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Optimisation Technology of UAV Aerial Remote Sensing Load Stabilisation Platform

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Abstract. With the rapid development of unmanned aerial vehicle aerial remote sensing technology, the performance of the remote sensing load stabilisation platform has a significant impact on the accuracy of remote sensing data acquisition. During flight, UAVs are affected by factors such as airflow disturbances and airframe vibrations, which degrade the quality of remote sensing imagery. Focusing on the optimization of UAV aerial remote sensing load stabilization platforms, this paper reviews relevant research achievements in recent years, emphatically analyzes key technical methods such as mechanical structure optimization, passive vibration reduction design, and active control algorithms, and conducts comparative analysis on technical routes including flexible hinge structures, magnetic bearing stabilization platforms, hoisting-type vibration reduction structures, and intelligent control algorithms. On this basis, and in light of typical application scenarios such as surveying and mapping and disaster monitoring, the applicable conditions and engineering effects of different stabilisation platform technologies are discussed. The research indicates that the combination of structural optimisation design and intelligent control methods is an important development direction to improve the performance of UAV remote sensing stabilisation platforms.

Keywords: UAV remote sensing. stabilisation platform. vibration reduction technology. structural optimization. active control

1. Introduction

UAV aerial remote sensing technology has been deeply applied in many key fields such as topographic mapping, power line inspection, environmental monitoring, and emergency rescue, due to its significant advantages of high maneuverability, cost-effectiveness, and rapid response. With the widespread use of high-precision instruments such as hyperspectral cameras and TDICCD aerial cameras, the accuracy requirements for remote sensing data acquisition have become increasingly stringent. As the core hub connecting the UAV body and remote sensing loads, the rationality of the mechanical structure and the effectiveness of the load stabilisation platform's vibration-reduction design directly determine the stability of the load attitude. This is not only the key to avoiding problems such as line-of-sight deviation and imaging blur, but also the core premise for ensuring high-resolution data acquisition [1-3]. This problem is particularly prominent in typical application scenarios, such as mapping, imaging, and disaster monitoring.

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During UAV flight, multi-source vibrations generated by engine operation, propeller rotation, airflow disturbance, and airframe resonance are directly transmitted to remote sensing loads through mechanical contact. Among them, vibrations in the 100 Hz~200 Hz frequency range have the most significant impact on imaging quality. Even slight vibration interference may lead to a sharp decline in the accuracy of remote sensing data [3]. Therefore, the stabilisation platform must meet two core requirements simultaneously: the mechanical structure must have the characteristics of lightweight, high rigidity, and compactness, and the vibration reduction system must have the capabilities of a wide frequency band, strong anti-interference, and fast response. The collaborative optimisation of the two is the core breakthrough in the technical research of this field [3]. Therefore, the research on high-performance stabilisation platform technology is of great significance for improving the quality of UAV remote sensing data.

In recent years, scholars have carried out systematic research on this topic. At the mechanical structure level, classic configurations of two-axis/three-axis frames have been established, and new structures, such as annular two-axis series circular flexible hinges and multi-stage elliptical arc flexible hinges, have been proposed [2,3]. With tools such as ANSYS and COMSOL, researchers have conducted modal analysis and topology optimisation, and some studies have increased the platform's first-order modal frequency by more than 40% through parameter adjustments, such as thickening the azimuth axis [1,2]. The introduction of magnetic bearing technology provides higher precision compared with traditional mechanical bearings [4]. In terms of vibration reduction technology, passive vibration reduction achieves basic vibration isolation through hoisting-type vibration reduction structures, viscous dampers, etc. In contrast, active vibration reduction integrates methods such as neural networks and optimal control, and gradually develops towards active-passive hybrid vibration isolation technology.

Although remarkable progress has been made in existing research, many problems remain to be solved: the design conflict between lightweight and high rigidity has not been completely resolved, the collaborative suppression effect of multi-frequency vibrations under complex working conditions is unsatisfactory, it is difficult to balance the response speed and control accuracy of active vibration reduction systems [1,3], and the personalized adaptive design for different remote sensing loads is relatively insufficient. Therefore, it is necessary to systematically sort out and comprehensively analyse the key technologies of the stabilisation platform from the perspective of combining structural optimisation and vibration reduction control. Taking the UAV aerial remote sensing load stabilization platform as the research object, this paper reviews the mechanical structure optimization methods, vibration reduction technologies, and control algorithms, analyzes the applicability and engineering effects of different technical routes combined with typical application scenarios such as surveying and mapping and disaster monitoring, and discusses the future development direction, to provide a reference for the design and application of high-performance stabilization platforms.

2. Definition and working principle of UAV remote sensing

2.1. What is UAV remote sensing

UAV remote sensing is a new technology that uses unmanned aerial vehicles (UAVs) equipped with remote sensing sensors to obtain spatial remote sensing information via telemetry, remote control, communication, and GPS differential positioning, and then process and analyse the data. It is characterised by automation, intelligence, and rapid response, and has demonstrated broad applicability across many fields [5].

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The Unmanned Aircraft System (UAS) is a system-of-systems. In other words, a set of complementary technologies is combined to complete specific tasks; therefore, a large number of different systems exist at present. It can be said that each technology combination has a corresponding system. At the highest level of UAS technology decomposition, three main components can usually be identified: the unmanned aerial vehicle (UAV), the ground control station (GCS), and the communication data link. Furthermore, other UAS components are critical, including autopilots, navigation sensors, imaging sensors, mechanical servos, and wireless systems [6].

2.2. Working principle of UAV remote sensing

The operation of UAV remote sensing comprises three steps: information acquisition, information transmission, and information processing. Firstly, the interaction between light waves and ground object molecules is sensed by the remote sensing instruments installed on the UAV. The effect of this interaction is transmitted to the UAV platform, after which algorithms analyse the perceived ground conditions.

3. Optimisation of UAV stabilisation platform

3.1. Influence of vibration on UAV remote sensing

UAVs are affected by various vibrations during operation. Internal components generate vibrations during operation, and external disturbances arise from vibrations caused by rapid changes in flight attitude and air turbulence, etc. These vibrations will reduce the accuracy of UAV-based remote sensing and degrade image quality.

3.2. Structural optimisation

3.2.1. Flexible hinge design

Aerial cameras, as the primary information-collection components of aerial imaging systems, are easily affected by carrier vibration and external disturbances during operation, resulting in imaging quality that falls short of expectations [7]. These vibrations and disturbances mainly arise from gas turbulence, carrier attitude changes, carrier self-resonance, external random disturbances, etc., in the airborne environment, leading to an unstable line of sight for the aerial camera. To reduce the line-of-sight deviation between the aerial camera and the target during imaging, some scholars have proposed schemes to optimise the support assembly's mechanical structure [8].

The support assembly is an important part of the line-of-sight rapid adjustment system, and its working bandwidth, positioning accuracy, and rotation range are all affected by it. By conducting dynamic and static analyses on flexible hinges, an annular two-axis series circular flexible hinge is designed, which can effectively reduce the impact of external disturbances on system performance and meet the requirements of stiffness and lightweight [2].

3.2.2. Genetic bearing technology

The aerial remote sensing inertial stabilisation platform can provide real-time attitude and position information and eliminate friction-induced interference between the load and the frame, as well as the impact of external disturbances. In traditional stabilisation platforms, the frame shafting relies

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solely on mechanical support. When carrying heavy loads, the pressure borne by each frame bearing is very high, increasing the friction torque of the mechanical bearings and thereby affecting control accuracy.

Therefore, some scholars have proposed introducing magnetic bearing technology [4]. Electromagnetic bearings offer advantages such as frictionlessness, no pollution, long service life, and active controllability, which can greatly reduce friction interference between frames and open new development directions for high-precision aerial remote sensing stabilisation platforms with large loads.

3.2.3. New hoisting-type vibration reduction structure

Compared with the press-fit vibration reduction structure adopted in old remote sensors, the new hoisting-type vibration reduction structure requires smaller installation space and has a simpler support structure.

When the aircraft's imaging window is large, limited installation space reduces structural strength. The traditional press-fit vibration-reduction structure is prone to inertially coupled angular vibrations in dynamic environments, degrading imaging quality. In contrast, the new hoisting-type vibration reduction structure not only requires less installation space but also attenuates vibrations in the 10~2000 Hz frequency range by more than 70%, achieving the expected vibration reduction effect [9].

3.2.4. Novel bellows viscous damper

Compared with other passive dampers, the novel bellows viscous damper has been successfully verified for its micro-vibration isolation performance under space loads due to its high energy dissipation density and minimal impact on the external environment. The structure of the novel adjustable-damping viscous damper is shown in the figure. The air pipe and flange are connected in series to form the damper's cavity and flow path, and the damping liquid flows between the cavities, dissipating energy through the damping holes.

Experiments show that the novel bellows viscous damper fluid damper exhibits obvious nonlinear damping characteristics in a wide frequency range.

3.2.5. Active-passive hybrid vibration isolation system based on superconducting magnetic levitation technology

Based on superconducting magnetic levitation technology, a new hybrid vibration isolation system can be developed. With real-time control of the current in the electromagnetic coil, active-passive hybrid isolation can be achieved. It can reduce low-frequency micro-vibrations without complex control, alleviate the thermal strain effect caused by suspension, and require no mechanical connection. Experiments have proved that the performance of the hybrid vibration isolation system is superior to that of the passive isolation system.

3.3. Algorithm optimisation

3.3.1. Backlash error compensation

Limited by the flight platform environment, the aerial remote sensing inertial stabilisation platform must be small, lightweight, and highly resistant to interference. Therefore, one or more stages of

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gear transmission are incorporated into the design of the power system of the inertial stabilisation platform to achieve compactness and high-torque drive. Effective transmission of gear meshing can only be achieved when certain continuous conditions are met. Otherwise, rotation stagnation will occur. Backlash exhibits strong nonlinearity, non-analytical behaviour, and non-differentiability, which reduce the system's transmission accuracy, cause low speed, instability, and platform lag, and even lead to commutation jump and shock oscillation [10].

To solve this problem, based on establishing a backlash nonlinear dead zone model and a frame position servo system model containing backlash nonlinearity, MATLAB can be used to analyze the impact of backlash on the accuracy of the control system, and an integral backstepping controller can be designed to reduce the impact of backlash on the performance of the frame position servo system and improve the tracking accuracy and stability of the system [6].

3.3.2. Active vibration reduction method and optimisation based on neural network

An active vibration-reduction method can be designed using neural network algorithms. Firstly, the input signal is preprocessed; then the processed signal data are fed into the hidden layer; and finally, the neural network training results are fed into the output layer. The output result of the output layer is compared with the expected result. When the result error does not meet the training accuracy requirement, the backpropagation process of error information will be entered. The error information from the training results will be propagated back through the output layer. The gradient descent algorithm will be used to adjust the weights and thresholds of each layer. The results will be output again for error analysis. This cycle is repeated until the difference between the output value and the expected value meets the accuracy requirement.

At the same time, the sparrow search algorithm is used to optimise parameters. The sparrow search algorithm can optimise the initial weights and thresholds of the BP neural network, thereby accelerating convergence and improving accuracy.

This method is used to train and predict the actual aircraft vibration data, and the predicted signal is used as the input reference signal for the actuator of the vibration reduction platform to realise active suppression of aircraft vibration [3].

3.3.3. Blind UAV images deblurring based on discriminative networks

An advanced UAV image deblurring method can be designed using a discriminant model. This model includes a classifier for blurred and clear UAV images, embedded within the maximum a posteriori (MAP) framework as a regularisation term. This regularisation term continuously optimises the ill-posed blind image deblurring problem to obtain clearer UAV images. Compared with other methods, the proposed method yields clearer images of various ground objects in image deblurring experiments using both simulated and real UAV images.

4. Applications

The ultimate goal of the UAV aerial remote sensing stabilisation platform's structural optimisation and vibration reduction control technologies is to improve the quality of remote sensing data acquisition and to meet the application requirements of different task scenarios. According to differences in UAV remote sensing task types and flight environments, different stabilisation platform structures and control methods have their own applicable load types and operating conditions. The analysis is presented below, along with typical application scenarios.

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4.1. Application in surveying, mapping, and geographic information acquisition

UAVs have also been extensively used in surveying and mapping to obtain aerial photographs. Most of them are fitted with high-resolution visible-light cameras or TDI CCD aerial cameras. These images are then used to produce Digital Elevation Models (DEM), Digital Surface Models (DSM), and orthophotos.

In this type of application, geometric precision is rather significant. Any minor anisotropy in the imaging direction could affect the results, particularly with a relatively large mapping area. As a result, the stabilisation platform will remain in attitude equilibrium to the greatest extent during flight. Nevertheless, in practice, the UAV is strictly nearly always influenced by vibration, and one can hardly eliminate these disruptions.

Other designs have flexible hinge designs. The structure is fairly basic and can absorb the portion of the transmitted vibration that reaches the optical payload. It does not solve all the problems and only partially helps. Moreover, passive vibration isolation techniques are often presented. One example of handling higher-frequency vibration, generally above 100 Hz, is the use of hoisting-type vibration reduction structures or viscous dampers. The improvement in image quality is indeed generally noticeable, though the effect can vary.

The situation can change again if the airflow is unstable, and the UAV is expected to spend more time on the process. The damping behaviour in such situations is sometimes inadequate. In practice, a structural design is not often sufficient. Mechanical optimisation and active control are regarded as the same; still, the extent to which improvement is possible remains case-specific.

4.2. Application in disaster monitoring and emergency remote sensing

Disaster monitoring and emergency remote sensing are also typical activities for UAVs. The most common uses comprise earthquake evaluation, flood monitoring and landslide evaluation. These scenarios tend to be more challenging, both in real-time performance and in environmental flexibility, than mapping tasks.

As an example, UAVs can be forced to operate at low altitude, and can even be expected to do relatively high-speed flights. Simultaneously, intense or unstable airflow conditions are widespread in disaster-affected regions. In such circumstances, vibration is more pronounced, and maintaining the imaging system is more difficult than under normal conditions.

In this case, active vibration control is often considered. Vibration signal processing and real-time system response can be performed using neural network-based methods and optimised control methods. It is also meant to minimise the effect of disturbances but not get rid of them altogether. Moreover, a magnetic bearing can be added occasionally. It can counteract the effects of friction more effectively than traditional mechanical supports and improve attitude-control accuracy.

Nonetheless, such procedures cannot always be implemented on small UAVs. Active control systems tend to consume more computational resources and may have more complex control architectures. In other instances, power consumption is also an issue. In these, their practical implementation remains slightly constrained by the platform's nature and mission needs.

5. Conclusion

With the rapid development of UAV-based remote sensing technology, the remote sensing load stabilisation platform is playing an increasingly important role in ensuring the accuracy of remote sensing data acquisition. UAVs are easily affected by factors such as airflow disturbance, airframe

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vibration, and attitude changes during flight, thereby reducing the quality of remote sensing imaging. Therefore, it is of great significance to optimise the structure and control technology of the UAV remote sensing load stabilisation platform.

Focusing on the key technologies of the UAV-based aerial remote sensing stabilisation platform, this paper reviews and analyses relevant research achievements. Firstly, the influence mechanism of UAV flight vibration on the stability of remote sensing loads is analysed. On this basis, the main technical routes for optimising current stabilisation platforms are summarised, including mechanical structure optimisation, passive vibration reduction structures, and active control algorithms. Furthermore, a comparative analysis is conducted on typical technologies such as flexible hinge structures, magnetic bearing stabilisation platforms, hoisting-type vibration reduction structures, and intelligent control algorithms, and the characteristics of these technologies in terms of structural complexity, control accuracy, and applicable scenarios are summarised. At the same time, the application effects and limitations of stabilisation platform technologies in practical engineering, including surveying and mapping, disaster monitoring, and infrastructure inspection, are discussed.

In general, in complex flight environments, a single technical method is often difficult to meet the requirements of high-precision remote sensing tasks. The comprehensive technical route, combining mechanical structure optimisation, passive vibration isolation design, and active control algorithms, is an important development direction for improving the performance of UAV remote sensing stabilisation platforms.

In the future, UAV remote sensing stabilisation platforms will further develop towards higher precision, lighter weight, and greater intelligence. By designing new lightweight structures and applying advanced materials, the platform's structural performance can be improved. Combined with artificial intelligence control algorithms and multi-sensor information fusion technology, it is expected to achieve adaptive vibration suppression and intelligent attitude control of the stabilisation platform, thereby obtaining higher-quality remote sensing data in complex flight environments.

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