Research Progress and Application of UAV Multi-Sensor Data Fusion Technology

Yifei Jia[1*], *Yuhan* Ji[2]

1The Leicester International Institute, Dalian University of Technology, Zhengzhou, Henan Province, China

2Sino-British College, a joint British Chinese partnership in Shanghai, 222000 Donghai County, Lianyungang, Jiangsu Province, China

Abstract. This paper reviews the research progress of UAV multi - sensor data fusion technology. With the complexity of application scenarios, single - sensor UAVs can't meet the requirements. Early research laid a foundation, and current key technologies include centralized, distributed and multi - layer fusion, each with its pros and cons. This technology has been applied in urban environment monitoring, mountain and ocean exploration, and natural disaster monitoring. However, there are still challenges like emergency handling and sensor failures. Future research directions focus on intelligent fusion algorithm innovation and edge computing - hardware integration. It is believed that with multi - field technology integration, the technology will develop towards algorithm intelligence, hardware miniaturization and system collaboration.

1 Introduction

Unmanned Aerial Vehicle, also called UAV, is an aircraft that does not require pilot operation on board, usually by remote control or autonomous flight. Now, with the increasing complexity of application scenarios, a single sensor can no longer meet the needs of drones for comprehensive perception of the surrounding environment. By integrating information from different sensors, multi-sensor data fusion technology can significantly improve the perception accuracy and decision-making ability of drones in complex environments and has become one of the key directions for the development of drone technology.

According to the Advances in UAV detection: integrating multi-sensor systems and AI for enhanced accuracy and efficiency [1], it reviews the progress of UAV detection and classification technology from 2020 to the present. The importance of artificial intelligence and machine learning in optimizing inspection techniques is explained. The application of these techniques in modern anti-UAV systems is also introduced, including various methods of suppression and destruction of UAV and the performance characteristics of typical anti-UAV systems. It has been pointed out that continued innovation in UAV

* Corresponding author: 1248709903@mail.dlut.edu.cn

detection and classification technology is critical to ensuring airspace safety and facilitating the safe integration of UAVs into civil and commercial environments (Fig.1).

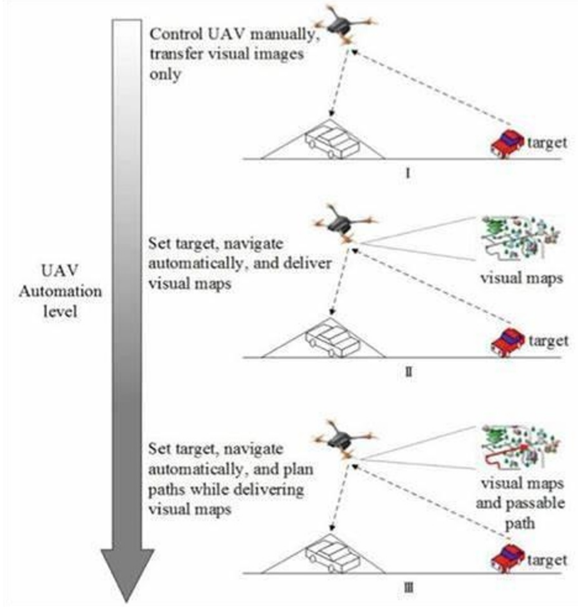

Fig.1. UAV automation level. (Photo credit: Original)

However, there still exist many challenges to be solved. Firstly, the ability to deal with emergencies needs to be optimized; Second, there is a contradiction between the traditional algorithm's high demand for computing resources and the limited computing power of the UAV embedded platform. Third, the problem of sensor failure in extreme environments has not been systematically solved.

In view of the above research results and shortcomings, the research progress of UAV multi-sensor data fusion technology will be systematically reviewed and will focus on analyzing the differences between classical methods and deep learning methods in theoretical framework, application scenarios and performance boundaries. At the same time, combined with the actual needs in the complex environment, the effect of multi-sensor fusion technology on the efficiency of UAV mission is verified by typical cases, and its potential value in multiple fields is foregrounded.

2 Overview of UAV multi-sensor data fusion technology

2.1 UAV sensor types and characteristics

As stated by John F. Guilmartin in Encyclopaedia Britannica [2], Unmanned Aerial Vehicles (UAVs) are military aircraft with a combination of autonomous, remotely piloted, or one or the other, typically carrying sensors, target indicators, offensive munitions, or electronic transmitters designed to disrupt or destroy enemy targets. With the advantage of being unencumbered by the design safety requirements of crew, life support systems and manned aircraft, it is highly efficient and can provide greater endurance than equivalent manned systems. It is a derivative of the target drones and remotely operated vehicles (RPV) used by many countries' militaries in the decades after World War II. The modern drone made its debut as a major weapon in the early 1980s.

3 UAV multi-sensor data fusion technology research progress summary

3.1 Early research basis

According to the Adaptive UAV Navigation Method Based on AHRS, an adaptive UAV navigation method based on AHRS is proposed to solve the problem of the inaccuracy of the traditional model in describing relative motion, and can effectively improve the navigation accuracy in the scene requiring high precision and robustness (Fig.2) [3]. As stated in the Beyond Static Obstacles: Integrating Kalman Filter with Reinforcement Learning for Drone Navigation an innovative UAV navigation method, which combines interactive multi-model (IMM) Kalman filter and near-end strategy optimization (PPO) to strengthen the learning algorithm for trajectory planning in dynamic environment, is proposed. It can make the UAV successfully avoid collision and reach the target, effectively improving the navigation performance and provide a new direction for the application of UAV in complex dynamic scenarios [4]. In the Visual - Inertial Autonomous UAV Navigation in Complex Illumination and Highly Cluttered Under-Canopy Environments, Zhao et al founded the DPRL navigation algorithm, which combines deep reinforcement learning with privileged learning, uses asymmetric Actor-Critic architecture to provide privileged information for Critic network, and adopts multi-agent exploration strategy to accelerate experience collection, thus providing an effective solution for autonomous navigation of UAV [5].

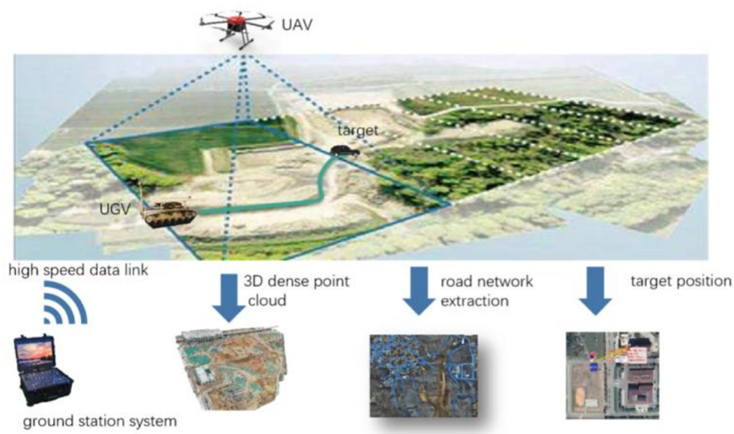

Fig.2. Technology for UAV. (Photo credit: Original)

3.2 Progress in key technologies

Autonomous drones' navigation system depends on a variety of sensors, including Global Positioning System (GPS), Light Detection and Ranging (LiDAR), cameras, Inertial Measurement Units (IMU), ultrasonic sensor, infrared sensor, barometer, magnetometer, sonar, temperature sensor, humidity sensor and gas sensor [6]. UAV navigation control system can coalesce those sensors to get environmental information. Nowadays, there are only three fusion modes, centralized fusion, distributed fusion and multi-layer fusion. Centralized fusion is the most basic fusion method. It directly integrates the original data from different sensors to generate more accurate and complete data. Distributed fusion is to use sensors process the data step by step and send obtained information in each level to the control center in layers. Multi-layer fusion is the combination of centralized fusion and distributed fusion [7]. Each fusion mode has its own advantages, thus, according to the condition and requirement to choose drones with different fusion mode is the key in actual application.

3.2.1 Centralized fusion

Centralized fusion uses filtering algorithms shown in Fig.3, such as Kalman filtering and particle filtering, to make time synchronization and spatial alignment of the original data. It consists of GPS, IMU, LiDAR and camera. These integrated sensors can improve positioning accuracy of UAV and generate high-precision environmental maps. This kind of fusion mode can retain the integrity of the original data well. However, the calculation volume is large, and the time synchronization and calibration requirement of the sensor are high.

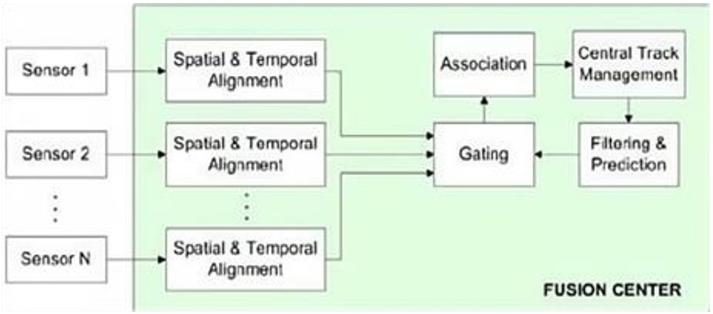

Fig.3. Working **of** centralized fusion (Photo credit: Original)

3.2.2 Distributed fusion

Distributed fusion extract key features shown in Fig. 4, such as edges, corners, targets and contours from sensor data. And then using feature matching, clustering and other methods to fuse features. The camera and infrared sensor are used to improve the accuracy of target identification, and the LiDAR and visual sensor are used to generate more accurate environmental maps. Distributed fusion reduces the amount of data so the computing efficiency is high, but it may loss some of the original information.

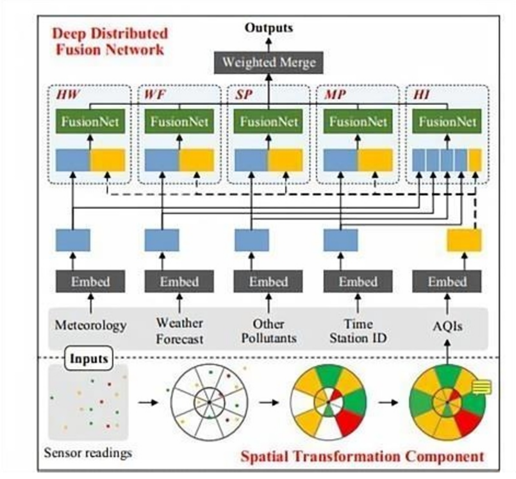

Fig.4. Working of distributed fusion (Photo credit: Original)

3.2.3 Multi-layer fusion

Multi-layer fusion has high accuracy, high efficiency strong fault tolerance and flexibility, however, it costs higher than other two modes shown in Fig. 5.

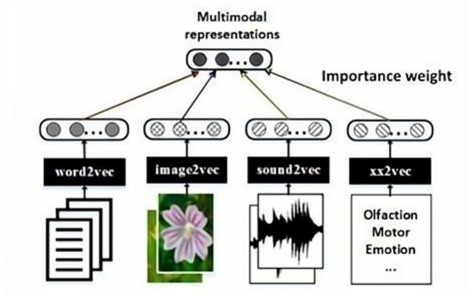

Fig.5. Working of multi-layer fusion.[11]

4 Application of UAV multi-sensor data fusion in complex environment

4.1 Monitoring the urban environment

UAV can use cameras and GPS to monitor vehicle flow, speed and other information in real time, providing data support for traffic management departments to optimize traffic signal timing and guide traffic. UAV can also use visual and radar sensors to track suspicious targets in real-time, providing timely intelligence support to the police.

4.2 Explore the mountain and ocean environment

UAV with magnetometers, gravimeters and so on can explore large-scale geophysical exploration of mountainous areas and search for potential mineral resources [8]. In the ocean environment, UAV can take advantage of water quality sensors to monitor marine water quality in real-time, analyze indicators such as dissolved oxygen, acidity, and heavy metal content in seawater, and promptly detect water pollution.

4.3 Monitoring the natural disasters

UAV with GPS, LiDAR, infrared sensor and so on sensors can provide help in the rescue operation [9]. In the earthquake with magnitude 6.8 in Shigatse Dingri County, Xizang, the pterosaur 2H emergency relief UAV which has optoelectronic equipment and synthetic aperture radar successfully detected the location of personnel in distress and the real-time distribution of ground rescue forces [10]. It can also provide stable external images and data under low visibility conditions at night.

5 Future research Directions and prospects

Despite significant progress, the field still needs to break through the following bottlenecks and explore new directions:

5.1 Intelligent fusion algorithm innovation

Develop a lightweight federated learning framework to address data privacy and bandwidth conflicts when collaborating with multiple drones.

5.2 Edge computing and hardware integration

Develop low-power AI chips (such as storage and computing integrated architecture) to support on-board real-time fusion processing.Develop flexible and stretchable sensor arrays to adapt to complex physical environments such as extreme temperatures and strong electromagnetic interference.

It is believed that with the cross-integration of artificial intelligence, new materials and communication technologies, UAV multi-sensor data fusion technology will show the following development trends: algorithm intelligence, hardware miniaturization, system collaboration, from data fusion to cognitive fusion, flexible perception and edge intelligence, group intelligence and cross-domain interconnection and other achievements.

6 Conclusion

In conclusion, Uav multi-sensor data fusion technology is of great significance in the development of UAV. As the application scenarios tend to be complex, it is difficult for a single sensor to meet the demand, and this technology has become a key development direction to integrate multi-source information and improve the environmental perception and decision-making ability of drones.

In the early stage, many research achievements laid the foundation for its development, such as adaptive navigation based on AHRS, navigation algorithm combining Kalman filter and reinforcement learning. Nowadays, centralized fusion, distributed fusion and multi-layer fusion have their advantages and disadvantages. Centralized fusion retains the integrity of the original data but has a large amount of computation; distributed fusion has high computational efficiency but may lose some information; multi-layer fusion has high precision and strong fault tolerance but high cost, and practical applications need to be selected on demand.In the application of complex environment, the technology has achieved remarkable results, and it has been found in urban environmental monitoring, mountain ocean exploration, natural disaster monitoring and other fields. The successful application of the "Wing Loong 2H" UAV in the earthquake rescue in Tibet is a powerful example.

However, there are still some problems such as emergency handling capability to be optimized, contradiction between traditional algorithm and UAV computing capability, and unsolved sensor faults in extreme environments. In the future, breakthroughs need to be made in the direction of innovative intelligent fusion algorithms, promoting edge computing and hardware integration, such as the development of lightweight federated learning frameworks, low-power AI chips and flexible sensor arrays. With the cross-integration of multi-field technologies, the technology will develop in the direction of algorithmic intelligence, hardware miniature, and system collaboration, realize the leap from data fusion to cognitive integration, release great value in more fields, and promote the application of drones to a new height.

Author Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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