

Applications of Remote Sensing and Sensor Technology for Unmanned Aerial Vehicle

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Abstract. As a relatively new remote sensing means, unmanned aerial vehicle (UAV) remote sensing has been widely used in the fields of agriculture, forestry, and urban construction surveying and mapping because of its low cost, high efficiency, and flexibility. This paper introduces UAV remote sensing sensor technology and its applications in different fields. First, the core role of sensors in UAV remote sensing systems is introduced, including the development of multispectral, hyperspectral, and LiDAR sensor technologies and their applications in UAV remote sensing. Then, the working principles, technical characteristics, and application scenarios of multispectral, hyperspectral, and LiDAR sensors are discussed. Then, multi-sensor integration techniques in UAV remote sensing are discussed in terms of their importance and challenges. Finally, through the application cases of agricultural monitoring, forestry resource management, and urban construction mapping, the practicality and potential of UAV remote sensing technology are shown. This paper provides a reference for the research and application of UAV remote sensing and its sensor technology in several fields. With the continuous progress and innovation of technology, UAV remote sensing technology is expected to play a key role in more fields and promote the sustainable development of related industries.

Keywords: Unmanned aerial remote sensing; multi-sensor integration techniques; multispectral; hyperspectral; LiDAR.

1. Introduction

Remote sensing technology is a vital tool for information acquisition across various fields, including agricultural monitoring, resource surveys, and urban construction mapping. Aerial remote sensing, known for its wide coverage and high-precision data, has become indispensable in scientific research and practical applications. However, traditional aerial remote sensing faces significant limitations, such as high costs, complex operations, and restrictions imposed by weather conditions and flight duration. With advancements in science and technology, particularly in unmanned aerial vehicle (UAV) technology, UAV remote sensing has emerged as a promising alternative and complement to traditional aerial methods.

UAVs offer several advantages, including lower costs, flexible operations, and timely data acquisition. They can collect high-resolution remote sensing data at low altitudes and in complex environments, making UAV remote sensing highly promising for applications in meteorological monitoring, environmental resource investigations, urban planning, and more [1]. The evolution of UAV remote sensing technology is closely linked to advancements in sensor technology. As the core equipment for data acquisition, the performance of sensors directly influences the quality of remote sensing data and its subsequent application. Currently, commonly used sensors in UAV remote sensing include optical sensors, thermal infrared sensors, LiDAR, and multispectral and hyperspectral sensors [1]. Each sensor type has its own strengths, making it suitable for different applications. Proper configuration ensures accurate information acquisition and analysis. However, much of the existing research focuses on specific applications or individual sensors, with a lack of comprehensive studies on UAV remote sensing sensor technologies and their broader applications.

This paper aims to explore UAV remote sensing sensor technologies and their applications across various fields. It will emphasize the critical roles of multispectral, hyperspectral, and LiDAR sensors,

as well as multi-sensor integration technologies in UAV remote sensing. Furthermore, the paper will present case studies demonstrating the practical applications of UAV remote sensing technology in agricultural monitoring, forestry resource management, and urban construction mapping. Finally, the paper will discuss the development trends and challenges of UAV remote sensing technology, offering insights into its future application prospects.

2. Remote sensing sensor technology for UAVs

As a core component of UAV remote sensing systems, sensor performance directly impacts the quality of remote sensing data and the effectiveness of its applications. In recent years, sensor technologies such as multispectral, hyperspectral, and LIDAR have advanced rapidly and found widespread use in UAV remote sensing. These sensors not only improve the accuracy of data acquisition but also provide technical support for multi-dimensional and multi-level information gathering. Additionally, the advent of multi-sensor integration technology offers new opportunities for remote sensing applications in complex environments and under diverse requirements, further enhancing the functionality and adaptability of UAV remote sensing systems.

2.1. Multi-spectral sensors

Multispectral remote sensing refers to a detection technology that utilizes sensors with more than two spectral channels for simultaneous imaging of ground objects. These sensors capture and record the electromagnetic wave information reflected from the target by dividing it into several spectral bands. The key instrument for multispectral remote sensing is the multispectral camera, which can capture multiple images with different spectral characteristics in a single shot [2]. As a novel aerial remote sensing technology, UAV-based multispectral remote sensing enables the acquisition of multispectral features, texture features, accurate geospatial locations of target features, and the quantitative inversion of surface parameters. With high mobility, all-weather capability, and detailed observation capabilities of airborne platforms, this technology rapidly acquires feature parameters and attribute information that meet industrial application needs. It plays a significant role in natural resource inversion, biodiversity monitoring, agricultural information analysis, disaster monitoring, and other fields [3].

However, due to the payload limitations of UAVs, multispectral sensors are generally required to be lightweight, compact, highly accurate, and energy-efficient. Depending on the detection wavelengths, these sensors are mainly classified into visible wavelength (400-760 nm) digital cameras, visible near-infrared wavelength (400-1100 nm) multispectral cameras, and thermal infrared wavelength (3.6-13.5 μm) cameras. Visible-band digital cameras are the most widely used sensors in UAV remote sensing, offering advantages such as low cost, high pixel density, and ease of operation, enabling quick acquisition of grayscale or color images in the visible band. Near-infrared multispectral cameras capture monochrome images across different bands through spectroscopy, generally categorized into single-lens with a spectroscopic system and multi-lens spectroscopy based on the method of spectral division. Thermal infrared cameras, on the other hand, image targets through detectors sensitive to the thermal infrared band, reflecting the temperature information of the target surface [2].

2.2. Hyperspectral sensors

Hyperspectral remote sensing, as a passive detection technology, acquires rich high-resolution spectral information through electromagnetic waves reflected by ground objects [4]. In UAV remote sensing, this technology involves the use of a hyperspectral imager mounted on a UAV, with imaging modes primarily categorized into two types: push-broom and stare. Push-broom imaging faces challenges in geometric correction due to limitations in the imaging process and the effects of UAV flight jitter. Achieving high-quality images typically requires a high-precision localization system and complex computational processing. In contrast, stare-based hyperspectral imagers use frame imaging, allowing geometric correction and image stitching without the need for a positioning and

staking system. However, the challenge in data processing lies in correcting spectral information due to the time differences in imaging across different wavebands [5].

In the field of aerospace remote sensing, advancements in satellite detection technology have highlighted the unique application value of hyperspectral remote sensing in areas such as surface and atmospheric parameter inversion, wind field measurement, meteorological forecasting, and disaster monitoring. Notable hyperspectral infrared sensors include the Infrared Atmospheric Sounding Interferometer, the Cross-track Infrared Sounder, and the Interferometric Atmospheric Sounder aboard the Fengyun-4 satellite [6].

Hyperspectral remote sensing technology excels in spectral recognition and near-continuous detection of spectral information, allowing for effective differentiation of features with varying material compositions. This capability is invaluable for acquiring detailed spectral information and fine recognition of features. However, the limitations of these sensors in capturing three-dimensional spatial information constrain their effectiveness in applications that require classification of features made from the same material [4].

2.3. LIDAR Sensors

LIDAR is an advanced radar system that detects the distance, position, and motion status of a target by emitting a laser beam and measuring the return time and intensity of the reflected or emitted laser signal. LIDAR's shorter wavelength and high collimation provide significant advantages in accuracy and resolution [7].

In UAV remote sensing, combining LIDAR technology with hyperspectral remote sensing enables comprehensive target detection. LIDAR can address the spatial dimension limitations of hyperspectral remote sensing, effectively merging spatial and spectral information. This combination allows for the acquisition of spatial location data and three-dimensional feature information while collecting spectral data, thereby enhancing target detection speed and significantly improving the accuracy of feature classification [4].

UAV-mounted LIDAR sensors are primarily categorized into two types: mechanical rotary and solid-state. Mechanical rotary LIDAR technology is well-established, utilizing mechanical components and motor servos for beam scanning, offering large aperture throughput and wide scanning angles for long-distance measurements. However, it has drawbacks such as large size, slow scanning speed, and complex assembly and debugging requirements. On the other hand, solid-state LIDAR employs technologies like microelectromechanical systems (MEMS), surface array flash, and optical phased arrays, which are characterized by miniaturization, integration, cost-effectiveness, and adaptability [7].

As an active detection technology, UAV LIDAR has clear advantages in acquiring three-dimensional information under all-weather conditions. Traditional single-band LIDAR provides point cloud data, including 3D coordinates, reflection intensity, time stamps, and echo information, which is essential for fine identification and classification in remote sensing scenarios. However, due to the wavelength limitations of LIDAR, it faces challenges in acquiring spectral information and lacks the ability to distinguish features with similar spatial structures based on spectral data alone [4].

2.4. Multi-sensor integration technology

With the rapid evolution of UAV remote sensing technology and the growing demand for data acquisition, UAV sensor design is progressing towards multi-mission, standardized, modular, and open architectures. Integrating various types of remote sensing payloads, such as optical cameras, imaging spectrometers, and LIDARs, to achieve synergistic operation is a key development direction for future UAV remote sensing [8].

The challenge of multi-sensor integration lies in achieving synchronized control of sensors with varying resolutions to ensure they operate within a unified temporal and spatial reference. This is

particularly crucial in UAV mapping applications, where the integration of imaging sensors, 3D laser scanning devices, and positioning and attitude sensors is required. Synchronized control is essential for achieving highly accurate measurements, especially when the UAV is moving at high speeds. Effective multi-sensor data integration necessitates unifying the time scale and synchronizing the data to the same time axis. Additionally, spatial synchronization is critical for successful data integration and fusion, requiring high-precision calibration techniques and software support [9].

Integrating smart payloads, which combine hardware and software, such as integrated sensors, not only enhances information collection capabilities but also improves data processing efficiency. Multi-sensor integrated UAVs are typically equipped with multiple microprocessors that support advanced digital signal processing techniques like Fourier transforms and self-diagnostic functions, thereby enhancing the system's stability, reliability, and overall performance [8].

3. Case studies of remote sensing sensors for UAVs

With the rapid development of UAV technology, UAV remote sensing has demonstrated significant application potential across various fields. The flexibility and efficiency of UAVs make them essential tools for acquiring high-resolution remote sensing data, providing critical support in agricultural monitoring, forestry resource management, and urban construction mapping. In these application scenarios, different types of sensors, including multispectral, hyperspectral, and LiDAR, play crucial roles by providing a reliable database for both scientific research and practical applications.

3.1. Remote sensing for agricultural monitoring

UAV remote sensing for agriculture offers a high-precision, high-resolution approach to monitoring and data collection in agricultural fields, combining UAV platforms with advanced remote sensing technology. This technology is pivotal in various aspects of agricultural production, including crop pest and disease monitoring, crop growth assessment, and precise measurement of planting density. To obtain comprehensive data on farmland and crops, UAV remote sensing in agriculture relies on various sensors, such as digital, multispectral, and hyperspectral cameras. These sensors provide robust data support for agricultural information collection and promote the advancement of precision agriculture research [10].

In the field of crop pest and disease stress monitoring, UAV remote sensing technology has been widely adopted and studied. Pests and diseases cause changes in the absorption and reflectance properties of crops in specific spectral bands, and these spectral responses are key to monitoring such stresses. When crops are affected by pests and diseases, changes in pigmentation, morphology, and structure occur, which can be detected by analyzing the crops' spectral response characteristics. Thus, UAV remote sensing techniques enable precise, rapid, and non-destructive detection of pest and disease stress. In this research area, commonly used airborne sensors include optical, optoelectronic, thermodynamic, and some acoustic sensors, such as multispectral cameras, hyperspectral cameras, digital cameras, thermal infrared cameras, and LiDAR, providing diverse technological means for monitoring pest and disease stress [11].

3.2. Remote sensing for forestry resource monitoring

The application of UAV remote sensing technology in forestry resource monitoring offers an innovative and efficient approach to forestry management. This technology allows for the rapid acquisition of detailed images and spectral data of forests through high-resolution cameras and multispectral sensors carried by drones [12]. UAV remote sensing can efficiently create accurate forestry maps, including information on the location, size, and distribution of trees. Regular drone monitoring can track tree growth trends and changes in biomass, helping predict future forest resource states and providing a scientific basis for developing sustainable forestry strategies. After deforestation or natural disasters, drones can assess damaged areas and guide forest restoration efforts.

Selecting suitable sensors based on the specific needs of forestry resource investigation and monitoring is crucial. Optical sensors, for instance, can acquire high-resolution color images, which are useful for identifying vegetation types and detecting pests and diseases. Thermal infrared sensors can detect temperature changes in vegetation, aiding in the identification of problems such as pests and diseases. Multispectral sensors can capture multi-band images, allowing for vegetation index calculations and analysis of vegetation growth states. When selecting and configuring sensors, it is also important to consider the UAV's payload capacity, navigation altitude, and the specific requirements of the remote sensing task. Appropriate sensor selection and configuration can significantly improve the accuracy and efficiency of forestry resource investigation and monitoring [13].

3.3. Remote sensing for urban construction mapping

With the advancement of urban construction, there is a growing need to integrate and optimize various types of information within the city to rationally plan and manage urban development and road systems. UAVs, due to their low cost, ease of operation, and quick data acquisition capabilities, are well-suited for real-time monitoring and data collection in complex urban environments. By equipping UAVs with various sensors and data collection devices, along with communication networks and data centers, it is possible to achieve real-time monitoring and collection of diverse urban data. This data can then be integrated and analyzed to optimize urban operations and enhance overall city management [14].

High-precision sensors carried by UAVs, such as LiDAR and high-resolution cameras, can rapidly acquire three-dimensional data of urban terrains. These data are crucial for creating accurate topographic maps, which provide essential information for urban planning and land use analysis. Drones can also conduct regular monitoring of urban infrastructure, including roads, bridges, and buildings, to promptly detect structural damage or functional degradation, thus informing maintenance and upgrade decisions. Furthermore, UAVs can monitor urban traffic flow, collecting data on congestion and vehicle distribution, which can provide real-time insights for traffic planning and management, ultimately helping to optimize traffic flow and reduce congestion. Additionally, UAVs can oversee construction projects in real-time to ensure quality and progress are maintained [15].

The application of UAV remote sensing technology in urban construction mapping not only enhances the efficiency and accuracy of data collection but also provides robust technical support for sustainable urban development. As technology continues to advance, the role of UAVs in urban construction will become increasingly comprehensive and integral.

4. Summary

The advancement of UAV remote sensing and its sensor technology has laid a strong foundation for the diversification and efficiency of remote sensing applications. UAV remote sensing has demonstrated significant potential across various fields, including agricultural monitoring, forestry resource management, and urban construction mapping. This paper highlights the diversity and flexibility of UAV remote sensing technology by examining these application scenarios and the corresponding sensors utilized. The application and optimization of sensors, such as multispectral, hyperspectral, and LiDAR, along with the integration of multiple sensors, have enabled UAV remote sensing to acquire comprehensive and high-precision data. These advancements allow UAVs to adapt to diverse working environments and perform a wide range of tasks simultaneously, underscoring their effectiveness and advantages in different applications. This provides valuable references for research and practice in related fields.

However, UAV remote sensing sensor technology also faces several challenges. For instance, the efficiency and accuracy of processing and analyzing sensor data require further improvement, and there is an urgent need to enhance the resolution, sensitivity, and stability of the sensors themselves.

In the future, UAV remote sensing technology is expected to benefit from the integration of artificial intelligence, cloud computing, and big data technologies, which will significantly enhance data processing and analysis capabilities. Concurrently, technological advancements will expand the application of UAVs into broader fields, including resource monitoring, urban planning, and agricultural environmental monitoring. As sensor performance improves and costs decrease, UAV remote sensing technology will become increasingly efficient and cost-effective.

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