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DESIGN AND IMPLEMENTATION OF LIGHTWEIGHT ADSORPTION UAVS

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Abstract: The increasing demand for intelligent monitoring in engineering and construction has highlighted several limitations within current Unmanned Aerial Vehicle (UAV) technologies. These challenges include inadequate flight endurance, restricted payload capacity, and a reliance on continuous manual control—particularly evident in tasks requiring reliable adhesion and autonomous operation in the assessment of vertical structures and high-altitude hazardous environments. To mitigate these issues, the present project proposes the development of a lightweight adsorption-capable UAV, designed to achieve attitude reversal during flight and to adhere to both horizontal and vertical surfaces of structures for the purposes of site surveying, monitoring, and data collection. This research details the design and production of a functional prototype of the adsorption UAV, which addresses the aforementioned deficiencies by enhancing endurance, increasing payload capability, and reducing dependence on manual intervention. This innovative solution offers significant advancements in automated monitoring capabilities within complex operational environments.
Keywords: Adsorption; Unmanned aerial vehicles; Flight control; Lightweight design

1 INTRODUCTION

The rapid advancement of drone technology has catalyzed its deployment in engineering construction and restoration, resulting in a multi-dimensional operational framework. In the construction domain, drones serve various functions, including site surveys, 3D modeling, and real-time monitoring. Furthermore, they are equipped with infrared sensors to facilitate nighttime inspections and can undertake material transportation tasks, thereby replacing traditional high-risk manual operations. In challenging terrain scenarios, such as water conservancy and ecological restoration, drones harness their high-precision aerial surveying capabilities to tackle the limitations inherent in conventional auditing and monitoring practices, which often suffer from difficulties in evidence collection and incomplete coverage. For instance, in a water environment remediation initiative, drones enabled accurate auditing of a significant investment project valued at 3.466 billion yuan. Nonetheless, the current technological landscape encounters two principal bottlenecks. Firstly, there are inherent limitations regarding flight endurance and payload capacity. Mainstream industrial-grade drones typically exhibit flight endurance ranging from 30 to 60 minutes, with individual units costing between 100,000 and 300,000 yuan. This presents challenges in meeting the continuous operational demands of extensive projects. Furthermore, the lack of breakthroughs in battery technology necessitates frequent replacements, while environmental factors such as wind and precipitation further impede operational efficiency. Secondly, there exists a pronounced reliance on human operators. Although some applications have achieved levels of semi-automation, complex tasks continue to necessitate real-time control by skilled drone pilots. Data indicate that in circumstances such as high-altitude curtain wall cleaning, human operational errors account for approximately 35% of high-altitude accidents. Compounding this issue is the shortage of qualified drone pilots, which escalates labor costs. Collectively, these challenges not only complicate project management but also constrain the scalable application of drones within long-term engineering projects.
In recent years, extensive research on drone - related technologies has been carried out globally. The research scope encompasses various aspects such as drone technology itself, its applications in different fields, and relevant algorithms. Regarding drone technology, Vergouw et al. provided a comprehensive overview of drone technology [1], covering types, payloads, applications, frequency spectrum issues, and future developments. They also explored the opportunities and threats of drone use from ethical and legal perspectives. Budiharto et al. focused on mapping and 3D modelling using quadrotor drones and GIS software [2], which is of great significance for applications like surveying and 3D reconstruction. In terms of sensor technologies on drones, Guo et al. reviewed the progress, challenges [3], and trends of vision sensing technologies in automatic/intelligent robotic welding. This has implications for drones equipped with vision - based sensors for tasks such as inspection and mapping. Deliry and Avdan studied the accuracy of unmanned aerial systems photogrammetry and structure from motion in surveying and mapping [4], which is crucial for applications requiring high - precision mapping, like topographic surveying.For the flight and control aspects of drones, Oosedo et al. investigated the flight control systems of a quad tilt rotor unmanned aerial vehicle for large attitude changes [5]. This research is beneficial for improving the stability and maneuverability of drones in complex flight conditions.Regarding algorithms, Grisetti et al. introduced a tutorial on graph - based Simultaneous Localization and Mapping (SLAM) [6]. SLAM technology is fundamental for drones to navigate and map their environment autonomously. Chetverikov et al. proposed the trimmed Iterative Closest Point(ICP) algorithm [7], which is useful for tasks such as point - cloud registration in drone - based 3D modelling. In the security and communication fields of

drones. However, challenges still remain, such as further improving the accuracy and reliability of sensors, optimizing flight control algorithms for more complex environments, and strengthening the security of drone communication. Future research could focus on integrating multiple technologies to enhance the overall performance of drones and exploring more innovative application scenarios.

This paper presents a novel lightweight adsorption UAV system design premised on a comprehensive analysis of existing research by scholars both domestically and internationally. The proposed system integrates advanced map-assisted positioning via SLAM technology to enhance the precision of locating adsorption points. The UAV is equipped with intelligent suction cups and a negative-pressure adsorption mechanism that interfaces with a ground control station and flight control operation code. This integration facilitates adjustments in flight attitude, enabling the UAV to execute horizontal and vertical adhesions on various engineering and construction surfaces. The overarching objective of this research is to bolster productivity in engineering construction while simultaneously advancing sustainable development, thereby advocating for environmentally responsible practices within the industry.

2 CONSTRUCTION OF THE MODEL STRUCTURAL FRAMEWORK

2.1 Design Principles for Lightweight Adsorption-Based Unmanned Structures

The paper presents a comprehensive design framework for a lightweight adsorption unmanned aerial vehicle [8], addressing critical factors such as weight, performance, and endurance in airframe design. The overall structural framework of the UAV is meticulously developed to optimize these parameters. The UAV system comprises several integral components, including a ground control station, a visual sensing unit, a flight control system, and an advanced computational algorithm. The visual sensor serves a pivotal role in determining the UAV's position during operational tasks. Communication between the UAV and the ground control station is facilitated through the MAVLink protocol [9], allowing for seamless data exchange. Furthermore, the flight control system is engineered to autonomously manage attitude stabilization and trajectory adjustments, thereby enhancing the UAV's operational efficacy.

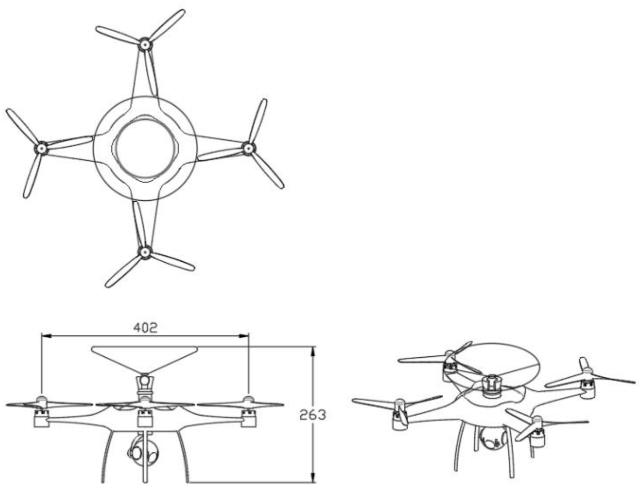

Figure 1 Overall Structural Design of the Unmanned Aerial Vehicle

The design of the unmanned aerial vehicle structure was conducted utilizing SolidWorks, and the resulting three-dimensional model is illustrated in Figure 1. The UAV structure comprises five integral components: the visual sensing system, flight control system, basic fuselage, suction cup control device, and electronic control system. Additionally, a servo-driven tilting mechanism has been developed at the terminal end of the suction cup robotic arm. This suction cup system is interconnected with the flight control system to receive PWM signals, which facilitate the adjustment of the arm's angle of rotation.

2.2 Adsorption of Unmanned Aerial Vehicles under Diverse Complex Conditions

In this study, we examine the characteristics of unmanned aerial vehicle adsorption systems by synthesizing existing literature and analyzing a variety of empirical data. The focus is placed on key factors influencing the adsorption process, including the adsorption mode and the implementation of adaptive control algorithms. The UAV is equipped with an intelligent suction cup designed to accurately detect the adsorption state, allowing for the effective planning of the UAV's movement trajectory while minimizing exposure to unfavorable adsorption conditions. Utilizing flow field theory as a foundational framework, we conduct a comprehensive modeling analysis of the adsorption system's flow dynamics. Moreover, we investigate the parameters that impact adsorption performance through the lens of structural optimization. The objective is to develop an integrated strategy aimed at enhancing the overall efficiency and efficacy of UAV adsorption performance. This research contributes to the advancement of UAV applications where precise adhesion capabilities are critical.

3 ALGORITHMS AND CONTROL

3.1 Design Principles for Lightweight Adsorption-Based Unmanned Structures

In the context of UAV localization, representative feature points, such as corner points and edge points, are meticulously extracted from captured images. Subsequent to this extraction, feature point matching is conducted against a pre - established map to ascertain the UAV's position and orientation. Specific markers or distinctive feature patterns are strategically positioned on the target surfaces, such as building walls. The UAV employs onboard cameras to acquire images, thereby computing its own position and orientation relative to these targets by analyzing the positional variations of the identified feature points within the images. To enhance the robustness of feature extraction across varying lighting conditions and viewing angles, algorithms such as Scale - Invariant Feature Transform (SIFT) and Speeded - Up Robust Features (SURF) are utilized. During the matching process[10-11], the similarity between feature points is evaluated using descriptor - based matching techniques, facilitating the identification of corresponding feature point pairs. The UAV's position and orientation are subsequently derived through triangulation methods, leveraging the geometric relationships among the matched point pairs. While in flight, the UAV employs LIDAR technology to systematically scan and analyze its surrounding environment, integrating this capability with Simultaneous Localization and Mapping (SLAM) methodologies[12-13]. In LIDAR-based SLAM systems, the laser beam emitted by the LIDAR system creates reflections on the surface of an object, and the time-of-flight of these reflections yields distance measurements to construct a point cloud representation of the environment. Concurrently, the ICP algorithm is implemented to match the real - time acquired laser point cloud data and image features with previously mapped information [14]. Through iterative optimization of these matching outcomes, the UAV's position within the map can be accurately determined, thus facilitating precise localization.

3.2 Adaptive Control (MRAC) Algorithms and Optimisation

In the domain of high - precision positioning for unmanned aerial vehicles, the performance of flight and adsorption can be significantly influenced by various environmental factors, such as airflow dynamics and variations in surface roughness. To address these challenges, an adaptive control algorithm has been proposed, which involves the development of a reference model that characterizes the desired dynamic behavior of the UAV. This model serves as a benchmark against which the actual system's performance is evaluated. By continuously monitoring the discrepancy between the actual outputs and those of the reference model, the control parameters can be dynamically adjusted, thereby ensuring that the UAV maintains a high degree of accuracy in locating and adhering to the target surface, even in the presence of environmental fluctuations and system uncertainties. The proposed control architecture comprises a feed - forward controller coupled with a feedback controller, allowing for real - time adjustment based on the adaptive rate. The reference model functions as an idealized control system, delineating the desired performance metrics essential for optimizing the system's characteristics, such as overshoot and damping time. The adaptive rate plays a crucial role in minimizing the error between the actual outputs and the prescribed outputs of the reference model. This mechanism facilitates the modification of controller parameters or the generation of auxiliary inputs, thereby enhancing the robustness and resilience of the UAV's positioning and adsorption capabilities under varying operational conditions.

3.3 Seal Cell Flow Field Modelling

The reduction of leakage and the enhancement of adsorption efficacy can be achieved by optimizing the sealing design of suction cups. This optimization allows for more effective control of negative pressure within the system, thereby amplifying the adsorption force while minimizing the potential for air escape. Consequently, the modeling of the flow field associated with the sealing unit establishes a theoretical framework for improving adsorption capacity. Given that the slit between the sealing unit and the adsorption wall is notably narrow, it can be approximated as a planar surface. Furthermore, the airflow in this region can be characterized as laminar, attributable to the minimal height of the slit and the resultant low Reynolds number. It is also reasonable to assume that the partial velocities of the airflow along the Z - axis can be considered negligible.

$$q_{V1} = \frac{lh^3}{12\mu} \cdot \frac{p_0 - p_1}{x_0 - x_1} = \frac{lh^3}{12\mu} \cdot \frac{\Delta p}{B} \tag{1}$$

In the formula (1), q_{v_1} represents the volumetric flow rate, which is the volume of fluid passing through a certain cross - section per unit time and is a key indicator for measuring the gas leakage amount. l is the length, often referring to the characteristic length related to the sealing unit. h indicates the height, generally being the gap height between the sealing unit and the adsorption wall. μ is the dynamic viscosity, reflecting the fluid's ability to resist flow deformation. p_0 and p_1 are the pressures at different positions respectively, and their difference Δp, namely the pressure difference, serves as the driving force for gas flow. x_0 and x_1 are position coordinates. B represents a characteristic quantity related to flow in different contexts, such as the gap width. This formula is used to quantitatively describe the gas leakage dynamics of the sealing unit. By correlating various parameters, it calculates the volumetric flow rate of gas leakage, which is of great significance for analyzing the performance of the sealing system and optimizing the sealing design.

The dynamics of gas leakage from a sealing unit can be quantitatively described through an established mathematical framework. According to Equation 1, the gas leakage—representative of power loss—exhibits a cubic dependency on the gap height, the seal circumference, and the pressure differential that generates the adsorption force. Conversely, the leakage is inversely related to the seal width. To further investigate the influence of specific design parameters on gas leakage, we analyze the effects of varying gas heights, specifically at 0.4 mm and 1 mm. This analysis facilitates an understanding of the relationship between gas leakage and the width of the sealing ring. It is observed that an increase in gap height significantly impacts gas leakage. Conversely, at a smaller gap height of 0.4 mm, variations in seal width and pressure differential exert a minimal influence on leakage rates. Moreover, the design constraints imposed by the overall dimensions of unmanned aerial vehicles restrict the possibility of arbitrarily increasing seal width to mitigate gas leakage. Such an increase could result in a disproportionate escalation of UAV weight, which does not necessarily correlate with enhanced adsorption safety. Thus, it becomes imperative to minimize the leakage gap during the design phase of the sealing unit. In scenarios where the seal width is predetermined, an increase in adsorption necessitates a corresponding rise in air leakage. Therefore, it is essential to upgrade centrifugal pumps to facilitate efficient gas removal, thereby sustaining a low negative pressure environment. By reducing the leakage gap within the sealing mechanism, gas leakage diminishes significantly, thereby enhancing the adsorption capacity of the negative pressure adsorption system.

In addition, the research on the flow field and sealing performance also refers to the work of Chen et al.[15], who conducted in - depth analysis on the flow field and sealing performance of compliant foil face gas seals, providing valuable insights for optimizing the sealing design of the adsorption system.

4 CONCLUSION

This project involves the design and preliminary production of a lightweight adsorption unmanned aerial vehicle prototype, addressing the prevalent challenges of limited endurance, inadequate load capacity, and restricted maneuverability observed in existing UAVs utilized within the engineering and construction sectors through a comprehensive and innovative design approach. In the realm of adsorption technology, advanced high-precision positioning techniques are employed, which include feature point matching, map-assisted positioning, and the optimization of adaptive control algorithms. These methodologies facilitate the precise positioning and adsorption of the UAV onto targeted surfaces in complex environments. Additionally, a thorough modeling analysis of the flow field associated with the intelligent suction cup sealing unit elucidates the impact of various structural parameters on adsorption performance, thereby providing a theoretical foundation for the design of the sealing unit and contributing to enhancements in both adsorption stability and efficiency. The lightweight adsorptive UAV exhibits considerable application potential within the engineering construction domain, enabling rapid site surveys, comprehensive multi-angle monitoring, and prompt data collection that supports engineering endeavors while ensuring the safety and quality of construction activities. Furthermore, this technology mitigates the need for personnel to enter hazardous work zones, thereby enhancing operational safety. From an environmental perspective, it aids in the timely identification of construction impacts on surroundings, advocates for sustainable construction practices, and further promotes the sustainable development of the engineering construction industry. Despite the advancements achieved, several areas warrant further improvement. Regarding endurance, while the adsorption design contributes to reduced energy consumption, further exploration into alternative energy sources or the optimization of energy management systems is necessary to extend the UAV's operational duration. To enhance load capacity, focus on material selection and structural optimization is required to increase load-bearing capabilities without compromising the UAV's lightweight design. Additionally, although multiple strategies have been implemented to address environmental interference, further enhancement is needed in the stability and reliability of UAVs under extreme weather conditions and strong electromagnetic interference. AS technology advances and research deepens, the lightweight adsorption UAV is anticipated to be applied across a broader spectrum of fields, including bridge inspections, high-altitude building maintenance, and logistics distribution. Through ongoing technological innovation and optimization, this UAV is poised to deliver greater efficiency and convenience across various industries, emerging as a pivotal force in driving industry progress.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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