Bionics-Based Research on Frog-Jumping Robots

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Abstract. With the expansion of robot applications, existing crawling, wheeled, and tracked biomimetic robots are difficult to adapt to complex terrains and have obvious limitations. Jumping robots can easily leap over large obstacles, adapt to unpredictable environments, and their sudden movements help avoid dangers. In fields such as interstellar exploration, archaeological detection, and military reconnaissance, jumping robots have broad application prospects. This design expects to design a frog-jumping robot based on bionics technology. Firstly, the physiological structure and motion characteristics of frogs are analyzed. Based on the frog's own skeletal and muscle structure, the structure and parameters of the biomimetic robot are designed. A three-dimensional model is established using SolidWorks software and imported into Adams software for motion simulation to simulate the jumping trajectory of the biomimetic frog and the forces during movement. Some parts are selected as references and imported into Ansys software for finite element analysis. The design is judged by the simulation results. Finally, the entire model is optimized and summarized.

Keywords: Bionics, Jumping Robots, Motion Simulation, Optimization Analysis.

1. Introduction

1.1. Research background and significance

Currently, with the burgeoning research in the field of robotics, the scenarios of its applications are becoming increasingly diverse, which in turn imposes high requirements on the autonomous action capabilities and flexibility of robots [1]. Bionic robotics technology, especially frog-like jumping robots, has emerged as a research hotspot. It integrates multiple disciplines such as biology, mechanics, and mechanical engineering [2], aiming to design intelligent and efficient robots to expand application fields and promote interdisciplinary integration.

Compared to traditional tracked robots and legged robots, frog-like jumping robots hold significant advantages in complex terrains and specific domains [3], such as rescue operations and military reconnaissance. Additionally, bionic jumping robots have potential in interplanetary exploration, capable of adapting to different gravitational environments on other planets, potentially bringing revolutionary changes to deep space exploration. The study of kinematics and dynamics of these robots is a necessary path for optimizing performance and achieving precise control, laying a theoretical foundation for their widespread application.

1.2. Research objectives

The objective of this design is to create a biomimetic frog jumping robot, using the actual skeletal structure of a frog as a structural reference and the muscle contraction during jumping as a dynamic reference. In terms of model establishment and simulation analysis, the design will be based on the real skeletal structure of the frog and the expected jumping function to design and draw a simplified mechanical motion diagram. When determining the dimensions, the actual body size data of the frog will be used in conjunction with the mechanical motion diagram to establish the size data and the primary moving parts. A three-dimensional model of the biomimetic robot will be created in SolidWorks. Considering the motion characteristics of the jumping robot, it is unreasonable to perform only static analysis [4]. Therefore, the model needs to be imported into Adams and Ansys software for kinematic simulation and finite element analysis, respectively. This will simulate the robot's motion trajectory during jumping, the overall force condition, and the force and deformation conditions of each component. Based on the simulation results, we will determine whether the design meets the expected goals.

2. Design proposal

2.1. Summary of frog biological characteristics

Based on the review of relevant literature, the biological characteristics of frogs can be summarized as follows:

(1) In terms of dimensional characteristics, the length of a frog's thigh and shank are similar, measuring 28.0 mm and 27.5 mm, respectively. Similarly, the lengths of the upper and lower arms are almost equal, both being 12.5 mm, and their total length (25.0 mm) is approximately half of the total length of the thigh and shank (55.5 mm). Notably, the frog's foot is unusually long, reaching 47.0 mm, which is almost equivalent to the total length of the thigh and shank. Additionally, the foot exhibits high flexibility, with its center of gravity positioned towards the hind limbs.

(2) The high flexibility of a frog's foot allows it to maintain maximum contact with the ground before takeoff during jumping, thereby ensuring efficient energy utilization throughout the jumping process [5].

(3) During the takeoff phase, the angle of a frog's hind limbs changes rapidly, posing a challenge in the design of mechanical systems [6]: it is difficult to achieve direct control of joints through motors, that is, to simulate the dynamic effects of muscles during jumping. Therefore, energy storage components are needed to assist in this process [7].

(4) The angle changes of the ankle, knee, and hip joints during a frog's jumping process follow a certain regularity: the angular velocity of the knee joint is equal to the sum of the angular velocities of the hip and ankle joints, and the ratio of the angular velocity between the hip and ankle joints is 3:2 [8].

2.2. Preliminary scheme discussion and determination

The schematic diagrams of the mechanism movement for this design are shown in Figures 1(a) and 1(b). After verification, it has been determined that when the number of primary moving parts is 1, the degree of freedom of the mechanism is equal to 1. The specific scheme is as follows:

As shown in Figure 1 (a), the front limbs of the biomimetic frog are composed of a double-bar linkage, while the hind limbs are composed of a connecting rod assembly. These components are connected to a crank-slider mechanism and a spring, which provides power to the entire mechanism and is mounted above the frame.

As depicted in Figure 1 (b), the extension and contraction of the spring are controlled by a gear train consisting of four gears, where gear 2 is an incomplete gear. A motor drives the rotation of gear 1, which is located above the frame. Gear 1, in turn, drives the rotation of gear 2. The incomplete gear 3 rotates on the same axis as gear 2 and simultaneously drives the rotation of gear 4. Gear 4 is fixed to a winch (5), around which a rope is wound. The rope passes through the back of the frame and is connected to the slider. The rotation of gear 4 controls the contraction and release of the rope, thereby controlling the movement of the slider and the extension and contraction of the spring.

When the incomplete gear 3 rotates to the position where its toothed section engages with gear 4, gear 4 rotates, simultaneously driving the rotation of the winch 5. As the rope contracts, it pulls the slider along the left side. During this phase, the spring gradually extends, storing energy, and the angle between the hind limb linkage and the frame gradually decreases.

As the incomplete gear 3 continues to rotate and reaches the toothless section, it no longer engages with gear 4, and its rotation is no longer constrained by gear 4. At this point, gear 4 and winch 5 reverse their rotation, releasing the rope. The spring, no longer subjected to the tension of the rope, rapidly contracts and releases energy. The slider quickly moves towards the right side, driving the movement of the linkage group and realizing the jumping motion of the entire robot as it pushes off the ground.

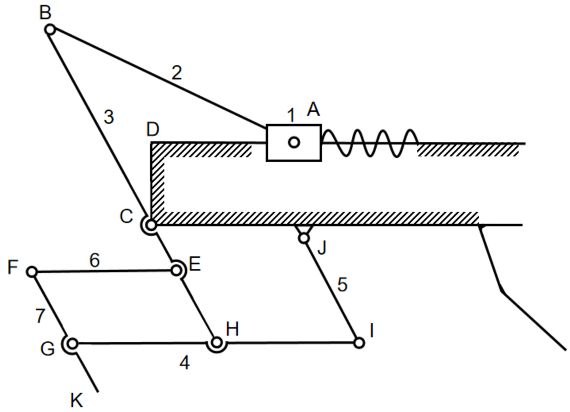

Figure 1. (a) Linkage group and crank-slider mechanism

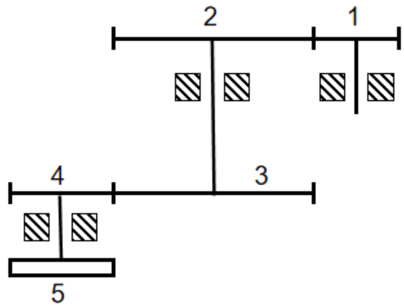

Figure 1. (b) Gear train

3. Dimensional design

3.1. Dimensional design of fixed-shaft gear train

As shown in Figure 3, the schematic diagram of the gear mechanism illustrates that power is input from gear 1. The power of the motor is represented by P, and the torque is represented by M. The compression process is slow and can be considered balanced. By calculating and taking into account the energy loss during transmission, and multiplying by an empirical coefficient of 0.7, the maximum force that the winch 5 can pull is determined to be

$$F_{max} = 0.7M(r_2 * r_4)/(r_1 * r_3 * r_5) \quad (1)$$

Given that the spring's extension deformation is x, the elastic potential energy stored in the spring is kx2/2. When the initial velocity is at a 45° angle, the horizontal displacement is maximized. Through the calculation of oblique projectile motion and the principle of work and energy, the expression for the horizontal displacement can be obtained as follows:

$$L = kx^2/mg = (M * r_2 * r_4 * x)/(mg * r_1 * r_3 * r_5) \quad (2)$$

The time required to compress the spring is t:

$$t = x/(w_5 * r_5) \quad (3)$$

$$x = t * N_5 * 2 * \pi * r_5 \quad (4)$$

Gear 5 is an incomplete gear with the number of teeth $Z_5 = 2 * n * r/m$, where m is the module and n are the ratio of the number of effective teeth to the number of complete teeth.

3.2. pring and gear mechanism coordination dimension design

As shown in Figure 2, there are incomplete gears, complete gears, and a capstan mechanism below the frame. Considering both the transmission ratio of the gear set and the contraction amount of the spring, the module of A and B is set to 1, with a diameter of 20mm, where the toothed and toothless parts of A each account for half. The expected goal is to stretch the spring by 40mm, so according to the formula:

$$L = (\pi * d)/2 \quad (5)$$

Among them, L = 40mm, which can be obtained d≥25mm. In order to appropriately improve efficiency, the final capstan diameter is set to 30mm.

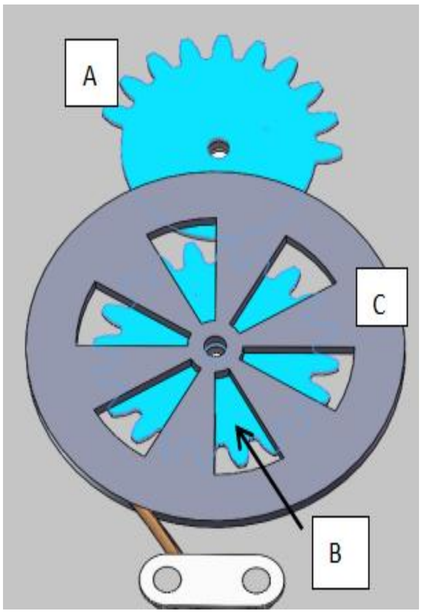

Figure 2. Gear 3, gear 4, and capstan 5 model

3.3. Slider and rear limb linkage mechanism dimension design

As can be seen from Figure 3, the entire hind limb mechanism is composed of a linkage group and a crank and slider mechanism.

Among them, the frame ACD, rod AB, rod BC, and slider together constitute the crank-slider mechanism, as shown in Figure 3. To facilitate subsequent calculations, the length of the frame CD is taken as 12.5mm. The dimension design of this crank-slider mechanism must ensure that the transmission angle θ is not too small, while the stroke of the slider is equal to the contraction amount of the spring.

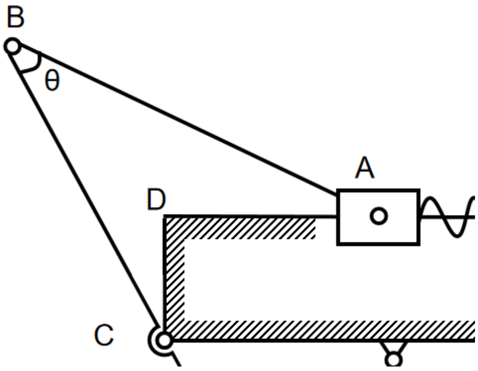

Figure 3. Crank-slider mechanism

When the slider is located on the same vertical line as point C, the lengths of rod AB (a), rod BC (b), and the transmission angle θ satisfy the cosine theorem. By using MATLAB to visualize the relationship between a, b, and cosθ, and based on the visualization results, the final dimensions are selected as follows: AB rod is 22mm, BC rod is 21mm, with θ being 35°. The slider stroke is 5mm, which meets the design requirements. According to the currently selected dimensions, combined with the geometric characteristics of the hind limb linkage group and the frog's body size data obtained from relevant literature, the dimension design of the hind limb linkage group can be presented as shown in Table 1 (units: mm).

Table 1. Hind limb linkage group dimensions

Rod	Length
CJ	15
CE	5
EF	25
EH	15
FG	15
GH	25
GK	15
HI	15
IJ	20

4. Model establishment and optimization

4.1. 4.1 Preliminary model proposal

After determining the kinematic diagram and dimensional parameters of the mechanism, the model established in SolidWorks is shown in Figures 4, 5, and 6:

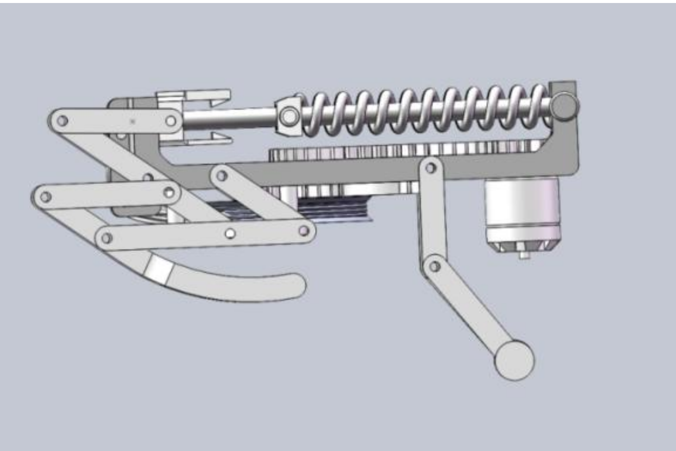

Figure 4. Front view of preliminary model

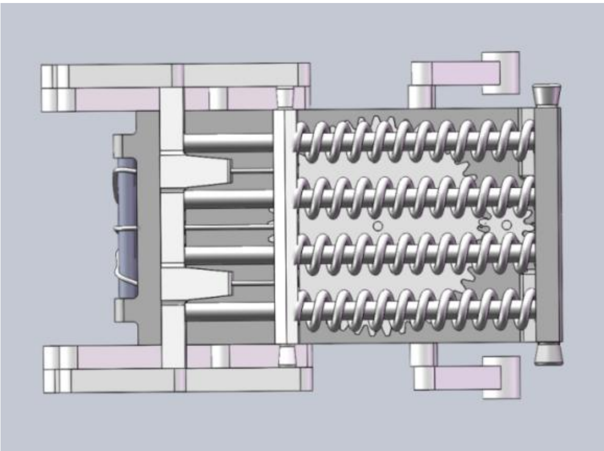

Figure 5. Top view of preliminary model

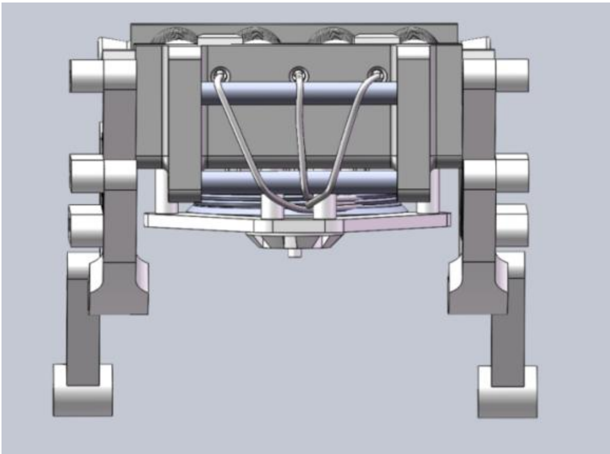

Figure 6. Left view of preliminary proposal

It can be seen that in this version of the model proposal, the bionic frog's back (i.e., above the frame) uses four springs as the power source. This design ensures that the power provided by the springs is sufficient to make the model jump normally, but there are the following issues:

Using four springs can lead to difficulties in maintaining balance, and it requires high precision and fit for the parts during actual assembly. If there is inconsistency in spring extension or contraction, it can cause instability of the center of gravity of the mechanism and nonlinear changes in spring force, which may result in instability during the jump and landing of the entire mechanism.

(2) The motor-driven gear group drives the capstan to retract the rope, thereby pulling the spring to extend. Since it is necessary to pull four springs simultaneously, the required traction force is significantly increased, which raises the requirements for motor power. Moreover, the engagement of the incomplete gear with the complete gear can lead to situations where the complete gear idles, namely, when the toothless part of the incomplete gear aligns with the meshing part of the complete gear. In this case, the energy output by the motor is wasted. Under such circumstances, the higher the rotational power of the motor, the lower the energy utilization rate.

(3) To ensure that the bionic frog can jump normally, the mass of the entire mechanism should be as light as possible. Therefore, if springs with suitable elastic coefficients are selected, it is possible to consider reducing the number of springs to achieve the purpose of reducing the mass of the entire mechanism.

4.2. Model optimization proposal

In response to the issues raised regarding the preliminary model proposal, the following improvements have been made to the model: the number of springs has been reduced from four to two to ensure stability of movement, improve energy efficiency, and reduce the mass of the mechanism [9]; the rest of the structure remains unchanged. The revised model is shown in Figure 7:

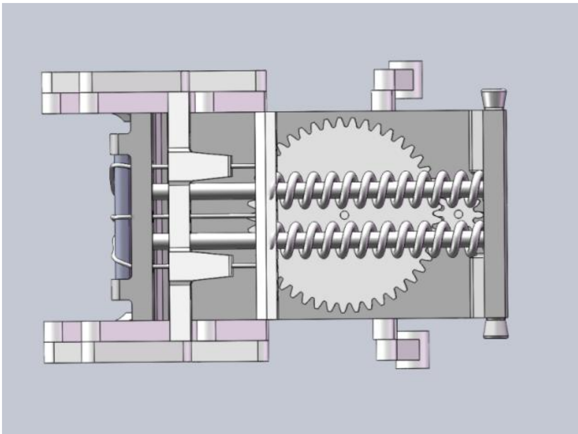

Figure 7. Overhead view of optimized model

5. Model simulation

5.1. Adams simulation

The optimized model is imported into Adams software for pre-simulation setup, such as defining material properties, adding drivers and kinematic pairs [10]. Then, the robot's jumping trajectory is simulated through motion simulation to determine whether the design meets expectations. The jumping trajectory of the bionic robot is shown in Figure 8. According to the simulation results, it can be seen that the bionic frog can achieve normal jumping, namely takeoff, flight, and landing, and the motion posture is stable, and the motion trajectory meets the design expectations.

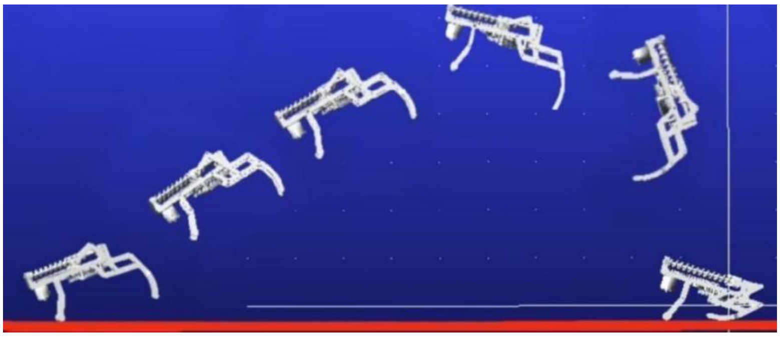

Figure 8. Bionic frog jumping trajectory

5.2. Ansys finite element analysis

After completing the Adams mechanism motion simulation, a rod from the slider and hind limb assembly is selected as the reference part, with structural steel as the material. It is imported into the Ansys software Workbench module for finite element analysis. The model diagrams of the selected slider and rod are shown in Figures 9(a) and 9(b), respectively.

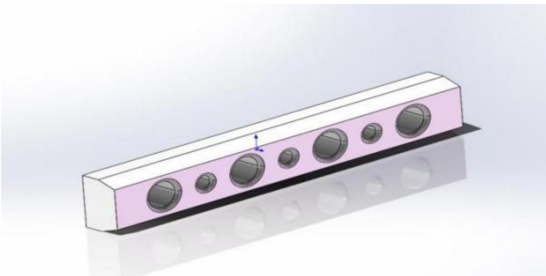

Figure 9. (a) Slider model diagra

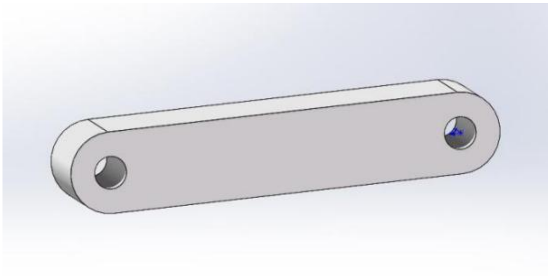

Figure 9. (b) Rod model diagram

The corresponding parts are meshed separately, and fixed constraints are added. In the ANSYS software, the total deformation, equivalent strain, and equivalent stress of the two parts under the extreme stress during the motion process are simulated separately. The simulation results show that the deformation of the parts after being subjected to the load is within the allowable range. It can be concluded that the size and material of the corresponding parts are reasonable.

6. Model Analysis

6.1. Model Summary

In this design, a bionic frog jumping robot was developed, which uses a motor as the power source, a gear train as the transmission mechanism, a linkage group to simulate the frog's hind limbs, and a spring to provide elastic force. According to the simulation results, it can be found that the bionic frog jumping robot meets the design expectations and can complete intermittent jumping movements while ensuring the stability of the bionic frog's movement throughout the jumping cycle. The overall design achieves the intended goals.

6.2. Model Optimization Analysis

Currently, the frog bionic jumping robot can achieve the intended goals, but there is still room for optimization. After analysis and summary, the following points are noted:

(1) During the kinematic simulation, there may be situations where the center of gravity is too forward, causing the bionic frog to be unable to perform normal jumps (such as anterior somersaults). After analysis, it is believed that the main reason for this phenomenon is the unreasonable magnitude of the driving force applied during the simulation. However, it is also necessary to optimize the design of the model parts, such as adjusting the position of the front parts of the mechanism and reducing the mass.

(2) To adjust the take-off angle of the bionic frog at any time, the forelimbs are designed as two rods connected by hinges, which may cause the forelimbs to sway randomly during the aerial phase. The corresponding solution is to increase the number of kinematic simulations, summarize the most suitable take-off angle of the bionic frog through repeated simulations, or use MATLAB software to write a program to find the optimal solution for the take-off angle as a reference to fix the forelimbs.

(3) The entire mechanism consists of complete parts, excluding the fixed parts below the winch, meaning there are no parts with holes or hollows. This can lead to the entire mechanism carrying unnecessary weight. In later optimization, it is possible to consider drilling holes in parts such as gears while ensuring strength. Of course, it is preferable not to do this if the mass already allows the frog to jump normally, in order to reduce the difficulty and economic cost of part processing.

7. Summary

The current design is based on bionics, taking frogs as the research object. By analyzing and summarizing the physiological structure and motion characteristics of frogs, a bionic jumping robot has been designed. This design focuses on analyzing the physiological structure data of frogs and strictly adheres to this data for dimensioning. Additionally, SolidWorks is used to establish a three-dimensional model, which is then imported into Adams and Ansys for motion trajectory analysis and finite element analysis, respectively. This verifies the correctness and rationality of the design, providing a theoretical basis for further structural design and optimization analysis of bionic frog robots.

Looking forward, bionic frog technology has immense application potential and is expected to bring significant convenience to human life and work in various fields. Subsequent research could consider integrating bionic robots with artificial intelligence to develop corresponding intelligent control systems, enabling robots to possess abilities such as autonomous learning, environmental perception, and decision-making, thereby enhancing their adaptability to environments and expanding practical application scenarios.

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