Design of Bionic Landing Gear with Multi-Link Mechanism for UAVs in Desert Terrain

Junhong Chen

Department of Mechanical Engineering, Tianjin University, Tianjin, China

3020001175@tju.edu.cn

Abstract. The terrain in desert areas is rugged and uneven, lacking suitable landing points for unmanned aerial vehicles (UAVs). In addition, sand and dust in the desert can easily damage the internal circuits of propellers through vortexes. To address the high demands for hardness and smoothness of landing sites for vertical takeoff and landing (VTOL) aircraft, as well as the low level of intelligence of traditional landing gear, an optimized biomimetic leg-type terrain-adaptive landing gear based on a multi-link hybrid mechanism was developed for landing in desert areas. First, the design configuration of a single leg was optimized, and the length of each link was calculated accordingly, followed by motion simulations. Secondly, the overall design was developed, and slope landing simulations were conducted on the four-leg mechanism. Research results showed that the optimized multi-link hybrid mechanism terrain-adaptive landing gear was better suited for adapting to desert terrain and could land on sand dune slopes, effectively improving the adaptability of VTOL aircraft in desert areas.

Keywords: Multi-Link Mechanism, UAV, Desert Terrain.

1. Introduction

Nowadays, UAVs are increasingly used in surveying, aerial photography, and other fields, with more complex tasks and unpredictable environments, resulting in higher landing requirements. Multi-rotor UAVs often adopt a fixed-style leg frame made of metal or carbon fiber tubes as landing gear, which have poor maneuverability and flexibility, requiring high ground flatness and slope angle during landing and taking off, or the need to find suitable sites or establish landing fields for UAVs [1]. However, desert terrain is often uneven and contains a lot of sand particles, which may cause problems for traditional UAVs during landing due to the lack of suitable landing locations, and sand or debris may enter the UAV itself, causing landing difficulties or even damaging the aircraft. Observing insects in nature such as locusts and dragonflies, they use multi-point landing by using compound eyes for observation, foot sensing, and coordinated leg extension, enabling them to land on any terrain such as treetops and flowers with stability. In recent years, the leg topological structure and driving mode of legged robots have mostly referred to the characteristics of animal leg structures, as they have higher flexibility and adaptability in complicated environments and are more likely to achieve stable walking and climbing in complex terrain [2]. Therefore, considering the landing characteristics of VTOLs and the similarities with flying insects, relying on the leg design technology of legged robots, a design method of terrain adaptive landing gear with a bionic leg-type and multi-link hybrid mechanism was proposed, showing its feasibility.

Foreign research institutions have conducted preliminary research on bionic landing gear technology and achieved certain research results. In 2015, the Georgia Institute of Technology designed the most mature design plan, the "quadruped bionic landing gear," with special funding support. It can be folded under the fuselage during flight and extended to support the ground during landing, equipped with sole pressure sensing equipment to ensure terrain adaptability and body balance adjustment ability [3]. In addition, the Zurich University of Applied Sciences has designed a four-degree-of-freedom bionic leg driven by an electric screw (one degree of freedom per leg) [4], the University of Edinburgh in the UK has designed a landing gear with a double-leg structure with straight rods attached to the foot [5], the Skolkovo Institute of Technology in Russia has designed an eight-degree-of-freedom four-legged landing gear with inertia units installed on the foot [6], and

Amazon in the United States has proposed a mechanical leg patent that achieves slope landing through a retractable pole [7]. However, the maturity of these designs is relatively low, reaching a maximum level. In recent years, China has also gradually carried out related research work and conducted some basic conceptual design and virtual simulation research. Nanjing University of Aeronautics and Astronautics designed a landing gear structure with three hydraulic telescopic rods [8], and Hefei University of Technology used a single-degree-of-freedom four-bar mechanism to design a bionic landing gear for small unmanned helicopters. However, the research is limited to conceptual design, and no corresponding results are seen in the literature [9]. Recently, the China Aircraft Strength Research Institute designed an adaptive landing gear device for unmanned helicopter platforms, which can better adapt to terrain and achieve adaptive landings on flat ground, slopes, steps, and complex terrains. The control algorithm can achieve system collaborative control, using a multi-rotor unmanned helicopter as a verification platform to prove the effectiveness of the bionic leg landing gear design method [10-11].

This article will be based on previous research results, focusing on designing for takeoff and landing in the desert, making special modifications to the original design to adapt to takeoff and landing in a desert environment. Dunes are common in the desert, and slopes are relatively smooth, so the design focuses on landing on a slope in a sand dune. Considering that sand dust in the desert may be stirred up by the propellers, the ground clearance needs to be increased. The original design's bottom-touching rods are extended, and the contact area of the round plate is increased to calculate the length of each rod based on existing data and modeled using SolidWorks software. Previous research has proven the feasibility of a hard ground slope, and the depth of sinking is obtained through pressure calculation. The final goal is to ensure that the distance between the propeller and the sand dune is over 200cm after landing and that the landing gear can complete the corresponding mechanical movements.

2. Method

2.1. Design of Multi-Link Hybrid One-leg Structure

The bionic leg-type terrain-adaptive landing gear is different from traditional landing gear structures, as it integrates bionic design concepts and adaptive landing control algorithms, including a terrain recognition and modeling system, control driving system, modular driving joints, leg load-bearing structure, and foot cushioning rubber, etc. Multiple legs are symmetrically distributed beneath the vertical takeoff and landing aircraft body, enabling the landing support and terrain adaptation of the aircraft.

2.1.1 Kinematics and dynamics modeling of one-leg mechanism

The bionic leg-type landing gear adopts multiple legs with the same design. Here the one-leg structure was taken as an example to provide the design method of the leg structure. For the design of legged robots, both the series-parallel structures are adopted, but the series structure has limited load-bearing capacity, while the parallel structure has strong load-bearing capacity but limited working space, making it unsuitable for the landing gear design of vertical takeoff and landing aircraft.

Considering the load-bearing capacity and the folding requirement of the bionic leg-type landing gear, multi-link hybrid mechanism is utilized for the single leg, as shown in Figure 1, which combines the advantages of series and parallel mechanisms while meeting the requirements of load-bearing and working space.

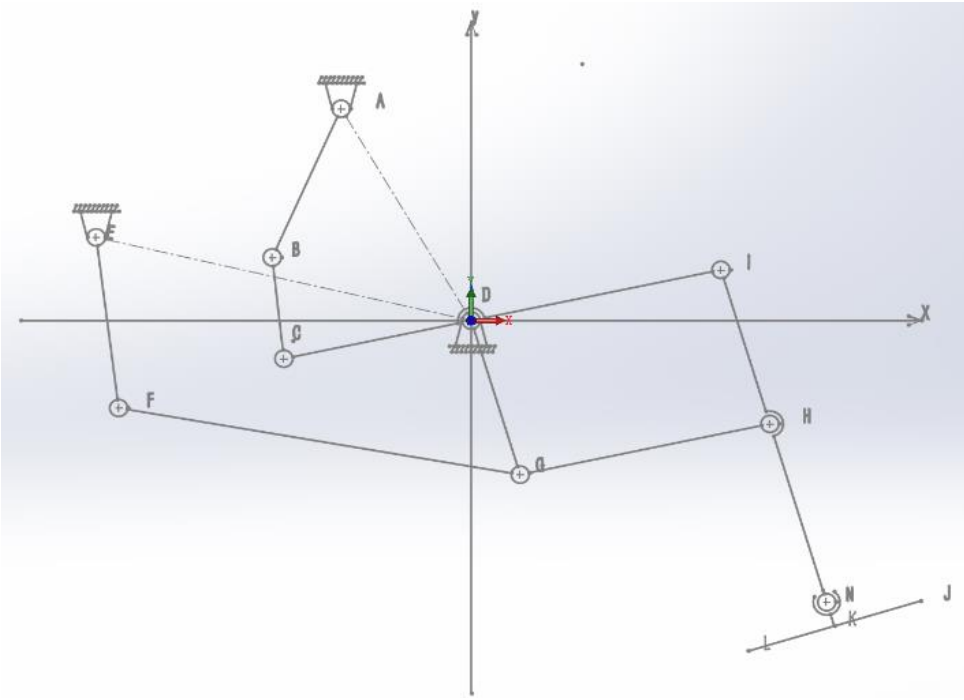


Figure 1. Mechanism diagram of one-leg

As a part of the multi-leg landing gear system, the single leg aims to adapt to the landing terrain while minimizing its weight, and thus rotational motion of the leg is not considered, making it a degree of freedom structure. The one-leg structure consists of two four-bar mechanisms ABCD and EFGD and one parallelogram mechanism DGHI, with two driving joints installed at points A and E.

The single leg mechanism has 2 degrees of freedom and 12 links, with the lengths of each link AB, BC, CD, DA, EF, FG, GD, DE, GH, DI, IH, and HN represented by L_{ab}, L_{bc}, L_{cd}, L_{da}, L_{ef}, L_{fg}, L_{gd}, L_{de}, L_{gh}, L_{di}, L_{ih} and L_{hn}. The link CD and the link DI are treated as one link with a hinge point D in the middle, and the same applies to the link IH and the link IN. The hinge points D, A, and E are connected to the aircraft body. By assuming that the positional angles of the links AB and EF with respect to the x-axis are known based on the rigid body assumption, using analytical methods, the theoretical kinematics and dynamics models of the single leg can be constructed, and the quantitative function relationship between the joint angles and the foot coordinates is established to solve for the coordinates of the foot endpoint N ($X_n Y_n$).

In the four-bar mechanism ABCD, AB is the driving link, CD is the driven link, BC is the coupler, and DA is the frame. Given the lengths of each link (L_{ab}, L_{bc}, L_{cd}, L_{da} for driving link, φ_{AB} for driving link angle, φ_{DA} for frame angle), calculate the coupler angle φ_{BC} and driven link angle φ_{CD}, as well as the coordinates of nodes A, B, and C. Based on the vector theory, establish the spatial position relationship between each link, and decompose it on the x and y axes to determine the coordinates of nodes A, B, and C. The solution method is the same for the similar four-bar mechanism EFGD.

Because the link DI and the link CD are fixed within the four-bar linkage mechanism, the orientation angle φ_{GD} of link GD can be obtained through the Shibuya Rin's Adventure Method. In the parallelogram linkage mechanism DIHG, the orientation angle φ_{IH} of link IH can be calculated. With φ_{DI} and φ_{IN} then solved by ΔDIN as the origin, the coordinates of the foot N can be decomposed using point D as the origin. Finally, applying the principle of virtual work allows for the determination of the relationship between joint driving force and foot load.

2.1.2 Optimization parameters for structure

Based on established theoretical analysis methods, a one-leg structural design and bearing capacity analysis is carried out for the structure design configuration of the graph. The design usage scenario is targeted for one-leg bearing F_{NY}=300N, adapting to landing situations on a 20° slope.

The optimization variables for the one-leg mechanism include the length of each component and the angle of the frame, with the constraint of designing landing terrain requirements that meet the desired range of foot motion for specific usage scenarios. With the objective of minimizing the output driving torque of the driving rod, the composite simplex optimization algorithm was used, with considerations for possible installation interference, and appropriate increases in the length of certain connecting rods to elevate the height of the drone chassis. The optimized variables for the one-leg mechanism are shown in Table 1.

Table 1. One-leg linkage dimensions

project	length	project	length
L_{ab}/mm	46.914	L_{di}/mm	300
L_{bc}/mm	81.64	L_{gh}/mm	300
L_{cd}/mm	100	L_{ih}/mm	90.67
L_{da}/mm	100	L_{hn}/mm	359.33
L_{ef}/mm	60.356	L_{NK}/mm	50.57
L_{fg}/mm	96.24	L_{JL}/mm	200
L_{gd}mm	90.67	α / (°)	160
L_{de}/mm	100	β / (°)	160

2.1.3 Design of one-leg structure

Based on the data in Table 1, a one-leg structure that meets the dimensions of the connecting rod shown in Table 1 has been modeled and is shown in Figure 2.

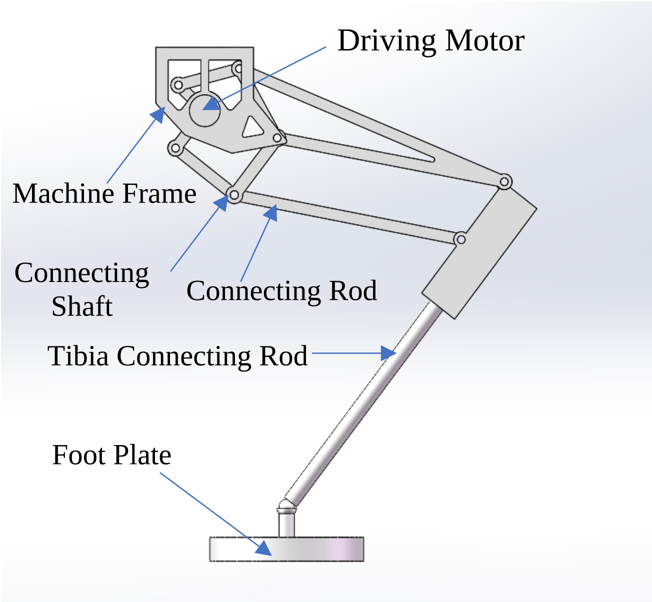
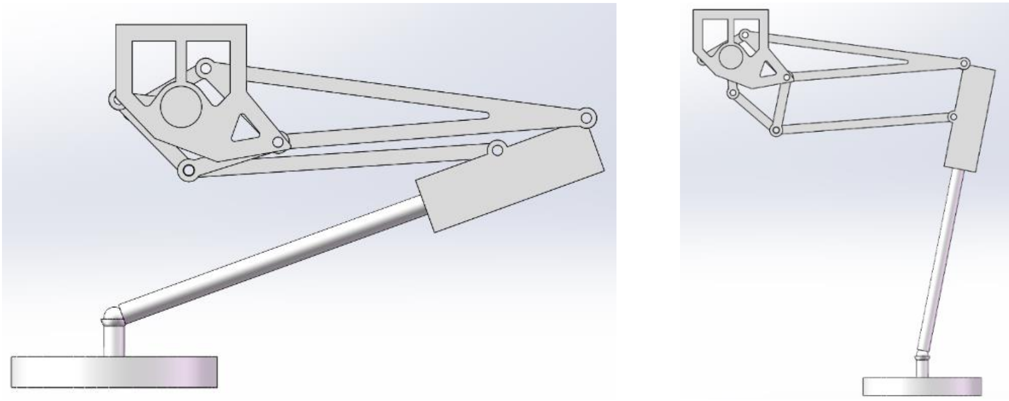


Figure 2. Two or more references

2.1.4 Validation of one-leg mechanical structure

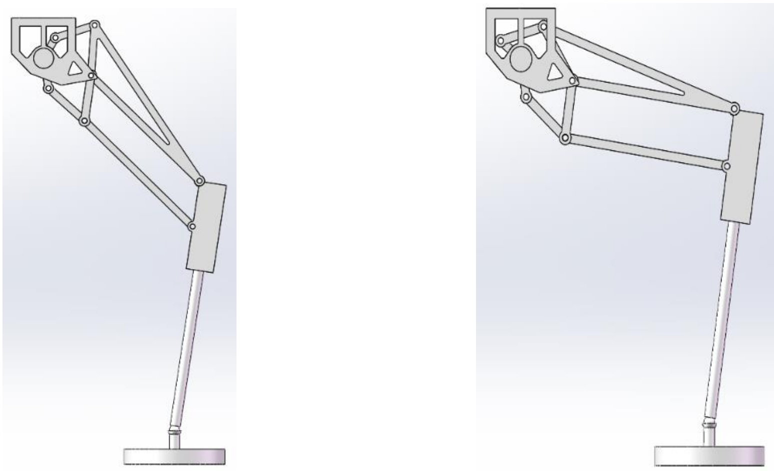
The one-leg structure needs to perform two actions: one is the main one-leg retraction and extension action driven by the EF rod during flight and landing, and the other is the adjustment action of the single leg driven by the AB rod when landing on the ground. Using motion simulation examples in SolidWorks, the mechanical motion is simulated by applying rotational driving motors to the AB and EF rods to observe the overall leg motion. The final state of the one-leg retraction and extension action is shown in Figure 3.



(a) One-leg retraction action (b) One-leg extension action

Figure 3. One-leg Retraction and Extension Action

The leg adjustment movement is shown in Figure 4.



(a) One-leg extension movement (b) Complete lift of one leg movement

Figure 4. One-leg adjustment movement

The final simulation results demonstrate that the mechanical structure is capable of completing the predetermined movements.

2.2. Design of Overall Multi-Legged Mechanism

2.2.1 Overall structure design

The overall design adopts a four-legged structure, with four identical single legs connected through a top plate. The four legs are evenly distributed around the top plate. The final design is shown in Figure 5.

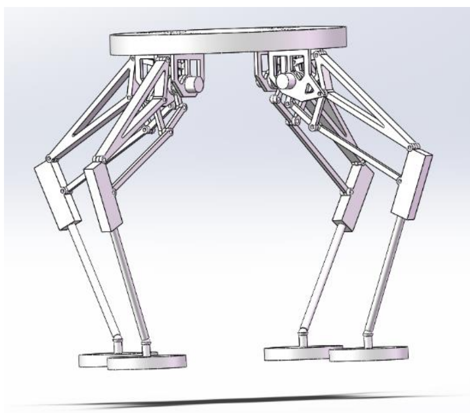


Figure 5. Diagram of overall structure design

2.2.2 Simulation of slope landing

The final landing is aimed at the slope provided in the sand dunes. Firstly, the landing on a slope on a hard ground is simulated. After adjustment, the three-dimensional simulation of landing on a 20° slope is shown in Figure 6.

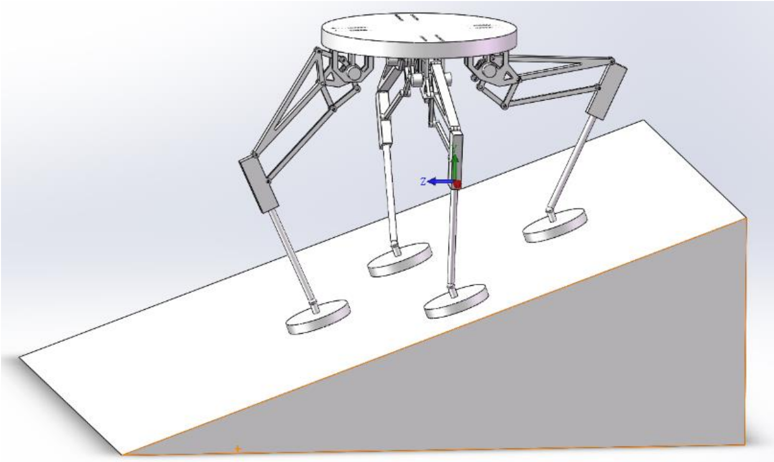


Figure 6. 3D simulation of landing on a 20-degree slope

2.3. Feasibility calculation of sand dune slopes

The total weight of the system design is 37kg, considering a 20% safety margin and effective bearing capacity of 110kg. The chassis consists of four 200mm diameter disks and the unmanned aerial vehicle (UAV) is positioned at the longest location of 2m on a 20-degree slope.

Pressure on the slope: P=(147×9.8×cos20°)/(4×π×0.1^2)=10772.57Pa

Similar to the pressure exerted by a person standing on the ground, the pressure on the slope is calculated based on a 200mm sinkage height, which is higher than the typical actual situation. The distance from the center of the top bracket to the slope is controlled at 800mm or more. The center of the unmanned aerial vehicle coincides with the center of the top bracket. The distance from the propeller height to the UAV chassis is less than 100mm, and the farthest propeller is 1m away from the center of the UAV. Through calculation, the closest point of the propeller to the sand is more than 315mm, which meets the requirements.

3. Discussion

The terrain-adaptive landing gear device of the multi-link hybrid mechanism optimized in this article is based on the existing design of previous researchers. It considers the problem of landings in the desert, where sinking and sandstorms can easily damage the drones. To address this issue, some linkages are added to increase the height of the drone and a bottom-touching disc is installed to increase the landing pressure, effectively increasing the height of the drone chassis. The disc is connected to the linkage of the shinbone by a spherical joint, which allows the disc to have high flexibility and change its angle freely with the slope of the sand dunes. During flight, the disc automatically stays parallel to the ground, reducing the wind resistance.

After modeling and simulation, the improved terrain-adaptive landing gear device of the multi-link hybrid mechanism can achieve the required contraction and adjustment movements during landing and takeoff. It can land smoothly in the sand dunes of the desert while maintaining the drone's stability, solving the problem of the high requirements for the hardness and flatness of the landing site for vertical takeoff and landing aircraft and the low degree of intelligence of traditional landing gear. This increases the number of suitable landing locations for drones in the desert.

In addition, after calculation, it is found that the improved terrain-adaptive landing gear device of the multi-link hybrid mechanism is far enough away from the sand dunes during landing, ensuring that no sand particles will enter the drone and cause damage, greatly improving the safety of drone takeoffs and landings in the desert.

However, the terrain-adaptive landing gear device of the multi-link hybrid mechanism has a large volume and weight and is only suitable for drones with greater carrying capacity. Moreover, installing this landing gear will affect the drone's payload and endurance, leaving significant room for improvement.

4. Conclusion

Based on a multi-linkage hybrid mechanism, an optimized design method for terrain-adaptive landing gear is developed for desert terrain, and the mechanism is optimized and theoretically verified based on this design concept.

The research shows that: (1) After calculation and simulation, the terrain-adaptive landing gear of the optimized multi-linkage hybrid mechanism can better adapt to desert terrain, can land on sand dune slopes, effectively improve the adaptability of vertical takeoff and landing aircraft in desert areas, and can effectively solve the landing and takeoff problems in the desert.

(2) Using a multi-rotor unmanned aerial vehicle as a verification platform, it is verified through calculation and simulation that the unmanned aerial vehicle equipped with the terrain-adaptive landing gear of the multi-linkage hybrid mechanism will not raise sand and dust during landing, which can effectively prevent sand particles from entering the UAV and causing damage, ensuring the safety of UAV landing and takeoff.

(3) This biomimetic leg-style landing gear design method can be used in the landing gear design of multi-rotor unmanned aerial vehicles. However, due to the complex structure, the weight of this landing gear is significantly higher than that of traditional landing gear, which reduces the effective payload capacity of the aircraft. The reliability of the system is also not as good as that of traditional landing gear, so further research is needed on load-bearing capacity, weight reduction optimization, system reliability, etc.

References

[1] Zhang Yueyi. UAV structure and principle [M]. Xian: Northwest-ern Polytechnical University Press, 2020.

[2] Chongyang, Mei Tao, Liu Yanwei. Research of control method and mechanism design of bio-inspired hexapod robot [J]. Mechanical Science and Technology for Aerospace Engineering, 2014, 11 (33): 1621-1627.

[3] Kiefer J, Ward M, Costello M. Rotorcraft hard landing mitigation using robotic landing gear J. Journal of Dynamic Systems, Measurement, and Control, 2016,1 38 (3): 216-224.

[4] Manivannan V, Langley J P, Costello M, et al. Rotorcraft slope landings with articulated landing gear [C]. AIAA Atmospheric Flight Mechanics (AFM) Conference, 2013: 5160.

[5] Stolz B, Brodermann T, Castiello E, et al. An adaptive landing gear for extending the operational range of helicopters [C]. 2018IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2018: 1757-1763.

[6] Boix D M, Goh K, Mcwhinnie J. Helicopter lands on uneven terrain by means of articulated robotic legs-modelling, simulation and control approach [C]. 2018 EEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM) 2018: 1282-1287.

[7] Sarkisov Y S, Yashin G A, Tsykunov E V, et al. Drone gear: A novel robotic landing gear with embedded optical torque sensors for safe multi copter landing on an uneven surface [J]. IEEE Robotics and Automation Letters, 2018, 3 (3): 1912-1917.

[8] Wang Xiaohui, Nan Ying. Helicopter landing gear design for special terrain based on bionics [J]. Aircraft Design, 2014, 34 (4): 46-48.

[9] Sang Zhe, Jiang Bin, Yang Jizhou, et al. Design of bionic landing gear for small unmanned helicopter [J]. Modern Manufacturing Technology and Equipment, 2016 (2): 79-81.

[10] Ren Jia, Wang Jizhen, Yang Zhengquan, et al. Design and simulation of multi-link bionic landing gear used on UAVs [J] Aeronautical Science & Technology, 2023, 34 (06): 77-85.

[11] Ren Jia, Liu Xiaochuan, Wang Jizhen, et al. Design of multi-ink hybrid bionic landing gear and landing test [J]. Technology and Science Engineering, 2023, 23 (11): 4881-4893.