms, such as fusing image and sensor data to extract environmental features; intelligent decision-making algorithms, in combination with task requirements and environmental conditions, generate strategies by applying machine learning, path planning, etc., and possess dynamic adjustment capabilities. The execution layer converts strategies into instructions, closely integrates with the flight control system to ensure accurate transmission and execution, and simultaneously feeds back flight status information such as position, speed, and attitude.

5.4 Design of Collaborative Communication Mechanism

By adopting a distributed communication architecture, communication tasks are decentralized, avoiding the communication bottlenecks of centralized architectures, reducing latency and enhancing scalability. By applying lightweight communication protocols, the volume of data transmission is reduced and communication efficiency is enhanced. To ensure reliable and secure communication, encryption technology is adopted to encrypt the transmitted data, preventing theft and tampering. Use the identity verification mechanism to verify both communication parties, ensure the access of legitimate nodes, and prevent illegal intrusions. Through the above design, the collaborative architecture of the unmanned aerial vehicle (UAV) flight control system and the multimodal information network can effectively enhance the operational capabilities and adaptability of UAVs in the low-altitude economy.

6. Conclusion

This paper designs a collaborative architecture of the unmanned aerial vehicle flight control system and the multimodal information network in the low-altitude economy. By analyzing the relevant concepts and technologies of low-altitude economy, unmanned aerial vehicle flight control systems and multimodal information networks, the principles and goals of collaborative architecture design are proposed. Based on the hierarchical architecture, the perception layer, decision-making layer and of the collaborative architecture were designed in detail, and the collaborative communication mechanism was also designed. This collaborative architecture can provide more comprehensive and accurate environmental perception and decision support for the unmanned aerial vehicle (UAV) flight control system, and improve the application efficiency of UAVs in the low-altitude economy.

Future research directions could include further optimizing multimodal information fusion algorithms to enhance the intelligence level of the system. Explore more advanced communication technologies to enhance the performance of collaborative communication; Carry out practical application tests to verify the feasibility and effectiveness of the collaborative architecture. At the same time, in line with the development needs of the low-altitude economy, the application scenarios of the collaborative architecture can be continuously expanded to provide more powerful technical support for the development of the low-altitude economy.

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