Mechanism design and optimization of a bionic kangaroo jumping robot

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Abstract. Hopping robots have broad application prospects in the fields of military reconnaissance, field search or life rescue. However, current hopping robots still face the problems of weak jumping ability and load bearing. Inspired by the jumping of kangaroo, we design a Kangaroo hopping robot "Zbot", which has two degrees of freedom and three joints. The geared five-bar mechanism is used to decouple the knee and ankle joints of the robot. In order to get a bionic performance, the coupling mechanism parameters are optimized. The simulation and experiments show that the robot has an excellent jumping ability and load capacity.

1. Introduction

Jumping robot is a hot branch of robotics research field. Compared with wheeled, legged and tracked robots, they are more adaptive in mountainous, ravine and other complicated terrains with high jumping ability and discreetness of location. In addition, the jumping robot can effectively absorb the landing buffer energy and release it on the next hopping, to realize the reuse of partial energy. Therefore, jumping robot shows some advantages than other robots.

In 1991, the MIT developed the biokangaroo robot "Uniroo", which consists of a body, leg and tail. It has four joints: the tail and hip have collinear pivot axes at the hip, and four actuators for each joint. The robot and its boom together mass about 25kg, and it hops forward about 1m/s [1,2]. SH Hyon and his co-workers of Tohoku University, proposed a simple mechanical model of hind-limb named "KenKen" by mimicking dog hind limbs. Its articulated leg is composed of three links and two hydraulic actuators are adopted as muscles and linear springs as a tendon. It exploits an empirical controller based on characteristic dynamics of the model. The experiment showed that the robot was able hopping well in planar [3]. In 2013, the Festo Bionic Learning Network developed a hopping robot “BionicKangaroo”, with a four-bar mechanism leg driven by pneumatic actuators. Elastic tendons connected with actuators in the leg kinematics are used to store the energy and to provide the power for hopping. In addition, the hip and tail joints are equipped with electrical drives to balance and stabilize the hopping cycle [4].
Miniaturization is another trend of hopping robot, because small robots have larger power mass ratio and more flexible characteristic jumping behaviour. Professor Paolo Dario developed a fast-long jumping robot "Grillo", at the taking-off phase, an escapement mechanism releases the drawn spring, and generates a power peak several times higher than that of using motor. In addition, The designer has developed a series of miniature jumping robots [5-7]. Based on the "Grillo", Micro Kovac of Federal Polytechnic Institute developed a 5cm 7g jumping robot. A four-bar leg linkage of robot is connected to the body on the ground link, which is extended via the input link using a torsion spring. The robot was able to jump up to 27 times than its own size. In their further research, the robot with additional wings can travel longer distances when jumping from an elevated starting position and reduce the kinetic energy on impact which needs to be absorbed by the robot structure [8, 9]. MSU jumper, developed by Zhao, can perform continuous jumping with four mechanisms. It charged the energy and performed the self-righting at the same time. The 23.5g robot could jump over 87cm high and 89cm away [10]. In 2016, Duncan W. Haldane, from the University of California at Berkeley, published on Science Robotics and presented a bionic galago robot "Salto". Using a series elastic actuator (SEA), Salto gains a surprising amount of power on the phase of taking-off. Salto was only 100g but can jump up to 1m every 0.58s averagely [11]. Xiaojuan Mo, the doctor of NWPU, China, proposed a jumping robot design scheme based on a four-bar mechanism to simulate the trajectory of the tibiae end of the locust and the knee joint rotation angle, which had been proved to be a good mimic of the movements of locusts jumping [12].

In this paper, we proposed a hopping robot model owning strong environmental adaptability, less freedom degree and strong load capacity. The hopping robot model imitates a kangaroo with thighs, lower legs and foot. In order to increase the kinematic flexibility, the ankle and knee joints are coupled through a geared five-bar mechanism. Two hydraulic cylinders are adopted to drive the robot's hip joint and ankle joint respectively. Secondly, the joint angles of the kangaroo are measured during the jumping, and the parameters of the coupled mechanism are optimized to imitate movement characteristics of kangaroo. Finally, the bionic performance and load-bearing capacity of robot are verified by both simulation and experiment.

2. Design of the mechanism

2.1. Design progress of bionic leg mechanism

Kangaroo hind-legs are very thick. It has a small body rotation angle while leaping in a large gait. It relies on the rapid swings of thighs, calves and feet to jump. Kangaroo can be seen as a chain of three degrees of freedom mode as figure 1 shows. This model requires three drivers, and the collaborative control is very difficult. Moreover, because of the existence of the hydraulic cylinder at the ankle joint, the lower body mass of the robot is too large. The body inertia at the time of taking off is relatively small, and the driving power is increased. Early our team's experimental studies have proved this mechanism is not effective.

![Figure 1. Three-link jumping robot model.](image)

The geared five-bar mechanism is richer in movement and force conversion features than the four-bar mechanism, and it can meet the requirements of a variety of motion trajectory. This paper develops a robot, "Zbot", of knee-ankle coupling based on a geared five-bar mechanism as shown in figure2. $I_i$, $I_2$,
$l_2$ and $l_3$ represent the lengths of Thigh, calf and foot of Zbot. Point $P$, $N$ and $C$ represent the hip, knee and ankle joints, and their corresponding angles are $\theta_i$, $\theta$, $\theta_f$. The parallelogram mechanism transmits the motion of the knee to the geared five-bar mechanism. The geared five-bar mechanism can be seen as a movement conversion device, which processed the knee movement with a certain law. Zbot retains the freedom of the hip, which can make the robot leg swing in the air so as to land smoothly. Zbot's knee and ankle are coupled by a mechanism, which not only reduces one degree of freedom of the mechanism but also improves the $MA$ [13, 11]. $MA$ is defined here as the ratio between the reaction force at the foot to the force applied by the actuator [11]. The foot made of silicon steel can increase the robot's power density when the robot takes off because it forms a series elastic actuator (SEA) with the driving cylinder.

2.2. Motion relationship between knee and ankle joints
The geared five-bar mechanism shown in Figure 2 is an essential part of the robot. It makes the ankle and knee angle has a certain relationship. The bar $AB$, $BC$, $CD$, $DE$, $EA$ hinge end to end, the two gears at point $A$ and $B$ are fixed on the $AE$ and $BC$ respectively, the characteristics of the mechanism can be expressed by nine quantities: $d_1$, $d_2$, $d_3$, $d_4$, $d_5$, $i$, $\theta_{i0}$, $\varphi_{i0}$, $\gamma$. The $d_1$, $d_2$, $d_3$, $d_4$, $d_5$ represent the lengths of each linkage, $i$ is the gear ratio, $\theta_{i0}$ and $\varphi_{i0}$ are the initial angle of $\theta_i$ and $\varphi_i$, $\gamma$. Since $BC$ and $EA$ are connected through the gear pair, we can get the following equations:

$$\varphi_i = \varphi_{i0} + i \cdot (\theta_i - \theta_{i0}) \quad (1)$$

If $d_{AC}$ is defined as the distance between point $A$ and point $C$ (The same below), the following equation can be drawn from the sine and cosine theorems of triangles.

$$d_{AC}^2 = d_1^2 + d_2^2 - 2d_1d_2 \cos \theta_i \quad (2)$$

$$\frac{\sin \varphi_i}{\frac{d_1}{d_2}} = \frac{\sin \theta_i}{d_{AC}} \quad (3)$$

Equation (3) can be written in the following form.

$$\varphi_i = \arcsin(\frac{d_1}{d_{AC}} \sin \theta_i) \quad (4)$$

And

$$\varphi_2 = 180^\circ - \theta_i - \varphi_i \quad (5)$$

In $\triangle ACE$, The following equation can be drawn.

$$\varphi_2 = \varphi_3 = \varphi_4 - \varphi_1 \quad (6)$$

$$d_{CE}^2 = d_5^2 + d_{AC}^2 - 2d_5d_{AC} \cos \varphi_4 \quad (7)$$

![Figure 2. The geared five-bar mechanism.](image-url)
\[
\sin \varphi_a = \sin \frac{d_s}{d_{CE}} 
\]

Equation (8) can be written in following form.
\[
\varphi_s = \arcsin\left(\frac{d_s}{d_{CE}} \sin \varphi_a \right)
\]

And in \( \triangle ECD \), The following equation can be drawn.
\[
d_s^2 = d_s^2 + d_{CE}^2 - 2d_s d_{CE} \cos \varphi_b
\]
\[
\varphi_b = \arccos\left(\frac{d_s^2 + d_{CE}^2 - d_t^2}{2d_s d_{CE}} \right)
\]

According to Figure 2 in the relationship between the angle can be drawn.
\[
\theta_j = \gamma - (\varphi_a + \varphi_s + \varphi_b)
\]

From Equation (3–11), the relationship between \( \theta_i \) and \( \theta_j \) can be derived.
\[
\theta_j = f(\theta_i) \quad (12)
\]

Equation (12) is the function between ankle and knee joints, which contains parameters: \( d_1, d_2, d_3, d_4, d_5, i, \theta_{\alpha}, \varphi_{\beta}, \gamma \). These parameters closely affect the knee-ankle movement. The value of each parameter corresponds to a movement relationship. A reasonable set of structural parameters would make the robot knee ankle joint motion characteristics achieve the best. The mechanism will be optimized in the next section to find out a set of structural parameters that make the jumping robot has bionic motion characteristics.

3. Biological observation and optimization of mechanism

3.1. Kangaroo morphology observation

This article directly regards the knee and ankle angle when kangaroo takes off as the optimization object. Firstly the key positions of the kangaroo are cut out during the whole cycle of kangaroo jumps as shown in figure 1. Then the knee angle and the corresponding ankle angles of each position are measured as shown in table 1. \( \theta_{\alpha} \) and \( \theta_{\mu} \) represent the measured knee and ankle angle respectively.

| Kangaroo positions | Measured knee angles \( \theta_{\alpha} \) (°) | Measured ankle angles \( \theta_{\mu} \) (°) |
|-------------------|---------------------------------------------|
| Position 1        | 95                                          | 82                                          |
| Position 2        | 112                                         | 95                                          |
| Position 3        | 120                                         | 125                                         |
| Position 4        | 125                                         | 130                                         |
| Position 5        | 132                                         | 152                                         |

3.2. Optimization of mechanism

The optimization of geared five-bar mechanism is to find out a set of parameter values that makes the movement of Zbot's knee and ankle imitate the corresponding movement of the kangaroo. If \( \theta_{\mu} \) represents the ankle angle value of the mechanism in position \( k \), and \( \theta_{\mu} \) represents the measured ankle angle value of the kangaroo in position \( k \), the expression of the optimized object function can be written as follow.
\[
\min f(\gamma, d_1, d_2, d_3, d_4, i, \theta_{\alpha}, \varphi_{\beta}) = \sum_{k=1}^{5} |\theta_{\mu} - \theta_{\mu_k}|
\]

Proportionally enlarging or reducing the size of the geared five-bar will not change the performance of mechanism as long as the initial posture of the mechanism unchanged. So according to
the overall size of the robot, we make \( d_1 \) equal to 54mm, \( \theta_{0i} \) equal to 80°. The initial value and range of each parameter are determined by the size of the robot, which are shown in table 2.

Table 2. Optimized variables and their ranges.

| Optimized variables | Range of optimized variables | Optimized results |
|---------------------|-----------------------------|------------------|
| \( d_1 \)          | 54 mm                       | 54 mm            |
| \( d_2 \)          | 50 mm ~ 80 mm               | 56 mm            |
| \( d_3 \)          | 20 mm ~ 80 mm               | 60 mm            |
| \( d_4 \)          | 20 mm ~ 80 mm               | 60 mm            |
| \( d_5 \)          | 20 mm ~ 50 mm               | 32 mm            |
| \( i \)            | \( 1/3, 1/2, 1 \)           | 1                |
| \( \theta_{0i} \)  | 80°                         | 80°              |
| \( \varphi_{0i} \) | 90° ~ 120°                  | 95°              |
| \( \gamma \)       | 180° ~ 250°                 | 198°             |

The enumeration method is used for optimization. 1) The values of each independent variable are substituted into (12) to get the function between the ankle and knee. 2) The values of the knee angles of position 1~5 are respectively substituted into the function, and the mechanical ankle angles of each position are obtained. 3) Comparing these ankle angles with the corresponding measured ankle angles, the difference of two sets of ankle angles will be got. 4) Take the values of different independent variables and repeat the above process until the set of variables appear that make the difference minimum. After the optimization, a best set of independent variables that make the bionic characteristic of the mechanism come to be obtained in table 2. The minimum value of the objective function is 18.9°. The deviation existing is caused by many reasons, such as the gap of each parameter and the discrete sampling points. The unavoidable error makes the optimization precision have a slight deviation, but the mechanism can still better imitate the position of kangaroo jumping.

By substituting the optimized results into (12), we can obtain ankle angle on the knee angle expression, and comparing optimized curve with the measured discrete point of knee-ankle joint in the coordinate, the figure 3 is obtained, which reveals the motion relationship of the knee and ankle during kangaroo jumping. The figure 3 shows, 1) The robot can mimic the kangaroo’s jumping position to a large extent; 2) Entering a smaller rang of knee motion (80°~128°) can get a larger range of ankle motion(60°~152°), increases of ankle angle is about 1.9 times than that of knee, which shows that the robot has the same acceleration characteristics as the kangaroo while jumping.

4. Kinematics simulation and experiments
4.1. Kinematics simulation

According to the results of optimization and the size of each robotic rod, a three-dimensional model of "Zbot" is established in SolidWorks and then imported into Adams. Materials properties, necessary markers, contacts and constraints are set up.

By planning trajectory and solving inverse kinematics of the robot, the displacement curve of the hip and knee cylinders can be obtained, and using them as the driving curve of the Zbot's hip and knee hydraulic cylinder. This article takes the robot jumping at 3m/s in the direction of 45° as an example. The trajectory of the body center of mass and the robotic position in different moment are shown in Figure 4. As can be seen from the figure 4, Zbot jumps away from the ground at about 0.2 s, and the maximum height of the jumping is 0.5m. Zbot has a bionic kangaroo position and its body moves in a straight line when taking off, which in line with the biological characteristics.

Figure 5 shows the change in Zbot center of mass velocity. As can be seen from the figure 5, the body is evenly accelerated and the maximum velocity is about 3m/s that in line with expectations.

4.2. Experiments

Based on the results of the optimization of the mechanism, the prototype Zbot is fabricated as shown in figure 6. The overall size is 375mm × 380mm, and the material is mainly aluminum (6061). Zbot
weighs 4.5kg and is driven by two hydraulic cylinders at ankle and knee joints. In order to verify the robot's load-bearing capacity, ten weights (total 4kg) are fixed on the body of Zbot.

![Figure 6. The prototype of Zbot.](image)

Figure 7 is the video capture of robotic taking off, which shows that Zbot had a bionic position and had an excellent jumping ability under loaded conditions. The height it jumps is from 375mm to 880mm, which is 1.3 times than its own size. The horizontal distance it moves in half cycle is about 470mm. This performance is better than any other existing continuity jumping robot driven by hydraulic cylinders. This experiment proved that Zbot has good locomotion ability. Moreover, the weight it fixed on (4kg) approaches that of its own (4.5kg), which explains the robot has a good load capacity. It is worth mentioning that the load capacity of jumping robot is very important in future application, but few researches focus on this point. We will make continuous research on this. The jumping shown in Figure 7 is just one kind of hopping modes of Zbot. In addition, the robot can jump in different directions at different speeds by changing the motion of two hydraulic cylinders.

![Figure 7. Video capture of Zbot's taking off.](image)

5. Conclusion.
This paper presents a two-degree-of-freedom jumping robot "Zbot", which is inspired by the kangaroo jumping. The use of a geared five-bar mechanism to couple the robot's knee and ankle makes the robotic movement more flexible. The mechanism is optimized based on the position measurement of the kangaroo during take-off. The robot simulation and experiments were performed, and the results proved the feasibility of the mechanism.

Through the research stated in this paper, the following conclusions can be drawn: Zbot can not only imitate kangaroo jumping, but also has the ability of bear weight. It provides a new idea for the research of hopping robot.
In the future work, we will study the position adjustment of the robot during the fight phase and tail-based balance control, as well as the stability of the robot landing phase. We believe Zbot will have a very bright future in application.

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