Design and Motion Analysis of Octopod Bionic Robots Based on a Multi-Link Walking Mechanism

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Abstract. In this paper, a bionic robot walking mechanism based on a multi-link mechanism was proposed, which consisted of two crank-rocker mechanisms, one parallelogram mechanism and two tripods, all of which were connected by hinges. An octopod bionic robot was designed by using the multi-link walking mechanism. The kinematics analysis of the robot walking mechanism was carried out by using MATLAB software, and the linear walking gait of the virtual prototype of the robot was simulated by using ADAMS software. The simulation results showed that the octopod bionic robot had good motion stability, strong terrain adaptability, and good practical application and popularization value.

1. Introduction
The walking mechanism is the key component of various mobile robots. The walking mechanism of mobile robots is mainly divided into three types, namely wheeled mobile mechanism, crawler-type mobile mechanism, and foot-type mobile mechanism, which are used to adapt to different environments and occasions [1]. The walking mechanism of the foot-type robot mostly adopts a linkage mechanism. With the help of the multi-joint of linkage mechanism, the foot-type robot can imitate human beings and animals' stepping. The feet can lift off the ground and leap forward. It can cross soft and uneven terrain to keep the body stable, cross obstacles and trenches, and have the strongest environmental adaptability [2, 3, 4]. At present, bionic walking mechanisms such as spider-type, Taba Mouse-type, snake-type, and insect-type have been intensely studied and vigorously developed [5]. Although the foot-type walking robot has strong terrain adaptability, it needs to plan its walking gait strictly. The mechanical structure is complex, the control system is difficult, there are technical and cost control problems, and it is difficult to realize large-scale marketization [6]. Therefore, in order to overcome the problems existing in the foot-type walking robot, a bionic robot based on a multi-link walking mechanism is designed. The robot is equipped with eight walking feet, which a motor can drive through a set of the worm gear and gear transmission systems. The overall structure is compact, the design and manufacture costs are low, and the control is relatively simple.

2. Design of Walking Mechanism
A multi-link type walking foot mechanism is designed, and its mechanism diagram is shown in Fig. 1. The mechanism consists of two crank-rocker mechanisms, one parallelogram mechanism, and two tripods, all of which are connected by hinges. Hinges $O$ and $C$ are fixedly mounted on the robot frame to form the frame of the mechanism. The rods $OA$, $AB$, $BC$ at the upper right of the mechanism and the frame $OC$ form a crank-rocker mechanism, while the rods $OA$, $AF$, $CF$, and the frame $OC$ at the lower right form another crank-rocker mechanism. The rod $OA$ serves as the crank of the two crank-rocker
mechanisms simultaneously and can rotate all the way. The crank $OA$ serves as a driving member and transmits motion through the two connecting rods to drive the whole mechanism to work. The left middle rods $CD$, $DE$, $EF$, and $CF$ form a parallelogram mechanism, and the upper left rods $BC$, $CD$, and $BD$ and the lower-left rods $EF$, $FG$, and $EG$ form two tripods, respectively. Point $G$ is the landing point of the robot walking mechanism. During the crank $OA$'s circular motion, the landing point $G$ will also move periodically with the whole linkage mechanism, thus realizing the walking motion of a single walking foot in one cycle.

![Schematic Diagram of Walking Foot Mechanism](image)

**Fig.1** Schematic Diagram of Walking Foot Mechanism

### 3. Kinematics Analysis and Simulation of the Walking Mechanism

The motion analysis of the walking mechanism is the basis of the overall structural design and gait planning of mobile robots. Firstly, the motor process of a single walking mechanism on the flat ground is analyzed independently. Taking the hinge connection center $O$ of the crank $OA$ and the frame as the origin and the connecting line of the two fixed points $O$ and $C$ and taking the connecting line $OC$ as the horizontal coordinate axis $x$, a rectangular coordinate system $Oxy$ is established as the fixed reference coordinate system of the single walking mechanism, as shown in Fig. 1. Then, the multi-link mechanism is decomposed, and the motion trajectory of the landing point $G$ relative to the coordinate origin $O$ is emphatically analyzed.

#### 3.1. Kinematics Analysis of the Upper Crank-rocker Mechanism

During the walking mechanism operation, the rocker $BC$ in the crank-rocker mechanism at the top right in Fig. 1 is always located above the fixed frame $C$, which is called the upper crank-rocker mechanism. The crank-rocker mechanism is disassembled from the multi-link mechanism diagram to facilitate kinematic analysis, as shown in Fig. 2.

![Schematic Diagram of the Upper Crank-rocker Mechanism](image)

**Fig.2** Schematic Diagram of the Upper Crank-rocker Mechanism

Let the distance between two fixed points $O$ and $C$ on the frame be $l$; The length of the crank $OA$ is $l_1$, and the included angle with the $x$-axis is $\theta$. The length of the connecting rod $AB$ is $l_2$, and the included angle with the $x$-axis is $\beta_1$. The length of the rocker $BC$ is $l_3$, and the angle between the rocker $BC$ and the $x$-axis is $\alpha_1$. When the crank $OA$ rotates around the center $O$ of the frame, the rocker $BC$ reciprocates around the fixed frame $C$. According to the motion law of the crank-rocker mechanism, each rod in the mechanism is projected to the $x$-axis and the $y$-axis, respectively, and the following balance equations can be listed as follows.
According to equation (1), the included angles $\alpha_1$ and $\beta_1$ between rocker $BC$ and connecting rod $AB$ and $x$-axis at any time in the working process can be obtained.

### 3.2. Kinematics Analysis of the Lower Crank-rocker Mechanism

During the walking mechanism operation, the rocker $CF$ in the crank-rocker mechanism at the lower right in Fig. 1 is always located below the fixed frame $C$, which is called the lower crank-rocker mechanism. The crank-rocker mechanism is disassembled from the multi-link mechanism diagram, as shown in Fig. 3.

![Fig.3 Schematic Diagram of the Lower Crank-rocker Mechanism](image)

In order to ensure the correctness of the motion position of the mechanism, the included angle between crank $OA$ and $x$-axis should still be set as $\theta$. Let the length of the connecting rod $AF$ be $l_4$, and the included angle with the $x$-axis be $\beta_2$. The length of the rocker $CF$ is $l_5$, and the included angle with the $x$-axis is $\alpha_2$. When the crank $OA$ rotates around the center $O$ of the frame, the rocker $CF$ reciprocates around the fixed frame $C$. Each rod in the mechanism is projected to the $x$-axis and the $y$-axis, respectively, and the following balance equations can be listed as follows.

\[
\begin{align*}
\begin{cases}
    l_1 \cos \theta + l_2 \cos \beta_1 - l_3 \cos \alpha_1 + l = 0 \\
    l_1 \sin \theta - l_2 \sin \beta_1 + l_3 \sin \alpha_1 = 0
\end{cases}
\end{align*}
\]

(1)

According to equation (2), the included angles $\alpha_2$ and $\beta_2$ between rocker $CF$ and connecting rod $AF$ and $x$-axis at any time in the working process can be obtained.

### 3.3. Kinematics Analysis of Landing Points

In Fig. 1, the rods $CD$, $DE$, $EF$, and $CF$ form a parallelogram mechanism, and the rods $CD$ and $EF$ are always parallel and equal in length during the motor process. In order to simplify the analysis, let the two tripods composed of rods $BC$, $CD$, $BD$, and rods $EF$, $FG$, $EG$ be congruent triangles. Then, the rods $FG$ and $BC$ have the same length and are both $l_3$, and they are always parallel in motion. Besides, the included angle between the two rods and the $x$-axis is also the same, both of which are $\alpha_2$. From this, the coordinates of the landing point $G$ in the coordinate system $Oxy$ can be calculated according to Fig. 1 as follows:

\[
\begin{align*}
    x_G &= l_3 \cos \alpha_1 - l_3 \cos (\pi - \alpha_2) - l \\
    y_G &= l_3 \sin \alpha_1 - l_3 \sin (\pi - \alpha_2)
\end{align*}
\]

(3)

From equations (1) to (4), it can be seen that the position of the landing point $G$ at any time is determined by the motion of the crank $OA$. The position coordinate of the landing point $G$ can be calculated by the angle $\theta$ between the crank $OA$ and the $x$-axis.

### 3.4. Motion Simulation Results and Analysis of Walking Mechanisms

In a design case of a robot multi-link walking mechanism, the distance between two fixed points $O$ and $C$ on the frame is $l=26.5$mm, the length of crank $OA$ is $l_1=12.5$mm, the length of connecting rod $AB$ is $l_2=40$mm, the length of the rocker $BC$ and rod $FG$ is $l_3=30$mm, the length of connecting rod $AF$ is $l_4=40$mm, the length of rocker $CF$ is $l_5=30$mm, and the lengths of rods $CD$, $DE$, and $EF$ are equal and
all 30mm. Assuming that the crank $OA$ rotates at a certain and constant speed, MATLAB software is used to simulate the motion of the landing point $G$ for one period, and the motion trajectory curve of the landing point $G$ in the coordinate system $Oxy$ can be obtained as shown in Fig. 4.

![Fig.4 Trajectory Curve of the Landing Point G](image)

According to whether the landing point is in contact with the ground or not, a single walking foot's motor process can be divided into two stages, namely suspension stage and support stage. In the suspension stage, the walking foot moves forward, and in the support stage, the walking foot contacts the ground to support the translation motion of the robot. As can be seen from Fig. 4, the motion track of the landing point $G$ is triangular, and the suspension stage and the support stage each accounts for 1/2 of the whole cycle. The maximum horizontal displacement of landing point $G$ in a motion period is 53mm, and the maximum vertical lifting height is 28mm. The maximum value of horizontal displacement is located at the midpoint of the whole motion cycle, while the maximum value of vertical displacement appears at 3/4 of the motion cycle, i.e., the midpoint of the suspended stage. The motion trajectory of landing point $G$ is basically parallel to the horizontal $x$-axis in the support stage, which can support the robot to move smoothly on the horizontal ground [7]. In the suspension stage, the motion track of the first 1/2 cycle is monotonously increasing, and the second 1/2 cycle is monotonically decreasing, which can ensure the walking mechanism completes the stepping motion in the working process stably.

4. Design of an Octopod Bionic Robot

According to the design case of the multi-link walking mechanism in Section 3.4, a 3D model of the single walking mechanism of the robot is designed, as shown in Fig. 5. In order to improve mechanical motion stability and reduce impact and vibration, the crank $OA$ is designed as a Flange Shape and driven by a motor. The landing point $G$ is designed as a large arc surface to reduce the contact pressure with the ground. The single walking foot shown in Fig. 5 has 1/2 time for stepping in a motion cycle and it is in the suspension stage. In order to increase the number of supporting points of the bionic robot in the motor process and improve the motion stability, a bionic robot with eight multi-link walking feet is designed, and its structural model is shown in Fig. 6. The robot's body has a cuboid structure, and eight walking feet are symmetrically distributed on both sides of the body. Wherein the rods of the walking feet $leg_1$, $leg_2$, $leg_5$, and $leg_6$ are assembled in the manner shown in Fig. 5; Compared with that, the rods' assembly mode in the walking feet $leg_3$, $leg_4$, $leg_7$, and $leg_8$ is that the positions of the rods except the crank $OA$ are symmetrically distributed relative to the vertical axis passing through the crank rotation center $O$. The eight walking feet can be divided into four groups according to the phase of crank $OA$, of which $leg_1$ and $leg_8$ are divided into the first group, $leg_2$ and $leg_7$ are divided into the second group, $leg_3$ and $leg_6$ are divided into the third group, $leg_4$ and $leg_5$ are divided into the fourth group. The cranks $OA$ of the two walking feet in each group have the same phase during the motor process. While between the groups, the phase difference between the walking feet of the first group and the second group is $\pi$, and that between the third group and the fourth group is also $\pi$. The first and fourth
groups are in phase, and the second and third groups are also in phase. This phase design method can ensure that at least four walking feet are in the support stage during the robot's walking process, thus making the robot move more smoothly. The transmission system of the robot adopts a worm mechanism and gear mechanism, with only one driving motor used, which has a compact structure, simple control, and high transmission precision, so that the cranks of four walking feet on the same side of the robot body have the same rotation direction, and meanwhile, the phases of each group of two walking feet can be kept the same in motion. All the fixed connection points like O and C of the eight walking feet and the frame are designed on the same plane.

Fig.5  3D Model of the Single Walking Foot  Fig.6  3D Model of Octopod Bionic Robot

5. Gait Analysis and Simulation of an Octopod Bionic Robot

5.1. Gait Analysis
In order to simplify the analysis process, it is assumed that the center of gravity of the robot is located in the geometric center of the body and on the plane formed by all the fixed mounting points like O and C of the eight walking feet on the frame. The position of the center of gravity remains unchanged when the robot walks on the flat ground. For the octopod bionic robot shown in Fig. 6, the eight walking feet are divided into four groups. Since the two walking feet in each group have the same phase in motion, the motion trajectories of the two walking feet's landing points are also the same. When the robot walks on flat ground, the two walking feet in each group can contact the ground simultaneously. Between the walking foot groups, the phase difference between the walking feet leg 1 and leg 8 of the first group and the walking feet leg 3 and leg 6 of the third group is π, and in these two groups of walking feet, except for the crank, the remaining rod positions are symmetrically distributed relative to the vertical axis passing through the crank rotation center O. From the motion trajectory curve of the landing point shown in Fig. 4, it can be seen that the motion trajectory curve of the landing point of the two groups of walking feet is also the same when moving. When the robot moves on the flat ground, four walking feet of the two groups can contact the ground simultaneously. According to the above analysis, it can be seen that the walking feet leg 2 and leg 7 of the second group and the walking feet leg 4 and leg 5 of the fourth group also have the same motion trajectory of the landing points, and they are also in contact with the ground simultaneously during the motion. When the walking feet of the first and third groups are in the support stage, the walking feet of the second and fourth groups are in the suspended stepping stage. When the robot moves on the flat ground, the support stage and the suspension stage of the four groups of walking feet alternate with each other. The robot has at least four contact points with the ground at any time, thus ensuring good stability of the robot's motion. Besides, this walking foot arrangement can also increase the translation distance to the ground by two times compared with a single walking foot when the robot completes a gait cycle phase.

5.2. Simulation Experiment and Result Analysis
The simulation environment is set as a rough floor with a flat surface, and the static friction coefficient between the walking foot and floor is set to 0.25. Then, the 3D model of the octopod bionic robot established by SolidWorks software is imported into the simulation environment to generate a virtual prototype model. Also, the ADAMS software is used to simulate the linear walking gait of the quadruped robot [8]. The drive motor's rotation speed is set to 25 r/min, and the simulation time is set to 8 s. The
curve of the robot's center of gravity height $h$ changing with time $t$ during the simulation process is shown in Fig. 7. The simulation results show that the height of the center of gravity varies from 61.7 mm to 63.9 mm, and the maximum change of that is 2.2 mm. Meanwhile, the horizontal displacement is basically in a uniform motion state, having good motion stability.

![Variation Curve of Robot Center of Gravity Height](image)

**Fig.7** Variation Curve of Robot Center of Gravity Height

### 6. Conclusion

The linkage mechanism has the characteristics of strong load-bearing capacity and rich motion trajectory shapes, which can well meet the gait requirements of mobile robot. In this paper, a walking mechanism scheme was designed by using a multi-linkage mechanism. Combined with actual design cases, the kinematics of the walking mechanism was analyzed by using MATLAB software. Meanwhile, an octopod bionic robot device was designed by using the multi-link walking mechanism, and the linear walking gait of the virtual prototype of the robot was simulated by using ADAMS software. Simulation results showed that the octopod bionic robot had good motion stability and environmental adaptability. This robot design scheme had certain practical value, which can provide a reference for the design and research of similar bionic robots.

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