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Development of a 3-Axis Gimbal for Drones to Improve Hyperspectral Imaging Quality of Large-Scale Natural Heritage

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Abstract

This study presents the design, fabrication, and performance validation of a precision 3-axis gimbal system for drone-mounted applications. Traditional fixed bracket systems have faced challenges in maintaining stable imaging angles and mitigating vibration, primarily due to sensor weight and structural limitations. These issues have resulted in diminished image alignment and reduced data reliability. To overcome these limitations, a precision 3-axis gimbal and external power supply system were developed, and their effectiveness in enhancing image quality was demonstrated using UgCS-based flight planning software. The system underwent two rounds of performance testing, which confirmed notable improvements in geometric calibration, power stability, imaging efficiency, and image alignment accuracy. The results of this study are expected to provide a strong foundation for precision monitoring and analysis using hyperspectral images in large-scale natural heritage applications.

1. Introduction

Hyperspectral imaging is an advanced remote sensing technique that enables the precise extraction of spectral characteristics from a target by capturing information across dozens to hundreds of contiguous wavelength ranges (Chang, 2007). This technology is capable of detecting subtle differences that are difficult to identify with the naked eye, such as those found in vegetation, soil, water quality, and the surfaces of cultural heritage sites. As a result, hyperspectral imaging has been widely adopted in fields such as environmental monitoring, agriculture, mineral exploration, and security surveillance. More recently, there has been increasing interest in applying this technology to the conservation and change detection of cultural heritage.

One of the major challenges in acquiring aerial hyperspectral images using drones is the degradation of image quality caused by vibrations and shaking during flight. Digital cameras mounted on drones are typically stabilized using gimbals, which are support devices that compensate for shaking and allow the camera to be oriented in the desired direction. There are various gimbal systems designed to accommodate different sensors, including multi-spectral and thermographic sensors. However, unlike these types of sensors, aerial hyperspectral sensors are structurally complex and acquire data across hundreds of spectral bands. They tend to be heavier and are equipped with highly sensitive components such as focal plane array detectors, which are particularly vulnerable to external shocks. Furthermore, when aerial hyperspectral sensors are mounted on fixed-angle brackets, both geometric and spectroscopic errors can arise in individual strip images as well as in mosaicked images.

To resolve these issues, this study aims to develop a precision 3-axis gimbal designed to improve operability, stability, and imaging precision for drone-based applications. In addition, the study adopts an integrated approach, addressing the physical alignment between the gimbal and sensor, distributed power supply, and precise flight path control, with the goal of enhancing the overall reliability of hyperspectral image acquisition.

2. Methodology and Results

2.1 Research Content

This research was conducted in a sequence beginning with the diagnosis of issues inherent in fixed bracket systems, followed by enhancements to aerial hyperspectral image quality through the development of a precision 3-axis gimbal system, a distributed power supply approach, and software optimization. Hyperspectral sensors are high-precision instruments based on focal plane array technology. Compared to standard RGB or multi-spectral sensors, they are heavier and structurally more susceptible to external shock. To ensure the stability of such sensitive equipment, this study involved the independent design of a 3-axis gimbal and the precise adjustment of physical alignment between the drone and the sensor. Furthermore, system stability was reinforced by separating the sensor power and supplying it through an external battery (Figure 1).

2.2 First Performance Test

The precision 3-axis gimbal for drone use was developed by integrating an existing gimbal system, taking into account the specifications and weight of the aerial hyperspectral sensor, the drone's payload capacity, and the presence or absence of onboard batteries. The performance test was carried out at Gangsang Sports Park in Yangpyeong-gun, Gyeonggi Province, a designated site for boresight calibration.

During aerial hyperspectral imaging, several issues were identified. In the resulting strip images, some files contained incorrect geolocation data, while others lacked the file necessary to input geometric information. Additionally, after imaging concluded, the system failed to maintain the intended imaging angle, leading to the imaging of unintended areas or the termination of imaging with the aerial hyperspectral sensor powered off (Figure 2).

a. Fixed-Angle Bracket

b. Precision 3-Axis gimbal system (improved design)

Figure 1. Fixed-angle bracket and precision 3-axis gimbal

The geometric errors were attributed to three primary factors. First, both the precision 3-axis gimbal and the aerial hyperspectral sensor drew power simultaneously from the drone’s battery during imaging. This led to duplicated power consumption, as the battery had to support both flight operations and the maintenance of gimbal attitude information. Due to limited power capacity, the sensor would occasionally shut down mid-operation. Second, a misalignment between the central axes of the aerial hyperspectral sensor and the precision 3-axis gimbal caused excess power consumption in maintaining the desired imaging angle and sensor attitude information, resulting in the imaging of unintended areas. Lastly, the combined weight of the aerial hyperspectral sensor and the precision 3-axis gimbal affected motor performance during turning maneuvers. During acceleration and deceleration phases, the drone’s motors failed to operate properly, leading to loss of angle stability, sensor shutdowns, and unintended imaging due to system overload (Figure 3).

a. Shooting Angle Issue

b. Sensor shutdown issue

Figure 2. Occurrence of hyperspectral sensor errors

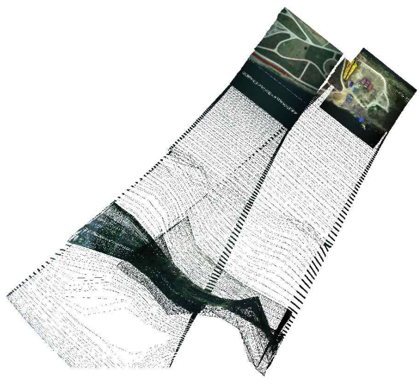


Figure 3. Hyperspectral image alignment errors

2.3 Supplement to the First Test and Second Performance Test

2.3.1 Use of External Battery and Development of Auxiliary Tools

The first performance test confirmed that it was not feasible to operate both the gimbal and the sensor simultaneously using the drone's battery. Accordingly, to maintain imaging operability and stability, the precision 3-axis gimbal continued to draw power from the drone's battery, as in the previous configuration. A separate external battery was used to operate the aerial hyperspectral sensor during the test flight. To accommodate the use of the external battery, a dedicated mounting tool was employed to secure the battery to the underside of the drone carrying the aerial hyperspectral sensor. Furthermore, considering the size of the precision 3-axis gimbal and the required imaging angle, the power cable and landing gear were extended beyond their original lengths to support the acquisition of uniform spectral data (Figure 4).
Following the installation of these tools, the aerial hyperspectral imaging test showed no instances of forced sensor shutdown from start to finish, demonstrating improved system stability and efficiency.

a. Aerial hyperspectral sensor mounting device

b. Power cable, Landing gear, External battery Installation

Figure 4. Use of external battery and auxiliary tool development

2.3.2 Center of Gravity and Precise Gap Adjustment

When the axis of the precision 3-axis gimbal is aligned with the center of gravity of the aerial hyperspectral sensor, the sensor can be adjusted to the desired direction and angle with minimal power consumption. However, if the center of gravity and axis are misaligned, additional power is required to maintain the imaging angle and attitude information set by the gimbal, which may cause the gimbal to malfunction or fix the sensor at an unintended angle during imaging.
Accordingly, the errors observed in the precision 3-axis gimbal were analyzed as stemming from the misalignment of the center of gravity and axis between the aerial hyperspectral sensor and the gimbal. Based on this analysis, using the aerial hyperspectral sensor as the reference, physical axis adjustments were made to the precision 3-axis gimbal to align the center of gravity and the axis (Figure 5).

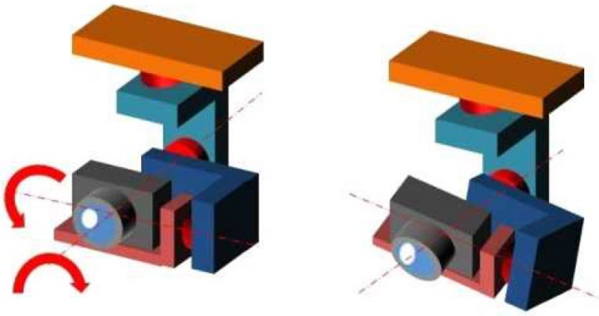


Figure 5. Weight balance and axis alignment between sensor and gimbal

After aligning the center of gravity and the axis, the system was evaluated to determine whether the aerial hyperspectral sensor made contact with the ground and whether any abnormalities occurred during side-to-side rotation. A ground-level imaging test was then conducted to verify the proper acquisition of spectral data. The test revealed a vibration issue on the side of the precision 3-axis gimbal.
Analysis of the vibration issue showed that the original gimbal was not designed or commercialized specifically for the aerial hyperspectral sensor, which caused a slight gap on the side. This gap generated vibration during sensor operation.
To resolve this, the aerial hyperspectral sensor was mounted to the precision 3-axis gimbal, and physical adjustments were made to eliminate the side gap. As a result, no vibration issues occurred even after the imaging session had ended and both the drone battery and the aerial hyperspectral sensor battery were fully depleted, leading to an improvement in overall image quality (Figure 6).

a. Aerial hyperspectral test imaging

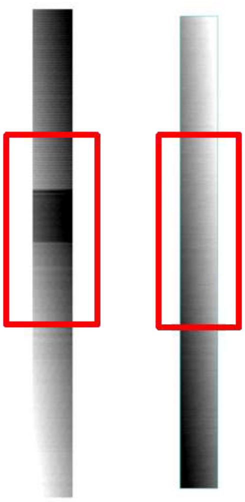
b. Imaging results using the precision 3-axis gimbal

Figure 6. Image capture and results using precision 3-axis gimbal

2.4 Comparison of Flight Planning Software

The existing DJI Pilot2 software offers an intuitive interface, but provides limited functionality for detailed flight control, particularly during turning maneuvers. Sudden deceleration and acceleration during these maneuvers caused physical impacts to the gimbal, leading to deviations in the sensor's imaging angle and GPS data errors (Figure 7).

a. Imaging angle deviation



b. GPS geolocation error (left: error / right: normal)

Figure 7. Issues caused by flight planning software

To resolve these limitations, this study introduced UgCS (Universal ground Control Software). Performance testing was conducted at Gongsanseong Fortress in Gongju. The software supports detailed setting of parameters such as turning speed, angle, and distance, making it well-suited for establishing a precision imaging environment. For the test site, the system was configured with a turning speed of 5 m/s, an angle of 15 degrees, and a distance of 100 meters, resulting in stable imaging performance (Figure 8).

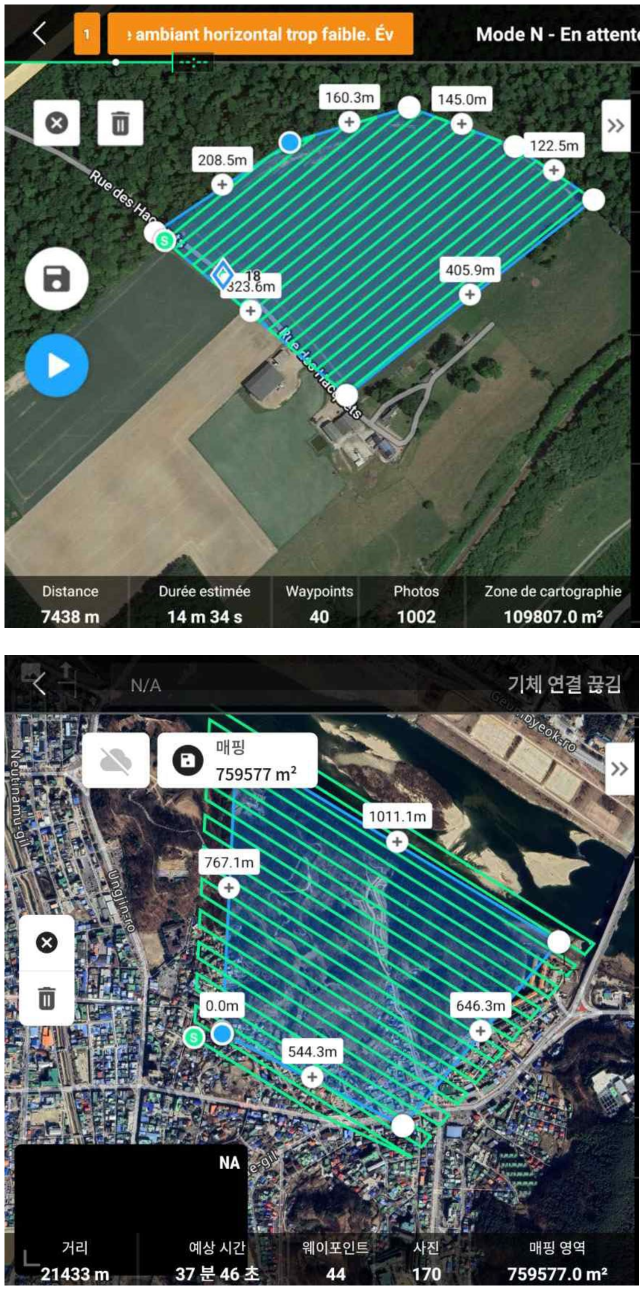
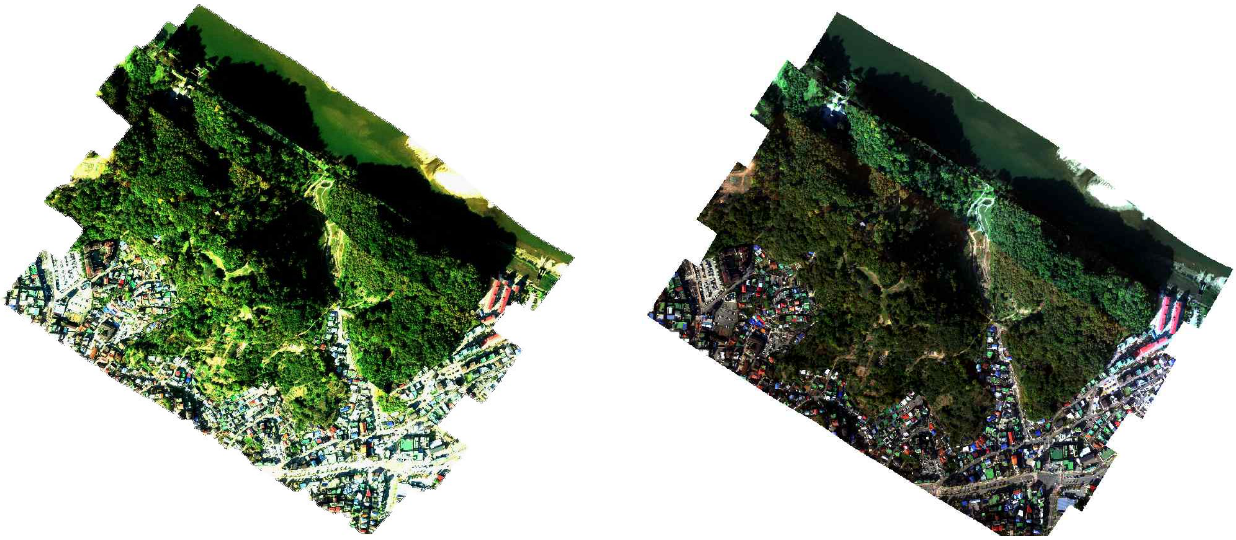


Figure 8. DJI Pilot2 flight parameter settings (imaging altitude, imaging speed, course angle, etc.)

After applying the UgCS-based system, measurable improvements were achieved in imaging duration, coverage area, and battery efficiency (Figure 9) (Table 1) .



a. Before improvement b. After improvement

Figure 9. Performance test results

	Before	After	Change
Imaging Duration	37 min 46 sec	14 min 30 sec	Approx. 61% reduction
Coverage Area (㎢)	0.46	1.18	Approx. 2.56× increase
Battery Efficiency (%)	16	70	54% increase

Table 1. Comparison before and after applying UgCS-based system

2.5 Research Results and Discussion

The test results of this study empirically demonstrated that the mechanical stability of the precision gimbal system and the precision of flight planning exert a decisive impact on aerial hyperspectral image quality. In particular, once the center of gravity between the gimbal and the sensor was properly aligned, issues such as sensor malfunction and shutdown were fully resolved, highlighting that mechanical alignment is just as critical as power distribution in ensuring data quality.

Changes in flight software also proved significant. While DJI Pilot2 offered user convenience, it lacked fine control during turning maneuvers, compr`omising the stability of the imaging direction. In contrast, UgCS enabled fine-tuned adjustments to turning speed, radius, and angle, and effectively reduced image distortion caused by vibration and rapid acceleration during imaging. As a result, seam artifacts in mosaicked images were reduced, and post-processing time was shortened.

The separated power system also proved to be practically important. When the hyperspectral sensor was powered by an external battery, not only was the power supply stabilized, but the imaging duration was shortened by more than 60%, and sensor malfunctions rarely occurred. This suggests that when handling complex sensors, a single shared power supply can undermine the overall system's performance.

2.6 Potential Applications and Impact

The precision 3-axis gimbal system developed in this study presents considerable potential for enhancing remote sensing applications beyond cultural heritage monitoring. Its ability to stabilize high-precision hyperspectral sensors in dynamic aerial environments enables accurate spectral data acquisition, even under challenging flight conditions. This capability opens opportunities for various high-impact applications across multiple fields.

In environmental monitoring, the system can be employed to assess ecosystem changes, detect invasive plant species, and monitor water quality in wetlands and coastal regions. Hyperspectral data, when combined with precise geometric stability, allows for the detection of subtle spectral signatures that indicate environmental stress or contamination. In precision agriculture, the system can facilitate early diagnosis of crop diseases, nutrient deficiencies, and drought stress by capturing detailed reflectance patterns at the canopy level, thereby supporting optimized farming decisions and yield management.

Forestry and land management agencies may also benefit from the system's integration with autonomous drone operations. Accurate spectral mapping of forest health, biomass estimation, and post-disaster assessment (e.g., wildfire or landslide monitoring) can be significantly improved by reducing image misalignment and motion artifacts. Furthermore, urban studies and infrastructure inspection could leverage the enhanced image quality to detect material degradation or thermal anomalies in buildings, roads, and cultural landmarks.

Finally, the proposed system's modular design and compatibility with existing flight planning software (such as UgCS) increase its scalability and applicability. This makes it suitable for real-time or near-real-time monitoring workflows, paving the way for integration with AI-based classification or anomaly detection models. Thus, the system not only addresses current limitations in hyperspectral imaging platforms but also lays the groundwork for a broader spectrum of precision-based remote sensing applications.

3. Conclusions

This study offers a comprehensive case of improving the vulnerabilities of existing hyperspectral imaging systems through both hardware and software enhancements, suggesting an integrated design approach for precision sensor platforms.

The proposed system is well suited for direct application across a range of precision remote sensing fields, including cultural heritage, agriculture, forestry, and environmental monitoring. Future work may require the incorporation of additional correction techniques to accommodate various sensor types and environmental conditions.

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