International Conference on Social Development and Intelligent Technology (SDIT2024)

Academic Education Publishing House

Design and Analysis of a Rotorcraft Unmanned Aerial Vehicle System with Active Adaptive Landing Function

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Abstract: In recent years, with the booming development of the drone market, multi-rotor drones have quickly attracted the attention of consumers with their excellent control performance and convenient vertical take-off and landing characteristics. However, the current rotor drone landing gear has relatively stringent requirements on the terrain. Under special terrain conditions, due to the unevenness of the ground, drones often have problems such as rollover, which may lead to serious economic losses. Based on the design of traditional drone landing gear, this project has designed and adjusted the height adjustment and telescopic mechanism of the landing gear to meet the needs of terrain adaptation. Through in-depth analysis of key parameters, the engineering feasibility of these design improvements and the improvement effects brought about in terrain adaptation have been verified. This innovative design adjustment is expected to effectively solve the problem of safe landing of drones in complex terrain, providing strong support for them to play a greater role in a wider range of application scenarios.

Keywords: Rotary-Wing UAV; Landing Gear; Telescopic Mechanism; Adaptive Landing; Vertical Take-Off and Landing

1. Introduction

With the disruptive development of technologies such as computers, global navigation, and artificial intelligence, drone technology is showing a trend of intelligent and collaborative development [1]. In the field of military applications, drone technology has gradually evolved from single-platform operations to multi-platform cluster operations. In recent years, drone cluster operations have transitioned from conceptual research to practical application. For example, in the armed conflict between Armenia and Azerbaijan, drone cluster technology has demonstrated its advantages in reducing dimensionality and asymmetric strikes. This technology may subvert the rules of future land and sea warfare. At the same time, rotary-wing drones have been widely used in many fields such as field site exploration, forest inspection, dynamic monitoring of sea areas, post-earthquake rescue, and military confrontation due to their advantages such as convenient deployment, low-demand take-off and landing conditions, and hovering in the air [2, 3].

However, compared with fixed-wing drones, although rotary-wing drones have lower requirements for the surrounding environment for landing, they still require a relatively flat area. On rugged and steep surfaces, ordinary landing gear cannot land safely, especially when the tilt angle exceeds 8°, there is a great danger [4]. In maritime military operations, due to the dynamic slope effect of ships, drones need to be able to land safely on ships and other maritime platforms. The current landing assistance system or ship-borne stabilization platform still has shortcomings under the action of waves and cannot meet the needs of drones that may need to land on other complex and rugged terrain during missions. Therefore, it is urgent to design a landing gear system that can adaptively land to meet these challenges. In general, rotary-wing drones have broad application prospects in the field of robotic applications [5-7]. With the in-depth research on rotary-wing drones, more rotary-wing drones with technological breakthroughs, artificial intelligence and higher autonomy will emerge in the future. With the rapid development of science and technology, the functions of rotary-wing drones will become more abundant. However, the traditional rotary-wing drone landing device has the problem that the mechanical configuration cannot be changed, and it is only suitable for ordinary working occasions with flat terrain and little change.

In order to solve some problems existing in the take-off and landing process of existing rotary-wing drones, this study focuses on the mechanical structure, movement mode and simulation analysis of the rotary-wing drone system. The designed rotary-wing drone has the ability to actively adjust the landing gear and can adapt to landing on different terrains. By changing the mechanical structure of the legs and branches of the landing gear robot, the rotor UAV can successfully land smoothly in unknown terrain in the wild, thus realizing the robot's adaptive landing capability. The proposed design method helps to provide a broader idea for the design and control of the adaptive landing gear of the rotor UAV, and can solve the problem of insufficient adaptability of existing rotor UAVs when facing unknown landing terrain structures, thereby achieving innovation in robot structural design and control methods. At the same time, the control scheme based on multi-sensor fusion provides a new idea for realizing intelligent control.

2. Mechanical Structure Design

2.1 Mission Requirements Analysis

Through a comprehensive survey of domestic and foreign literature, we found that rotary-wing UAVs are currently widely used in military missions and civil rescue due to their excellent maneuverability and high flexibility. However, due to the limitations of its landing gear structure, currently UAVs can only choose flat or relatively flat ground for landing. Therefore, solving the problem of adaptive landing gear for rotary-wing UAVs to adapt to different terrains has become an important direction in helicopter research. The adaptive landing gear can adjust its attitude according to the landing terrain, allowing the helicopter to land safely on complex surfaces. Therefore, the control system is crucial for the adaptive landing gear to adapt to different landing terrains.

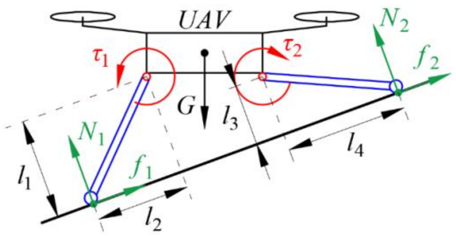
For drones, installing adaptive landing gear will undoubtedly significantly increase its weight and may affect the endurance of the drone. Therefore, studying the design and control scheme of an airborne platform with adaptive landing function is of great significance to expand the application scope of land and sea UAVs, improve the deployment efficiency of UAVs, and enhance the combat capabilities of the troops, as shown in the figure 1 shown. At the same time, due to the relatively simple sensing system of existing rotary-wing UAVs, their intelligent control capabilities are limited. Therefore, solving the problems of landing capability and intelligent control/autonomous control of rotary-wing UAVs and designing a new type of rotary-wing UAV with strong terrain adaptability and intelligent control capabilities has become a scientific research topic with practical value. Under this trend, rotary-wing UAVs with active adaptive landing control capabilities will usher in a broader development space.

Figure 1. Bio-Inspired Passive Adaptive Landing Gear System.

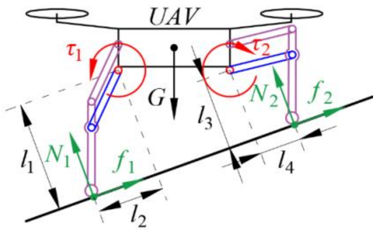
In general, the UAV's adaptive landing platform is a deformable robotic landing gear device with terrain adaptive capabilities. It can automatically adjust its posture according to the terrain or the swaying of the ship's surface, thereby avoiding the UAV's rollover or a large collision with the ship's surface. This helps ensure the safe takeoff and landing of the UAV on dynamic swaying or rugged terrain. This technology is of great significance for expanding the application scope of rotary-wing UAVs, improving the take-off and landing efficiency of UAVs, reducing collision forces, reducing the maintenance cost of UAVs, and improving their combat effectiveness.

2.2 Work mode analysis

When landing on uneven terrain, adding an external parallelogram frame to each branch chain can effectively reduce the driving force required by the actuator, as shown in Figure 2-1. When the mechanism lands on a slope, since the lever arm l4 on the right is longer than when landing on horizontal ground, the output torque required by the right motor becomes larger, and the power and weight of the drive motor required by the mechanism need to be increased accordingly. As can be seen from Figure 2, after adding the parallelogram frame, the landing point is lowered in the vertical direction, which greatly reduces the lever arm l4, thereby effectively reducing the required load of the drive motor.



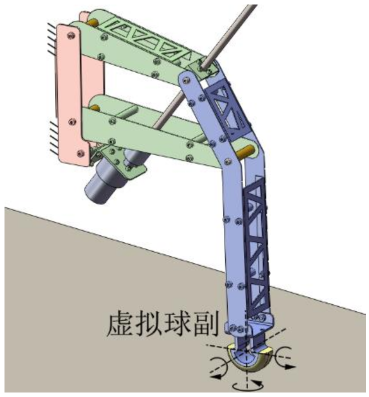
(a) Single-rod structure



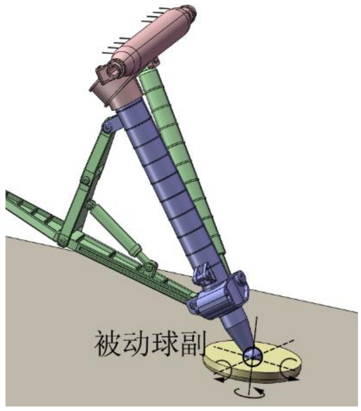
(b) Parallelogram frame structure

Figure 2. Comparison of the Forces Acting on Two Structures.

When a single leg of the landing gear of an aircraft or robot contacts the ground, it can usually be divided into two states: a rotatable state and an anchored state, as shown in Figure 3. Legs in the rotatable state are mainly used in small and medium-sized aircraft or robots, while legs in the anchored state are generally used in large aircraft or landing capsules. In a rotatable leg, once in contact with the ground, the leg can still rotate three-dimensionally around the contact point, so its contact point with the ground can be equivalent to a virtual ball pair. On the contrary, in an anchored leg, the leg will not rotate or move after contacting the ground, and its movement depends entirely on the movement of the leg body, although this type of leg usually has a passive ball pair added to the structure. It is worth noting that for the rotatable leg, we will focus on the study of the design of the virtual drive branch chain, because the analysis idea of the anchored leg is consistent with it.



(a) Rotatable state;



(b) Anchored state

Figure 3. The Contact State Between the Landing Gear Legs and the Ground.

3. Mechanical Systems Design and Analysis

3.1 Structural Design of Supporting Chain

For the landing gear described in the literature [3], its single leg can be regarded as a single rotational freedom leg. This type of landing gear has the ability to achieve sliding cushioning landing on both moving and fixed inclined planes. Since this type of landing gear adopts sliding cushioning landing in both cushioning landing methods, the constructed virtual drive branch chain is the same. Therefore, in this topic, we choose to focus on the virtual parallel mechanism in the case of sliding cushioning landing on a moving inclined plane.

As shown in Figure 4, a quadcopter drone is connected to three single-degree-of-freedom tandem landing gears to form an adaptive landing drone and landing gear system. The landing gear consists of three branches, each of which is connected to the chassis of the drone through a one-degree-of-freedom rotation pair (R) and contains a drive motor. At the same time, the contact point between the landing gear branch chain and the ground can be equivalent to a three-degree-of-freedom virtual ball pair (S). Therefore, in the equivalent virtual parallel mechanism, each branch chain is composed of an equivalent RS branch chain structure with 4 degrees of freedom.

Figure 4. Landing gear 3D model.

3.2 Support Chain Module Motion Analysis

In the adaptive cushioning landing mission, ensuring safety is of vital importance, so it is necessary to ensure that the landing gear has at least three degrees of freedom, including the rotational degree of freedom in the xy direction (horizontal direction) and the translational degree of freedom in the z direction (vertical direction). In the xy direction, position control is used to adjust the tilt angle of the landing gear during landing to effectively prevent the dangerous situation of the drone overturning. In the z direction, impedance control is applied to adapt to different landing speeds to obtain a better cushioning effect.

However, in the case of adaptive landing gear, there are usually multiple legs, and the movements between these legs are independent of each other. When the control system is constructed for each leg separately, it is often difficult to clearly show the possible coupling relationship between the legs during the landing process. This means that in order to more comprehensively consider the dynamic characteristics of the system, it is necessary to introduce the consideration of the mutual influence between the legs in the control strategy. Only in this way can we more effectively achieve coordinated motion in the landing mission and improve the stability and safety of the overall system. For a landing gear in a buffer state, each leg is in contact with the ground, and the landing gear and the ground can form a virtual parallel mechanism, as shown in Figure 5. When the depth camera sensor installed on the chassis of the rotor UAV detects the height of the non-structured terrain at the landing site, the driving motor of the landing gear branch chain is adjusted according to the height difference corresponding to the three branches to drive the rotating pair R to rotate, so as to initially achieve the balance state of the UAV. Each leg can be regarded as a branch of the parallel mechanism, and the base and ground of the landing gear serve as the fixed platform and mobile platform of the parallel mechanism respectively. By establishing a suitable O-xyz task coordinate system on the parallel mechanism, the control system of the entire landing gear can be easily designed according to the above control scheme without the need to independently control each leg.

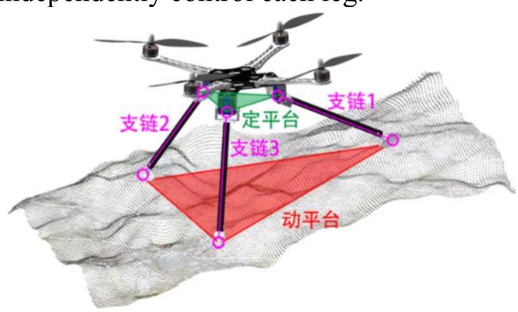


Figure 5. Schematic Diagram of the Virtual Parallel Mechanism Proposed in This Project.

4. Adaptive Cushioned Landing Control and Analysis

4.1 Adaptive Cushioned Landing Control Scheme

During the landing process of the adaptive landing gear, the interaction with the ground will affect the movement of the landing gear legs. Due to the constraints of the external environment, the realization of adaptive cushioning landing requires not only ensuring that the landing gear can remain horizontal when the slope of the offshore platform changes, but also offsetting the impact energy of the drone in the vertical direction. According to the literature [8-10], a relatively accurate offshore platform motion model can be fitted through motion data. Therefore, the horizontal stability of the landing gear can be maintained through motion control throughout the landing process, and the cushioning effect can be achieved through vertical force control. Therefore, this section will study the adaptive cushioning landing control scheme that meets the above landing requirements when landing on a plane with a changing slope.

One of the methods to achieve cushioning landing is to install elastic elements such as springs on the landing gear of the drone to achieve passive cushioning. However, the stiffness of the elastic element is fixed, and the optimal cushioning landing performance cannot be achieved for different impact speeds. In contrast, the active cushioning landing algorithm has the ability to adjust the stiffness of the adaptive landing gear, thereby achieving a more optimized cushioning effect.

4.2 Adaptive Landing Control Method

In the context of robot-environment interaction, the constraints faced by the robot can be divided into two types: natural constraints and artificial constraints. Natural constraints refer to the inherent conditions imposed on the robot by the external environment, while artificial constraints are artificial robot constraints set to complete specific tasks.

The basic concept of force-position hybrid control is to map the position and force in the robot joint space to the task space through coordinate transformation, consider the natural and artificial constraints of the task in the task space, determine the control strategy in each degree of freedom direction, and design the control rate of output motion and force. Then, these control rates are transformed back to the control rate of the joint space to achieve synchronous control of the motion and force of the robot end. When the robot motion is subject to natural constraints in a certain degree of freedom direction, it is necessary to specify the force required to be output by the robot in that degree of freedom direction; when the robot is not subject to motion constraints in that degree of freedom direction, it is necessary to manually control the robot motion in that direction. Therefore, in the adaptive cushioned landing task, it is necessary to establish an appropriate coordinate system to analyze the constraints in the six degrees of freedom directions of the robot.

The adaptive landing gear is in contact with the terrain during cushioned landing control. Therefore, we can imagine a virtual 6-DOF manipulator fixed to the ground to facilitate the analysis of the constraint state of the adaptive buffer landing task. For example, as shown in the figure 4, we assume that a manipulator fixed to the ground grabs the drone from the air and assists it in completing the adaptive buffer landing. For the drone in the air, due to its suspended state, there are no natural constraints on the movement in the six degrees of freedom. However, in the buffering task, the movement of the drone in the z direction is a buffering movement, so the movement in the z direction is subject to natural constraints, and artificial constraints need to be imposed on the rotational movement, translational movement and z-direction force at the end of the manipulator. Therefore, in this manipulator, force control should be used for the translational movement in the z direction, and position control should be used in other degrees of freedom directions.

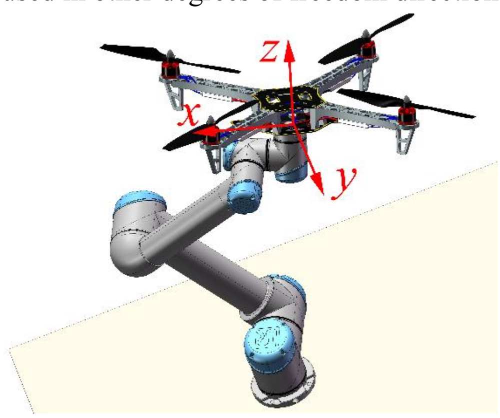


Figure 4. Schematic Diagram of the Adaptive Buffer Landing Task Constraint State.

5. Conclusion

In order to solve some problems in the take-off and landing process of rotary-wing UAVs, this study focuses on the mechanical structure, motion mode and simulation analysis of the rotary-wing UAV system. The designed rotary-wing UAV has the ability to actively adjust the landing gear and can adapt to the landing position of different terrains. By changing the mechanical structure of the legs and branch chains of the landing gear robot, the smooth landing of the rotary-wing UAV in unknown terrain in the wild was successfully achieved, thus having the adaptive landing capability of the robot. The proposed design method provides a broader idea for the design and control of the adaptive landing gear of the rotary-wing UAV, which can solve the problem of insufficient adaptability of the existing rotary-wing UAV when facing unknown landing terrain structures. This innovative method has made breakthroughs in robot structure design and control methods, and the control scheme based on multi-sensor fusion provides new ideas for realizing intelligent control.

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