Review

Multi-Rotor UAVs for Meteorological Sensing: Status, Key Technologies, and Trends

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Abstract: Traditional weather observation methods have limitations in detecting low-altitude, small-scale areas and sudden weather events. They often have insufficient coverage, slow response, or high costs. Multi-rotor unmanned aerial vehicles (UAVs), with their strong vertical take-off and landing ability, precise hovering, flexible movement, and ability to carry various small sensors, are gradually becoming key tools to fill these gaps and build three-dimensional weather observation networks. They show important value in medium- and small-scale weather monitoring and emergency weather support. This paper reviews the main sensors for multi-rotor weather drones, their operating modes, and key supporting technologies, summarizes the current state of technology, and provides references for future development.

Keywords: multi-rotor unmanned aerial vehicle; meteorological detection; meteorological payload

1 Introduction

Weather forecasting is important for keeping society and the economy running smoothly and for minimizing the effects of weather-related disasters. Its accuracy and timeliness have a direct impact on decisions in fields like farming, transportation, and emergency response[1]. However, the atmosphere is highly complex and dynamic, and traditional weather observation methods face significant limitations, especially when monitoring low-altitude areas, small-scale spaces, or sudden weather events[2]. Weather balloons can collect vertical profile data, but they have low spatio-temporal resolution and cannot provide continuous observations. Ground-based automatic weather stations have limited reach and cannot detect small weather differences in a region. Manual observations are affected by takeoff conditions, costs, and safety risks, making them slow to react to sudden weather changes. These problems result in a poor understanding of important weather situations, which limits the accuracy

of forecasts and early warnings for disasters. The industry needs new weather observation equipment that is flexible, high-quality, and affordable[3].

With the rapid development of drone technology, its applications in fields like environmental monitoring and resource exploration are continuously deepening. Drones are gradually becoming an important solution to break through the limitations of traditional weather observation methods. Among them, multi-rotor drones generate lift through the high-speed rotation of their rotors, allowing them to take off and land vertically, hover freely, and fly at various speeds and flight profiles. These features make them invaluable in weather observation. Compared to fixed-wing drones, multi-rotor drones don't require specialized takeoff and landing areas, and their vertical takeoff and landing ability allows them to adapt to complex terrains. Compared to tethered balloons, multi-rotor drones are more maneuverable, allowing for flexible adjustments to observation paths and altitudes. Additionally, multi-rotor drones have high hovering

precision, enabling vertical profile measurements at specific points, and can carry various small, integrated meteorological payloads to meet the need for multi-parameter measurements. These features allow multi-rotor drones to accurately cover the blind spots of traditional observation methods, effectively addressing issues like low-altitude detection limitations, small-scale monitoring gaps, and delayed responses to sudden weather events. They have become a core tool in the field of weather observation[4].

Currently, multi-rotor drones are gradually being used in medium and small-scale meteorological observation and disaster emergency weather support. The high temporal and spatial resolution meteorological data they collect provide crucial support for improving numerical weather forecasting models and enhancing disaster warning effectiveness. A research team from Nanjing University of Information Science and Technology has designed a boundary layer meteorological detection system based on a quadcopter drone[5]. The system achieves high-precision measurements of temperature, humidity, and pressure, with its core including a new temperature measurement module and flow field analysis based on Computational Fluid Dynamics (CFD). The system also uses Random Forest (RF) and Multilayer Perceptron (MLP) algorithms to correct radiation errors. In field experiments conducted at the Nanjing Meteorological Observation Center of the China Meteorological Administration, the system showed low average absolute differences in temperature, humidity, and pressure compared to weather stations during hover tests. In the EU-funded Train2Wind project, which focuses on offshore wind power[6], multi-rotor drones serve as flexible meteorological observation platforms. They are primarily used for precise measurement of meteorological parameters in offshore wind fields, including wind field and turbulence observation, aerosol and sea salt concentration measurement, and high-resolution humidity monitoring. Although the project did not fully resolve the core issue of optimal spacing between wind turbines and large offshore experiments were affected by external factors, it still provided support for multi-parameter coupling studies in offshore wind fields, turbine protection, and observation methods. In a study[7] on the thermodynamic measurement accuracy of multi-rotor drones equipped with unshielded sensors, six-rotor drones were used in flight experiments at eight different sensor positions. The measurements were compared to values obtained from tethered radiosondes and flux towers. To avoid biases from specific sensor and position combinations, sensor rotation was used, and data quality control was implemented to ensure reliability. This study offers suggestions for future deployment of unshielded sensors in outdoor atmospheric research.

This paper, grounded in the practical requirements of meteorological observation, provides a systematic review of multi-rotor meteorological UAVs. It examines their core payloads, diversified operational modes, and key enabling technologies, while outlining the current state of technological development. The study conducts an in-depth analysis of the challenges encountered and offers insights into future development directions.

2 Payload for Multi-Rotor Meteorological Drones

Meteorological payloads are the instruments used to collect weather information. They are the core components that enable multi-rotor drones to measure meteorological parameters. Their performance directly affects the accuracy, reliability, and completeness of the data. Currently, the payload system of multi-rotor meteorological drones is centered around basic weather parameters such as temperature, humidity, wind speed and direction, and air pressure, while also incorporating a diverse range of configurations for measuring air quality parameters[8-10]. The complete structure of a multi-rotor meteorological drone is illustrated in Figure 1.

2.1 Thermal Load

The temperature detection on current multi-rotor UAV platforms primarily relies on two technical approaches: direct detection and remote sensing.

Direct detection remains the mainstream method for obtaining real-time temperature data on multi-rotor UAVs. This involves mounting temperature sensors typically used in traditional ground weather stations onto the UAV, such as moving temperature sensors, semiconductor resistance temperature detectors (RTDs), metal resistance temperature detectors (MRTDs) [11], semiconductor diodes (Figure 2), and thermocouple temperature sensors. The temperature-sensitive elements directly contact the atmospheric environment and, through the sensor's sensitivity to temperature changes, convert the environmental temperature into an electrical signal that can be collected. After the signal is amplified and filtered by the signal conditioning circuit onboard the drone, real-time temperature data for the drone's location is obtained. Due to potential temperature interference from the drone's motor heat dissipation and battery warmth, the direct detection payloads include a temperature compensation mechanism. This system sets an environmental temperature reference point near the sensor probe, using algorithms to correct errors caused by the platform's heat dissipation, ensuring accurate temperature measurement.

Remote sensing detection serves as a vital supplement to direct measurement methods, with thermal infrared surface temperature inversion being a commonly employed technique[12, 13]. By installing a miniaturized thermal infrared sensor on a multi-rotor drone, the drone can capture thermal infrared radiation emitted by the
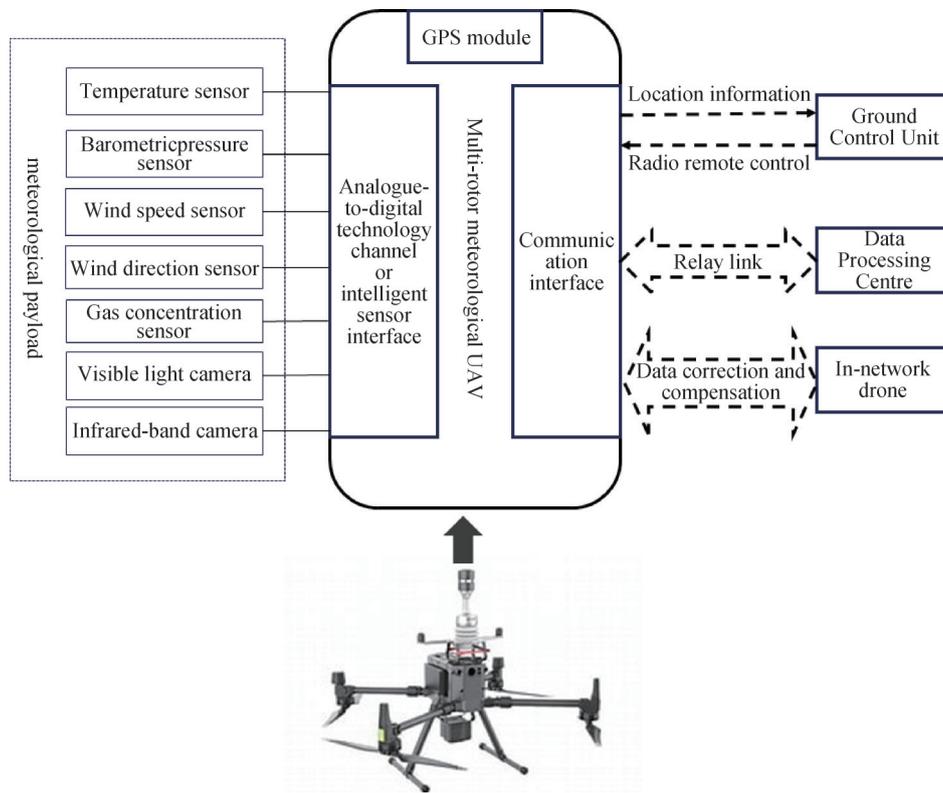
Fig.1 Structure of a multi-rotor meteorological unmanned aerial vehicle

Fig.2 Semiconductor diode

Fig.3 Infrared remote sensing image captured by a drone

atmosphere or the surface within the detection area. Using the blackbody radiation law and a radiation transfer model, the received thermal infrared signals are processed to calculate the temperature distribution of the surface or atmosphere in the detection area (Figure 3). However, water vapor and clouds in the atmosphere can absorb or scatter the thermal infrared signals, leading to temperature inversion errors. To address this, thermal infrared surface temperature inversion payloads often integrate multi-band infrared detectors. By comparing radiation signal differences across different bands, they reduce interference from water vapor and clouds. However, this method still faces challenges in complex weather conditions, such as high humidity and heavy cloud cover.

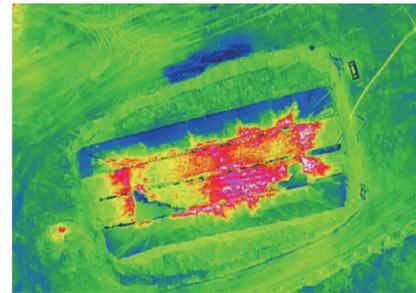In recent years, with the continuous development of temperature payloads, the temperature measurement systems on drones have been evolving towards higher resolution measurements and better adaptation to extreme environments. A study in article[14] used a multi-rotor drone to measure atmospheric vertical temperature profiles in urban environments. The research team selected the DJI M300 drone, equipped with the high-precision TMP117 temperature sensor and SHT41 humidity sensor, and used Vaisala RS41 radiosonde data as a reference standard. The accuracy of the drone measurements was verified through 28 flights, with 16 valid data sets selected. The experimental results showed that, after applying Newton's law of cooling, the deviation between the drone data and radiosonde data was low, exceeding the accuracy requirements of the World Meteorological Organization. Additionally, the drone's measurement cost was significantly lower than that of weather balloons. The study also highlighted the drone's high-resolution measurement capability in the lower atmospheric boundary layer. Article[15] aimed to study the near-surface winter temperature inversion phenomenon in the high Arctic using a multi-rotor drone.

The research team used the DJI M100 and M210 RTK drones, equipped with a custom data collection system based on Raspberry Pi and platinum wire resistance temperature detectors. In extreme low-temperature environments, they achieved vertical temperature profile measurements at heights up to 75 meters. The experimental results showed that the drone measurements were highly consistent with data from the NOAA flux tower and radiosonde. Ultimately, it was confirmed that multi-rotor drones can effectively capture the spatiotemporal characteristics of near-surface temperature inversions in the high Arctic during winter, filling the gap for high-resolution temperature data at heights of 0-10 meters.

2.2 Moisture Load

Current multi-rotor drones mainly use two types of humidity sensors based on capacitive and optical principles. Capacitive humidity sensors[16] measure humidity by detecting changes in the dielectric constant caused by humidity variations. This principle allows for fast response times, making them suitable for tasks that require quick detection of humidity changes. Optical humidity sensors, on the other hand, perform better in high humidity environments or in conditions with fog or dew. Their unique ability to resist interference from condensation ensures more accurate readings, maintaining the reliability of the data.

In the article[17], the humidity measurement relies on two temperature and humidity sensors mounted on the drone, with the Raman Lidar RALMO used as a reference instrument. During the experiment, the drone's humidity measurement performance showed significant improvement. Initially, there was a large deviation due to sensor issues, but after replacing the sensors, the performance improved. The reference Raman Lidar RALMO, on the other hand, maintained stable humidity measurement performance throughout. After filtering out the abnormal data, the drone's humidity measurements met the threshold requirements set by the World Meteorological Organization for high-resolution numerical weather forecasting and were quite close to the performance of the RALMO sensor.

2.3 Wind Speed and Wind Direction Loads

The multi-rotor drone platform is equipped with various wind speed and direction sensors, including silicon membrane-based wind speed sensors, silicon beam-based wind speed sensors, wing-style solid-state wind speed sensors, ultrasonic wind speed sensors, and five-hole probe wind speed and direction sensors. Currently, the wind speed and direction sensors on multi-rotor drones are mainly designed based on two core technologies: ultrasonic wind speed and direction sensors[18] and five-hole probe wind speed and direction sensors.

The ultrasonic wind speed and direction sensor (Figure 4) uses the characteristics of sound waves traveling through the atmosphere. By placing multiple ultrasonic transmitters and receivers in an array, it measures the time difference of sound waves traveling in different directions. Then, using a model that links the speed of sound to wind speed, it calculates real-time wind speed and direction data[19].

Fig.4 Ultrasonic wind speed and direction sensor

The five-hole probe wind speed and direction sensor (Figure 5) focuses on high-precision measurements, making it more suitable for tasks that require strict wind field parameters[20]. Its core structure is a metal probe with five pressure-sensing holes. By collecting total pressure, static pressure, and dynamic pressure differences from different pressure holes at the probe's head, it calculates wind speed, direction, and airflow angles using fluid dynamics formulas and attitude compensation algorithms. Compared to ultrasonic sensors, the five-hole probe offers higher measurement accuracy, capturing even small airflow changes and providing high-resolution wind field data for atmospheric boundary layer studies.

Fig.5 Five-hole probe anemometer

Due to the characteristics of drones, their impact on wind speed and direction measurements has been a key focus of research. As wind speed and direction sensor applications continue to mature, drone-based wind measurement has recently been moving toward using machine learning algorithms combined with drone flight dynamics data. This approach aims to optimize sensor configurations, improve data fusion accuracy, and enhance wind measurement accuracy and reliability. Additionally, it is expanding into areas such as urban wind forecasting and boundary layer meteorology, gradually replacing traditional, expensive fixed wind

measurement platforms. The article[21] focuses on developing an accurate and practical drone wind measurement system. It designs a custom lightweight rotary-wing drone and selects full-size industrial-grade ultrasonic anemometers. The system increases the distance between the sensor and the propeller and proposes a compensation algorithm based on motor throttle to effectively eliminate the interference of propeller-induced airflow on vertical wind speed measurements. Furthermore, the study significantly reduces the coupling of ground speed and wind speed through data fusion techniques. Experimental results, verified by dual-base lidar, show that even in complex turbulent environments, the wind speed and direction measurements are highly consistent with reference values. This system offers long endurance and high practicality, making it a useful supplement to wind measurement towers and lidar systems. The article[22] addresses the accuracy optimization of drone wind speed and direction measurements, highlighting that traditional methods often have biases and significant errors. It proposes a machine learning-based solution. Using high-resolution lidar ground truth data as a training reference, a random forest algorithm is applied to train a model with 28 flight control parameters collected by onboard sensors, enabling precise estimation of wind speed and direction. In the experiments, smoothing window processing of data showed that as the smoothing window length increased, measurement accuracy continued to improve. This method not only significantly outperforms traditional wind measurement techniques, but also exceeds the single-height measurement accuracy of lidar under longer smoothing windows, achieving unbiased measurement. The method does not require additional specialized wind measurement instruments and relies solely on the drone's own flight dynamics data to achieve high-precision wind measurements.

2.4　Atmospheric Pressure Load

Most drones determine their flight altitude by detecting the surrounding atmospheric pressure. Therefore, using a multi-rotor drone for pressure detection is a relatively mature technology. Currently, pressure sensors adapted for multi-rotor drones have developed into a product system focused on miniaturization, low power consumption, and high stability. These products are mainly divided into three types: micro absolute pressure sensors, micro differential pressure sensors, and integrated pressure-temperature modules.

The micro absolute pressure sensor[23] is currently the mainstream application for atmospheric pressure detection in multi-rotor drones. It directly measures the absolute atmospheric pressure, offering advantages such as small size, low power consumption, and fast response speed, as shown in Figure 6. The sensor detects atmospheric pressure using a micro-sensitive structure,

either based on a piezoresistive or capacitive principle. Pressure causes the sensitive structure to deform at the nanoscale to the micrometer level. This deformation leads to changes in the resistance of the piezoresistive material or the capacitance between the plates. The electrical changes are then converted into weak electrical signals through a Wheatstone bridge or high-frequency oscillation circuit. After amplification and filtering by an internal signal conditioning circuit, a stable electrical signal is generated to precisely measure the absolute atmospheric pressure.
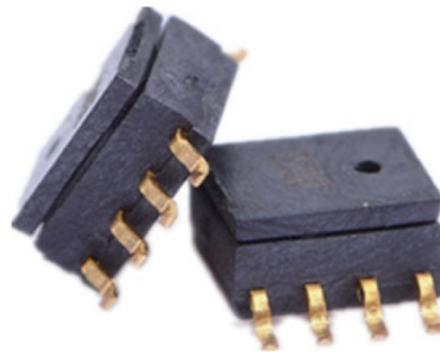

Fig.6　Miniature absolute pressure sensor

In the measurement system design of the study[24], the multi-rotor drone used is equipped with an iMet-XF sensor package. This sensor package includes an integrated pressure sensor that collects atmospheric pressure data in real time, transmitting and storing it at a frequency of 1 second via serial output, providing essential data support for further analysis. Additionally, the study also addresses the impact of airflow on pressure sensor readings, noting that pressure readings from the drone's sensor are easily affected by airflow. However, there is currently no standardized optimal installation method for the sensor. The study only mentions possible ways to reduce interference, such as mounting the sensor on a horizontal tube outside the propeller wash or at the top of a vertical boom above the drone, to help ensure the accuracy of the pressure data.

2.5　Air Quality Load

Air quality payloads, as expandable detection components for multi-rotor meteorological drones, are mainly used to monitor atmospheric pollutants and particulate matter[25,26]. These include optical scattering sensors for PM2.5/PM10 and electrochemical gas sensors (such as SO_2, NO_2, and O_3 sensors), as shown in Figure 7. These payloads must balance sensitivity and stability while maintaining a lightweight design. For example, the PM2.5 sensor measures particulate concentration using laser scattering, while the electrochemical gas sensors use gas filters to reduce cross-interference, ensuring selective detection of specific pollutants.

In recent years, with the continuous development of air quality payloads, there has been an evolution from

Fig.7 Multi-parameter gas detector

low-cost, single gas and particulate sensors to high-precision multi-component monitoring systems. These systems are designed to fit various drone platforms, such as multi-rotors and fixed-wing drones, and can be used in different scenarios, like natural and human-made pollution sources. Efforts are being made to optimize sensor installation positions to reduce interference from drone wash effects and to strengthen the integration of data with numerical models to improve pollution analysis and forecasting capabilities. The study in[27] focuses on urban air quality monitoring in Vietnam and proposes a solution based on drones equipped with smart sensors. In terms of research methodology, the study highlights the importance of selecting the right drone platform according to monitoring needs and emphasizes sensor installation optimization. It also suggests precise flight path planning to collect 3D atmospheric data. The study in[28] explores for the first time the integration of drone-observed data into chemical transport models to improve air quality predictions. The research uses standard ozone and nitrogen monoxide vertical profile data and applies a high-resolution air quality model with a 4D variational assimilation system to jointly optimize initial values and emission rates. The experimental results show that after assimilating drone data, the accuracy of the vertical distribution of ozone and nitrogen monoxide significantly improved. However, the study also points out limitations: it only assimilates data from a single grid cell, and the observation window is short. Future work will need to conduct observational system simulation experiments to further verify the added value of drone data compared to traditional observations, providing a new technological pathway for air quality forecasting.

3 System Modes Detected by Multi-Rotor Meteorological Drones

The detection system model of multi-rotor meteorological drones is built around the goal of accurate, efficient, and comprehensive weather data collection. It mainly consists of a single-drone independent detection system and a multi-drone networked detection system. In practical applications, there are also expanded modes such as air-ground-space

coordination and heterogeneous platform collaboration.

3.1 Single-drone Independent Detection

Single-drone independent detection refers to a single ground control unit remotely controlling a single drone to complete weather monitoring tasks. A complete single-drone detection system consists of a multi-rotor drone platform, a single or integrated weather payload, a ground control station, and a data processing module, as shown in Figure 8.
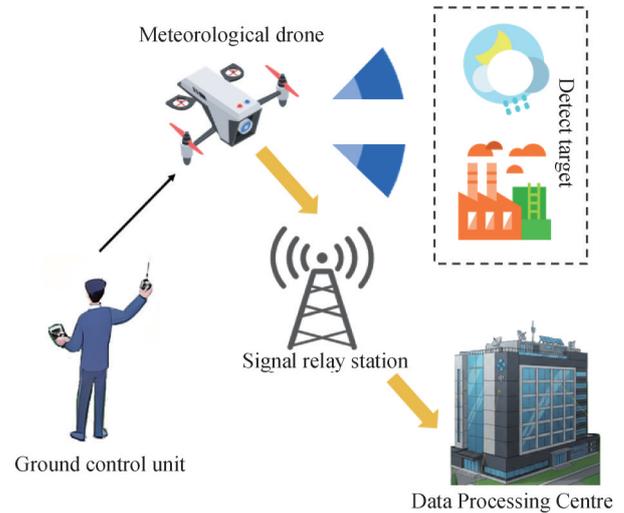

Fig.8 Single-drone independent detection system

The single-drone independent detection system involves a ground control station that works with nearby fixed meteorological stations to provide baseline weather data for calibrating the weather payload on the drone. The drone follows a pre-set flight path, with the weather payload directly interacting with the atmosphere. It converts environmental factors like temperature and wind speed into weak electrical signals. These signals are then amplified and filtered by the built-in signal conditioning circuits in the payload and converted into standardized digital signals. The drone transmits the digital signals in real-time back to the ground control station via a data transmission radio or 4G module. The ground processing module cleans the data in real-time, removing outliers and correcting deviations based on flight attitude, generating a raw data set that can be used for initial weather analysis.

Using a single multi-rotor drone to independently complete weather monitoring tasks is the main detection mode used in current meteorological drones. The multi-rotor drone can be manually transported to the detection area, where the drone and weather payload are assembled and tested on-site. This system is simple, highly robust, cost-effective, and offers excellent mobility. However, there are still significant drawbacks to the single-drone independent detection mode. Due to the limitations of a single platform, the coverage area can only meet the grid-based weather detection needs of small-scale regions and cannot capture the meteorological changes in medium-

scale areas. In terms of endurance, mainstream multi-rotor drones cannot support long-duration monitoring tasks such as tracking thunderstorm evolution or low-altitude inversion layer changes when carrying meteorological payloads. Furthermore, due to the limitations of payload capacity and power supply, a single drone can typically only carry a single type of weather payload, making it difficult to simultaneously detect multiple weather parameters such as temperature, humidity, wind speed, air pressure, and air quality, resulting in lower detection efficiency.

An article[29] proposes using a six-rotor drone equipped with an ultrasonic anemometer to measure the airborne wind field. It focuses on the accuracy of the meteorological payload measurements. Wind tunnel experiments were conducted to analyze how the drone's body posture affects the accuracy of wind measurements. After correcting for body posture coefficients, the average wind speed measured by the drone's wind system matched the data from a comparison anemometer. When compared with the results from a wind tower, the corrected wind speed, wind direction, turbulence intensity, and other parameters showed minimal differences from the data collected by instruments at the same height on the wind tower. The vertical fluctuation wind power spectra obtained from both methods were nearly identical and aligned with the von Kármán spectrum. The system also measured the wind field characteristics of a specific location and compared them with relevant parameters from national standards, further confirming the feasibility of using this system for airborne wind field measurements.

3.2 Multi-drone Networking Detection

The multi-drone network detection is a technology model designed to address the limitations of single drone detection in terms of coverage, endurance, and simultaneous multi-parameter observation. By using multiple multi-rotor drones to build a distributed collaborative detection network, it completes meteorological detection tasks. This approach can overcome the boundaries of small-scale detection and achieve grid-based, high spatio-temporal resolution monitoring of meteorological parameters in a medium-scale area. The main components of the system are shown in Figure 9.

A multi-drone network detection system requires a ground control center as the core for global scheduling. The center integrates geographic information of the detection area, meteorological data, and the status information of various ground control units. It then issues task instructions to different ground control units through a dedicated scheduling algorithm. Each drone is equipped with specialized meteorological payloads like temperature, humidity, wind speed, and wind direction sensors. The drones follow a flight path planned by the ground control center to form a distributed detection
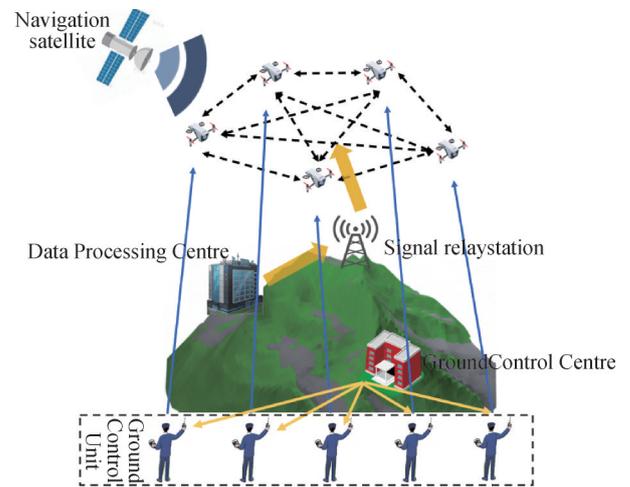

Fig.9　Multi-drone networked detection system

network in the air. They also use real-time communication links to exchange data bidirectionally, enabling data compensation and relay. For drones located at the edges of the detection area or in regions with weak signals, the collected data is first transmitted to nearby drones with stable signals. These relay drones then gather the data and upload it, preventing data loss caused by the insufficient communication range of a single drone. All drones rely on satellite navigation for real-time positioning. The ground control center dynamically corrects the flight path deviations based on the drone's position and heading data from the satellites. The meteorological data, after compensation and relay by the drones, is transmitted through a chain of links, including drones, signal relay stations, and ground data processing centers.

Current mainstream communication methods can be categorized into four types: fully centralized networking, layered centralized networking, fully distributed networking, and layered distributed networking[30, 31], as shown in Figure 10.

3.2.1 Fully centralized network architecture

In a fully centralized network, a single ground control center acts as the central node. All communication between drone nodes is directly with the ground control center, and there is no direct data transfer link between drones. In this setup, the ground control center is responsible for task scheduling, data reception, and issuing instructions. The drones only need to execute the center's commands and collect parameters, without handling complex coordinatiologic.

3.2.2 Layered centralized networking architecture

The layered centralized network builds upon the fully centralized structure by adding ground control unit center nodes, creating a three-tier communication architecture with the ground control center, ground control units, and drones. This is the mainstream choice for balancing control efficiency and network stability. The ground control center, as the global scheduling layer, is responsible for designing the overall detection plan,
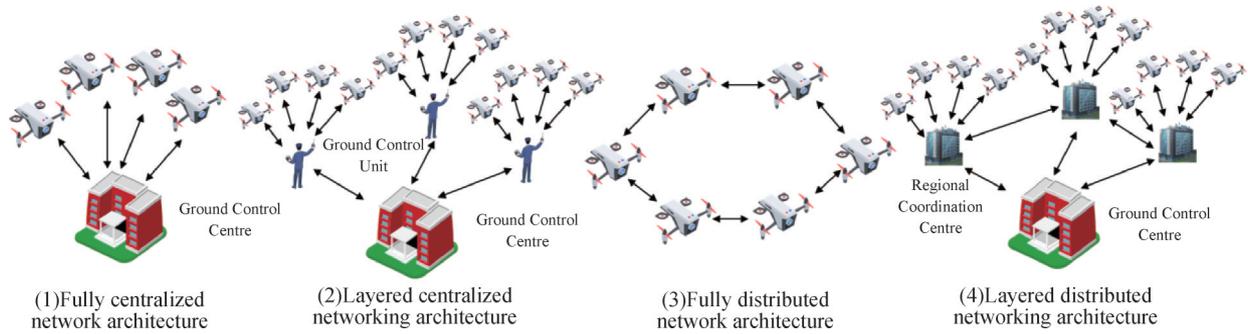
Fig.10 Mainstream communication methods for multi-rotor drones

allocating detection areas, and exchanging data with multiple ground control units. The ground control unit, as the local execution layer, issues detailed instructions in real-time, receives raw data collected by the drones, performs preliminary processing, and then uploads the processed data to the ground control center. Drones can establish simple communication links as needed, only for sharing location information to avoid collisions, without participating in complex data relays or compensation.

3.2.3 Fully distributed networking architecture

The fully distributed network eliminates the need for a single central node, where all drone nodes are equal and communicate directly with each other. In this structure, each drone serves both as a weather data collection terminal and a data relay node, while also communicating with the ground data processing center. The control of the network is evenly shared by all nodes, requiring full synchronization across all nodes to manage the network effectively. The main advantage of this communication method is its resilience—if some drones fail, the remaining nodes can automatically rebuild the communication links, ensuring uninterrupted data transmission without the need for complex ground control facilities. This makes it suitable for detecting in areas with complex or remote terrain. However, drones must carry more complex communication and computing modules, which increases payload weight and power consumption. Also, the synchronization accuracy of distributed algorithms can be affected by communication delays, potentially leading to reduced spatial and temporal consistency of the weather data.

3.2.4 Layered Distributed Networking architecture

The layered distributed networking integrates both layered architecture and distributed characteristics. The drones in the detection area are divided into several subnetworks. Communication within each subnetwork is fully distributed, and interaction between subnetworks is achieved through regional coordination center nodes. Within each subnetwork, drones perform data collection, relaying, and local task adjustments through self-organized communication. Each subnetwork has a

regional coordination center node responsible for gathering meteorological data and communicating with coordination nodes of other subnetworks or the ground control center, transmitting cross-region task adjustment instructions and aggregated data. The ground control center only handles global coordination between subnetworks, without interfering with the internal communication details of each subnetwork. This method combines the anti-destruction ability of a fully distributed system with the controllability of a layered architecture. It can accommodate large-scale detection while ensuring local data consistency through subnetwork division. However, this approach has high design complexity and communication protocol complexity, requiring drones to have stronger autonomous decision-making capabilities. Additionally, failure of the regional coordination node can prevent the uploading of subnetwork data, and the overall hardware and software cost is significantly higher than other networking methods.

Multi-drone network detection has significant advantages: wide coverage, breaking through the limitations of small-scale detection, and by using layered flight to cover the low to mid-altitude atmospheric regions, it compensates for traditional observation deficiencies and captures the spatial distribution of mesoscale meteorological fields. The data is highly valuable, as synchronized observations from multiple drones improve spatiotemporal resolution. The system also has strong redundancy and fault tolerance, ensuring high mission reliability through dynamic task reallocation and communication backups. The data consistency is good, supporting multi-source fusion. By time synchronization and path coordination, the data from multiple drones has a unified spatiotemporal reference, which can be directly fused with ground station and satellite data, enhancing numerical weather prediction model accuracy. However, multi-drone network detection also has notable disadvantages: the system complexity is high, requiring solving issues such as topology design, task scheduling, multi-drone collision avoidance, and data synchronization. The cost and maintenance pressure are also high, requiring periodic calibration of payload consistency. Communication is dependent on the environment, and in remote areas, satellite communication is needed due to the lack of public

networks. Data processing faces challenges with real-time performance, as the data volume from multiple drones is several times that of a single drone, requiring high-performance computing capabilities for real-time processing. Collaborative control is also susceptible to interference, as communication signals can be disrupted in electromagnetically complex areas, leading to communication breakdown or scheduling disorder. Strong winds and thick fog can also affect drone attitude and disrupt the spatial consistency of observations. Additional investment in anti-jamming and attitude compensation technologies is required, further increasing system complexity. These are the technical challenges that multi-drone network detection faces and the issues the system currently needs to address.

3.3 Air-Ground-Space Integrated Operations Model

The air-ground-space integrated model is a deep integration of multi-rotor drone detection and traditional meteorological observation systems. In this model, the multi-rotor drone serves as the low-altitude detection node, the ground weather station acts as the fixed observation base, and the meteorological satellite provides large-scale background support. These three components work together through data exchange protocols[32]. The ground station monitors and preprocesses the drone's flight status and detection data in real-time, while transmitting ground reference data to the drone for payload calibration. The meteorological satellite provides macro data such as regional cloud images and water vapor distribution, which helps in selecting the drone's detection area and planning its tasks. The model is shown in Figure 11.
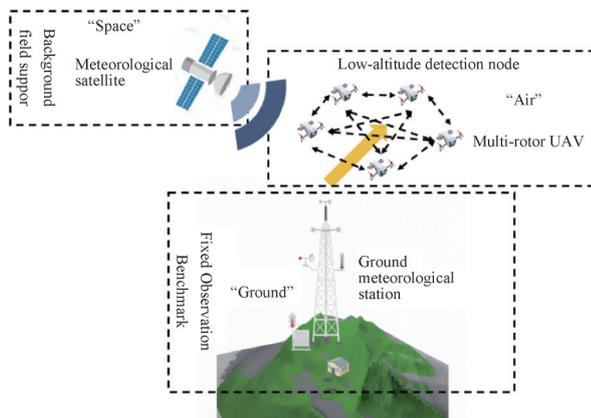

Fig.11 Air-ground-space integrated operation model

In recent years, the main challenges of the air-ground-space coordination model are as follows: there are large differences in the time and spatial resolution between satellite, ground station, and drone data, making time synchronization and spatial matching difficult, which can lower the accuracy of data fusion. Satellites struggle to update regional background data in real time,

and their update pace does not match that of drones and ground stations, affecting the timeliness of coordination. The data formats and communication protocols of different platforms are often inconsistent, leading to compatibility issues and increasing system integration costs. In complex environments, satellite signals can be blocked, and air-ground communication can be interrupted, destabilizing the coordination.

3.4 Heterogeneous Platform Collaboration Model

The heterogeneous platform coordination model integrates the advantages of multi-rotor drones with other types of detection platforms, such as fixed-wing drones, tethered balloons, and unmanned surface vehicles, to achieve three-dimensional, multi-dimensional meteorological detection[33]. In this model, multi-rotor drones, with their low-altitude maneuverability, are responsible for detailed near-ground detection. Fixed-wing drones, with their long endurance, perform wide-area surveillance at mid-to-high altitudes, while tethered balloons provide long-term, stationary vertical profile observations. These three platforms are coordinated through a unified control center, allowing for task collaboration and data sharing. After data fusion, the combined information can fully present atmospheric structure characteristics, overcoming the limitations of single-platform detection. This is shown in Figure 12.
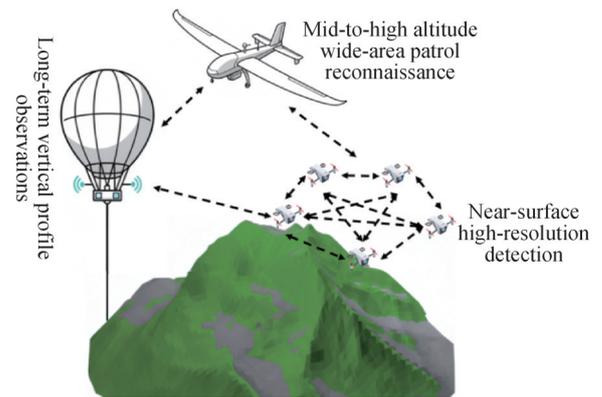

Fig.12 Heterogeneous platform collaboration model

However, there are significant differences in the flight characteristics, detection accuracy, and data formats between different platforms, making task scheduling and multi-source data integration challenging. The system control is complex, as it requires real-time coordination of the detection range and paths of each platform to avoid conflicts, placing high demands on the coordination algorithms. Maintenance costs are high due to different hardware maintenance and payload calibration standards for each platform, adding to the operational burden. Time and space synchronization of data is also difficult, as the detection rhythms of each platform vary, leading to potential mismatches in time and space, which affects the

reliability of the fused data.

4   Key Technologies for Multi-Rotor Meteorological Unmanned Aerial Vehicles

The technical system of multi-rotor meteorological drones focuses on stable flight, precise detection, efficient transmission, and reliable application. It covers four key technologies, with each technology supporting and working together to ensure the successful execution of detection tasks and the reliability of data quality.

3.1 Stabilized Flight Platform Technology

The stable flight platform technology ensures stable flight of drones in complex weather conditions through a high-precision flight control system and optimized power configuration[34]. The flight control system must have high-accuracy attitude sensing and fast-response attitude control capabilities to counteract the effects of air turbulence on the flight attitude in real time, ensuring that the drone follows the preset flight path. The power system needs to use high-power-density motors and batteries, combined with intelligent power distribution algorithms, to ensure long flight endurance while providing a stable power supply for the payload, preventing power fluctuations from affecting sensor performance.

Currently, the stable flight platform technology for multi-rotor drones has developed into a pattern of traditional control and intelligent algorithms working together. A comparison table of the core technologies for stable flight is shown in Table 1.

Table 1 Core comparison of stable flight technologies

Comparison dimensions	Improved self-noise-resistant attitude control and trajectory tracking for quadcopter drones	Attitude control of quadrotor drones based on deep reinforcement learning	A novel multi-modal and drone-assisted method based on collaboration
Core research objectives	Enhancing the attitude control accuracy and trajectory tracking stability of quadcopter drones in complex interference environments	Addressing the shortcomings of traditional Proportional-Integral-Derivative (PID) parameter tuning in highly dynamic and complex environments, enhancing adaptive stability in attitude control.	Through drone collaboration, indirectly ensuring the deployment and flight stability of unmanned aerial vehicles.
Core methods for stability control	Improved anti-interference control and PID position control	Cascaded PID and deep deterministic policy gradient hybrid control	Multi-modal nomadic algorithm optimizes unmanned aerial vehicle deployment and flight self-organizing network coordination
Applicable scenarios	Attitude control and precise trajectory tracking of quadrotor drones under complex interference	Attitude control of quadrotor drones in highly dynamic and variable environments	Multi-drone cooperative stable deployment

The improved Active Disturbance Rejection Control (ADRC) achieves real-time disturbance compensation through an extended state observer, showing excellent robustness in strong wind scenarios like meteorological detection[35]. However, nonlinear ADRC has issues with complex parameter tuning and reliance on a solid theoretical foundation. Deep reinforcement learning optimizes control strategies for complex scenarios through trial-and-error learning[36], but it faces problems such as gaps between simulation and real-world environments, lack of safety mechanisms, low training efficiency, and delays due to complex network structures and limited computing power of edge devices. In multi-drone formation scenarios[37], issues include state space explosion, communication delays leading to coordination imbalance, sensor noise amplifying control errors, and insufficient parameter robustness under dynamic conditions.

4.2 Meteorological Payload Integration Technology

Lightweight, high-precision meteorological payload integration technology is key to enhancing detection capabilities. It enables the miniaturization, high precision, and integration of meteorological sensors while meeting drone payload weight limits[38,39]. By reducing the sensor size and using a multi-sensor integration design, temperature, humidity, pressure, and other sensors are combined into a single payload module. This reduces the weight of redundant structures and eliminates signal interference between sensors through electromagnetic compatibility design and calibration technology, ensuring accurate parameter measurements.

Currently, most multi-rotor drone meteorological monitoring platforms install a ground-based miniature tower-shaped meteorological data collector on the upper part of the drone. Miniaturization technology is used to keep the sensors' size and weight within the drone's payload capacity. This allows integration of multiple sensors for temperature, humidity, pressure, and some air quality parameters. At the same time, electromagnetic compatibility and anti-interference performance are optimized through metal shielding, circuit isolation, and digital signal transmission, with calibration mechanisms

in the lab and field to ensure detection accuracy. However, due to the limitations of drone payload weight and endurance, there is a conflict between lightweight design and sensor stability and wide-range performance. After multi-sensor integration, the differences in power requirements and sampling frequencies between different types of sensors create complex coordination mechanisms. In extreme weather conditions, the stability of the sensors and integrated modules is still insufficient. Furthermore, the calibration of the integrated module requires multi-parameter error coupling models and expensive equipment. Custom designs also lead to poor load expandability and compatibility, making it difficult to flexibly expand detection parameters. Therefore, developing meteorological detection equipment suitable for multi-rotor drones is one of the key technologies to improve the detection accuracy of multi-rotor meteorological drones.

4.3 Stable Data Transmission Technology

Data transmission technology needs low latency and high reliability to enable real-time meteorological applications. It must solve the problem of fast and stable data transmission between drones[40,41] and from drones to the ground. For the real-time requirements of meteorological data, current mainstream technologies use 4G/5G public networks or data transmission radios for short-range data transfer from drones to the ground. Data transmission radios have stronger anti-interference capabilities and are suitable for areas with complex electromagnetic environments. For long-range or remote detection, satellite communication modules are needed to achieve beyond-line-of-sight (BLOS) data transmission. Moreover, data transmission systems should use error control coding and data compression algorithms to ensure data reliability while reducing bandwidth usage, preventing delays or data loss from affecting the timeliness of meteorological analysis.

The main challenges in stable data transmission between drones are interference from complex environments, protocol efficiency bottlenecks, resource constraints, security and real-time conflicts, and multi-device collaboration interference. Currently, there is no universal optimization framework to achieve dynamic balance[42,43]. In addition, the development directions for drone-related data transmission technologies include: building air-space collaborative networks with drones and satellites, expanding coverage while providing positioning assistance for ground terminals, improving data transmission stability, and reducing transmission interruptions; drones using dedicated optical signal transmission solutions, with electromagnetic interference resistance and high transmission speed, combined with customized optical transmission and reception modules, enabling stable and high-speed data exchange in specific airspaces. Based on this, multi-drone collaborative transmission optimization can further enhance data relay

efficiency between nodes by adjusting device deployment using location prediction models, improving overall system data throughput. Meanwhile, dynamic scheduling of working times can maximize data transmission within energy constraints, ensuring that the basic data transmission needs of all terminal devices are met and enabling resource allocation as needed. The core technologies of data transmission are compared in Table 2.

4.4 Multi-source Data Assimilation and Quality Control Techniques

Multi-source data assimilation and quality control techniques[44,45] are used to improve the reliability of detection data. For multi-rotor drone payload data, ground station data, satellite data, and other heterogeneous data, data cleaning and fusion are performed. The quality control process involves using outlier detection algorithms to remove abnormal data caused by sensor malfunctions or sudden changes in flight posture. Then, assimilation algorithms such as Kalman filtering and ensemble Kalman filtering are applied to merge the high-resolution spatio-temporal data from the drone with benchmark data from ground stations and satellites. This helps to correct system errors in the drone's data, improving its consistency and accuracy, as shown in Figure 13.

5 Conclusion

The current development of multi-rotor drones in weather observation has built a well-established technical system and application model. These drones' payload systems can measure temperature, humidity, wind speed and direction, air pressure, and air quality. Depending on the observation needs, the system can choose from various modes, such as single-drone independent observation, multi-drone networks, air-ground-space coordination, and cooperation among different platforms. Key technologies have greatly improved flight stability, payload accuracy, and data transmission, overcoming the limitations of traditional weather observation in low-altitude, detailed, and dynamic monitoring. This has been crucial for improving weather forecasting, reducing disaster warning times, and advancing atmospheric science.

In the future, the development of drone-based weather observation will focus on three main areas: First, improving payload technology by creating smaller, more accurate, and energy-efficient meteorological sensors using new materials and manufacturing methods, while increasing the range of parameters that can be detected. Second, making the system smarter by using artificial intelligence to enable autonomous decision-making and dynamic task adjustment for multi-drone coordination, enhancing detection efficiency and flexibility. Third, integrating drones into the next-generation weather observation system, creating a smooth "air-ground-space"

Table 2 Comparison of core data transmission technologies

| Comparison dimensions	Multi-drone wireless relay transmission technology	Drone swarm optical communication transmission technology	Air-Ground-Space integrated transmission technology	Satellite and drone non-terrestrial network (NTN) transmission technology
Technology types	Wireless radio frequency relay communication	Free-space optical communication	Integrated air-ground-space collaborative transmission	NTN integrated transmission
Transmission mediums or frequency bands	Radio frequency	Free-space optical	Radio frequency	Radio frequency and free-space optical
Key characteristics	Real-time capability: Unscented Kalman filter provides real-time prediction of drone position, suited to highly dynamic scenarios; Interference resistance: Accounts for non-line-of-sight and obstacle avoidance; Dynamic deployment: Hybrid particle swarm optimizationoptimizes relay station positioning.	Resistance to electromagnetic interference: No radio frequency spectrum overlap; High bandwidth: Supports 100Mbps transmission; Resistance to jitter: Specific divergence angle adapted to drone flight jitter.	Wide coverage: Low earth orbit satellites fill coverage gaps in remote areas; Cooperative transmission: Drone relays reduce satellite link loss; Multi-scenario adaptability: Supports multi-user data uploads and multi-target sensing.	Seamless coverage: Satellites and drones fill gaps in high-altitude urban blind spots or remote areas; Resource efficiency: Shared spectrum and hardware for positioning and communications; Dynamic adaptation: Time-frame optimization to counteract the Doppler effect.
Applicable scenarios	Multi-drone mobile relay; Highly dynamic drone network.	Electromagnetic complex environments; Emergency response; Cooperative operations of drone swarms in severe electromagnetic interference conditions.	Multi-user data collection in remote areas; Multi-target sensing; Wide-area air-ground-space data integration.	High-altitude urban blind spot positioning and communication; Remote monitoring; Disaster relief.
Core Strengths	Adapted to the high dynamic characteristics of drones, without complex pre-training; Real-time optimization of relay deployment ensures stable dynamic links.	Completely avoids electromagnetic interference, ensuring high safety; Hardware is lightweight.	Combining the flexibility of drones with the broad coverage of satellites, without reliance on ground infrastructure; Supporting the dual-function integration of communications and sensing.	Deep integration of positioning and communication reduces beam scanning overhead; Supports collaborative operation across heterogeneous platforms for seamless blind spot coverage.
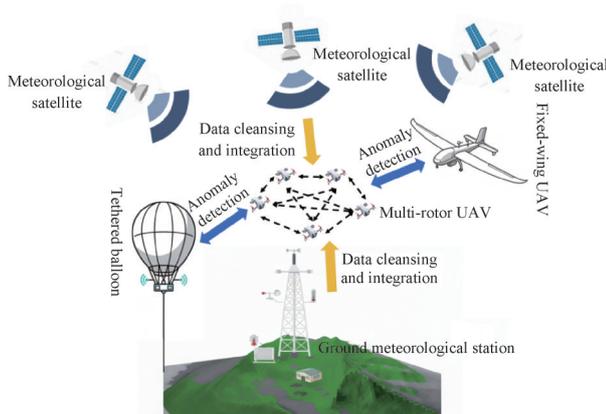
Fig.13 Diagram of multi-source data assimilation and quality control techniques

network to provide stronger technical support for the high-quality development of meteorology.

This paper gives a detailed analysis of the payloads, system modes, and key technologies of multi-rotor drones in weather observation, both domestically and internationally. It explains the strengths and weaknesses of these drones in meteorological observation and predicts future trends and research priorities, offering useful references for promoting their use in weather monitoring.

Author Contribution:

Tianhao Hou: Conceptualization, Validation. Hongyan Xing: Supervision. Jie Hao: Writing-Reviewing and Editing. Tianhao Hou: Conceptualization; Investigation; Writing-original draft. Hongyan Xing: Supervision; Funding acquisition; Writing-review & editing; Validation. Jie Hao: Visualization; Writing-review & editing; Methodology.

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The authors declare that the main data supporting the findings of this study are available within the paper and its Supplementary Information files.

Conflicts of Interest:

The authors declare no competing interests.

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