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# Crawling Gait Planning and Simulation Analysis of Closed-chain Walking Leg Robot

Yongming Wang, Qiang Wei, Tengfei Ma

School of Mechanical Engineering, Anhui University of Technology, Ma'anshan, 243032, China

wangym@ahut.edu.cn

**Abstract.** This paper presents a new type of closed-chain walking leg mechanism, which can swing through a crank-rocker mechanism, and a crank-slider mechanism to achieve leg extension. On this basis, a quadruped robot is constructed, the crawling gait planning is carried out, and the leg swinging time sequence of the robot crawling is given. Based on ADAMS simulation software, the virtual prototype model of quadruped robot is established, and the relative simulation parameters are set up to simulate the robot motion. The displacement curve and velocity curve of the body centroid and foot end of the quadruped robot are obtained. The simulation results show that the quadruped robot can walk stably in the crawling gait.

## 1. Introduction

Walking robot has outstanding contributions in many aspects, such as detection, rescue, military reconnaissance, underwater exploration. So many scholars are dedicated to the study of the robot with new structure. Reasonable leg mechanism is the basis of walking robot design. Most of the existing leg mechanisms are multi-joint open-chain mechanisms composed of connecting rods [1-2], which have many degrees of freedom and complex control. The typical representatives include Japan's Roller-Walker [3], Boston Dynamics' Cheetah Robots[4], WildCat[5], Italy's HyQ[6] and Japan's SQ43[7] and so on. Compared with open-chain leg mechanism, closed-chain leg mechanism has the advantages of simple control and strong load-carrying capacity. Through reasonable design, it can meet the needs of robot leg mechanism. In this paper, a double closed-chain mechanism is proposed as the leg mechanism of the robot, and a new quadruped robot is constructed based on this leg mechanism, and its crawling gait planning is carried out. The virtual prototype model of quadruped robot is established in ADAMS, and the motion simulation of the robot is carried out to verify the stability of its motion.

## 2. The quadruped robot based on closed-chain walking leg mechanism

The principle of the closed-chain walking leg mechanism is shown in figure 1. The crank-rocker mechanism is used to provide the main force for the movement of the leg mechanism. When it rotates, the crank will drive the connecting rod up and down and produce a certain degree of swing, which provides the main motive mode and motive force for the leg mechanism. If the connecting rod is lengthened in reverse, the trajectory of the end of the connecting rod is close to that of the foot of the robot leg mechanism. In addition, the crank-slider mechanism is used to adjust the length of legs. The concrete realization process is that one end of the crank in the crank-slider is fixed on the connecting rod of the crank-rocker mechanism. When the crank rotates, the slider moves along the connecting rod, which to adjust the length of the leg. During the movement of the robot, different walking effects can



be achieved by adjusting the length of the legs. The designed leg mechanism is a planar linkage mechanism with two degrees of freedom. The trajectory of the foot can be adjusted by the rotation angle of the crank to meet the motion requirements of the leg mechanism of the foot robot.

Based on the above leg mechanism, a quadruped robot is designed as shown in figure 2. The leg mechanism of the designed robot is a two-degree-of-freedom closed-chain mechanism, which can complete the motion in the plane. In addition, the freedom bogie connected to the body rotates around the z-axis, and the robot can move in all directions in space.

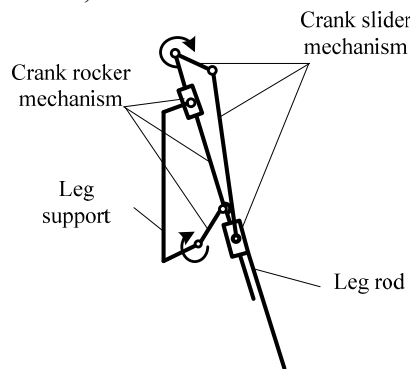


Figure 1. The closed-chain walking leg mechanism

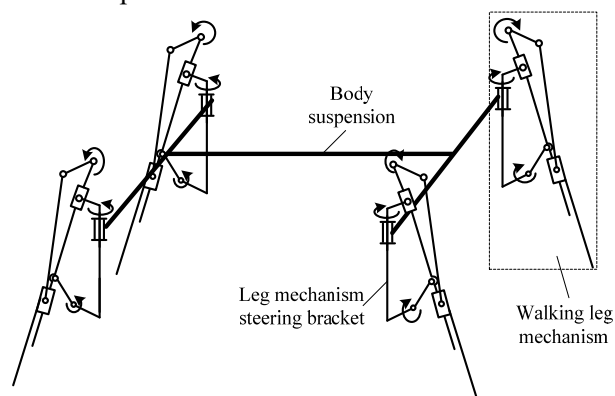


Figure 2. The quadruped robot based on closed-chain walking leg mechanism

### 3. Gait planning of the quadruped robot

Gait planning is the basis of robot control. The robot motion is mainly realized by the leg mechanism according to the set motion mode to complete the periodic motion. Gait planning directly determines whether the robot can keep stable and flexible in the process of walking, and it will also affect the continuity of the whole motion and the mobility of the robot [8]. When the gait is determined, the speed, direction and stability of the robot will be determined.

The gait of a robot moving in a static equilibrium state becomes a static balanced gait, that is, the robot has at least three legs in contact with the ground ( $\beta > 0.75$ ), which is also known as a crawling gait. The four-foot crawling gait has six different order of swinging legs, namely 1234, 1243, 1324, 1342, 1423 and 1432. When 1423 is used as the swing order of the crawling gait, the robot has the largest stability margin [9]. Therefore, this paper takes the leg swing order of 4231 (or 1423) as the walking order of crawling gait. After determining the order of swing legs in the crawling gait of the robot, it is necessary to divide a whole motion cycle into several sub-cycles, corresponding to the swing and support phases of each leg respectively. Before dividing the cycle, it is necessary to determine whether the robot crawls continuously or intermittently during the crawling process.

During the continuous crawling process, there is no separately divided sub-cycle of the center of gravity movement, and the center of gravity movement is completed in the single leg lifting process of the robot. Intermittent crawling separately divides the sub-cycle of the center of gravity movement, designs the stage of four legs supporting at the same time to ensure the center of gravity movement, and does not actively adjust the position of the center of gravity of the robot in the process of single leg lifting [10].

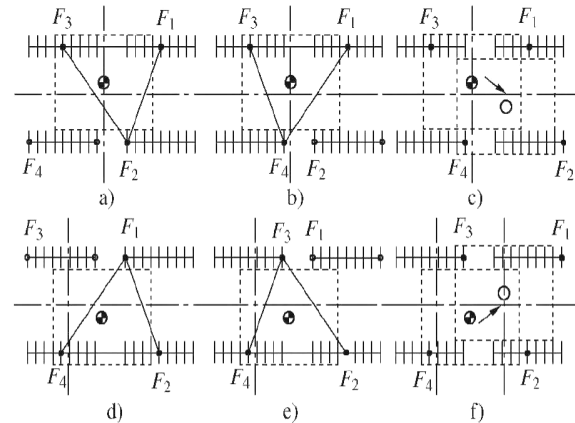
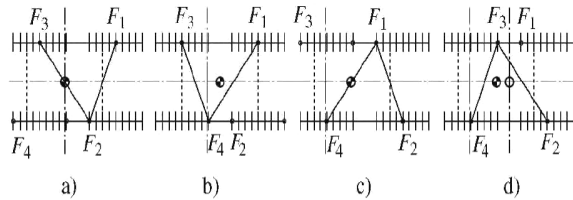


Figure 3. Continuous crawling stability diagram      Figure 4. Intermittent crawling stability diagram

Due to the lack of the adjustment action of the center of gravity, the stability of the robot is poor in the course of motion, and the critical state of the tilting of the robot occurs when the COG point falls on the stable triangular side line composed of the foot end. In this state, the robot is operated in this state, and the instability phenomenon can be caused by the slight influence of the external environment. For the critical instability state of the continuous crawling gait, the intermittent crawling gait with high stability is designed. In the middle of the robot's step, the sub-cycle of center of gravity adjustment is added to ensure that the COG point of the robot is always in the stable triangle composed of the landing foot. This kind of gait is relatively stable, can better adapt to the rugged road, and is not easy to fall.

Considering comprehensively, in order ensuring the stability of the quadruped robot in the process of motion, it is decided to adopt intermittent crawling gait to realize the crawling motion. In order to achieve intermittent crawling, a motion cycle is divided into six sub-cycles, which realize the swing of four legs and the two adjustment of the robot centroid. The walking time and sequence of the legs in the six sub-cycles are shown in Figure 5. The solid line represents the foot landing and the blank represents the lifting.

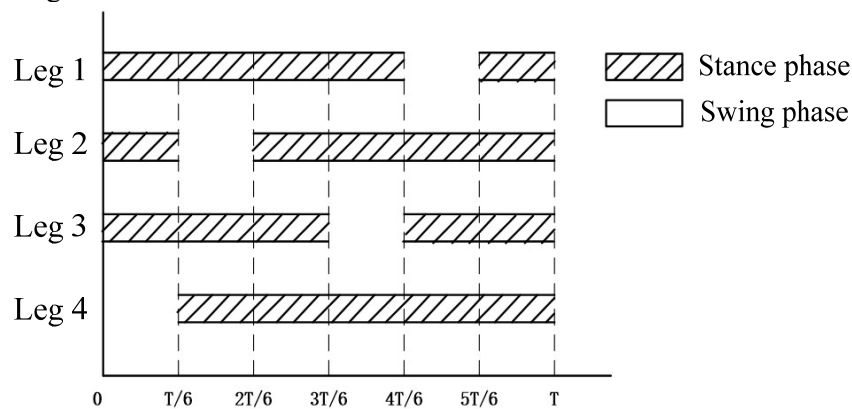


Figure 5. Intermittent crawling gait leg sequence diagram

## 4. Motion simulation of the quadruped robot

### 4.1. Simulation parameters setting

The basic design parameters of the quadruped robot are shown in table 1. For kinematics simulations and kinetic analysis, only physical parameters such as mass and centroid of the model need to be considered. In order to reduce the workload of modeling and simulation, the joint parts are simplified according to the requirements of the designed model. The virtual prototype model of the quadruped robot is finally established, as shown in figure 6 .

Table 1. Basic parameters of the leg mechanism

Parameters	Length /Angle
Main closed chain crank	47mm
Main closed chain rocker	230mm
Secondary-closed-chain crank	60mm
Secondary closed-chain slider connecting rod	150mm
Leg rod	348mm
Leg support	190mm
Initial rotation Angle $\alpha$ of the main closed-chain Crank	$0^\circ$
Initial rotation Angle $\beta$ of Secondary closed-chain Crank	$0^\circ$

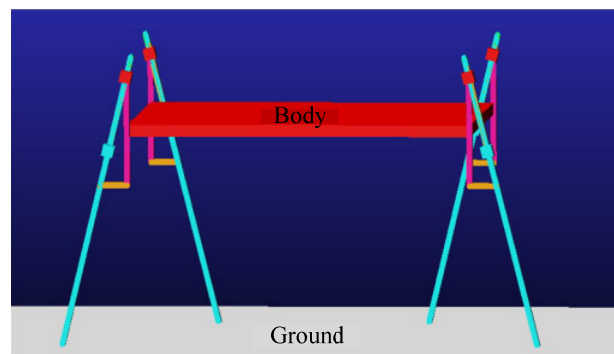


Figure 6. Virtual prototype model of quadruped robot

According to the gait planning, the two drives of the leg mechanism are designed in ADAMS software. Since the initial posture of the leg mechanism model is not the initial posture of the designed gait, the first is the leg posture adjustment and then to design the driving function according to the planning of the step sequence. Because the moving speed of the swing phase and the support phase is different, the driving function step5 is used in ADAMS, as shown in Table 2.

Table 2. Crawling gait driving function

Joint	Motion function
leg1- $\alpha$	step5(time,0,-90d,1,-90d)+step5(time,2,0d,3,-36d)+step5(time,3,0d,4,-36d)+step5(time,4,0d,5,-36d)+step5(time,5,0d,6,-36d)+step5(time,6,0d,7,-36d)+step5(time,7,0d,8,-180d)
leg2- $\alpha$	step5(time,0,162d,1,162d)+step5(time,2,0d,3,-36d)+step5(time,3,0d,4,-36d)+step5(time,4,0d,5,-180d)+step5(time,5,0d,6,-36d)+step5(time,6,0d,7,-36d)+step5(time,7,0d,8,-36d)
leg3- $\alpha$	step5(time,0,-126d,1,-126d)+step5(time,2,0d,3,-36d)+step5(time,3,0d,4,-36d)+step5(time,4,0d,5,-36d)+step5(time,5,0d,6,-36d)+step5(time,6,0d,7,-180d)+step5(time,7,0d,8,-36d)
leg4- $\alpha$	step5(time,0,126d,1,126d)+step5(time,2,0d,3,-36d)+step5(time,3,0d,4,-180d)+step5(time,4,0d,5,-36d)+step5(time,5,0d,6,-36d)+step5(time,6,0d,7,-36d)+step5(time,7,0d,8,-36d)

Table 2 only lists the driving function of the rotation angle  $\alpha$  of the main closed-chain crank, and the drive of the secondary closed-chain crank is calculated according to  $\beta=2\alpha$  and simulated in the model. Table 1- $\alpha$  represents the rotation angle of the main closed-chain crank of the first leg.

In order to accurately reflect the overall motion of the robot, it is particularly important to set the simulation attributes about contact force between the foot and the ground, as shown in Table 3.

Table 3. Simulation attributes about contact force

Attributes name	Value
Static Coefficient	2.0
Dynamic Coefficient	2.1
Stiffness/(N/mm)	100000
Force Exponent	2.2

Damping/(N.s/mm)	10000
Penetration Depth/(mm)	0.1
Stiction Transition Velocity/(mm/s)	10
Friction Transition Velocity/(mm/s)	100

#### 4.2. Analysis of simulation results

The crawling gait of the quadruped robot is simulated in ADAMS. The simulation time is 8s, including 2s posture adjustment and 6s period crawling motion. The crawling gait simulation screenshot (not including the 2s posture adjustment) is shown in figure 7. In figure 8,  $x$  direction is forward direction of robot,  $y$  direction is vertical direction,  $z$  direction is left and right direction of robot. It can be seen from the curves in the figure that the robot begins to crawl after adjusting its posture, and after completing a crawling cycle, the center of mass of the body moves about 280 mm in the direction of advance, while there is periodic fluctuation in the vertical direction, but basically maintained on the designed body height 400mm. Through the numerical curve, it can be seen that the robot will have a certain amount of left and right sloshing in the course of crawling, but ultimately it can basically maintain in the direction set, that is to say, it can basically meet the demand of straight line forward.

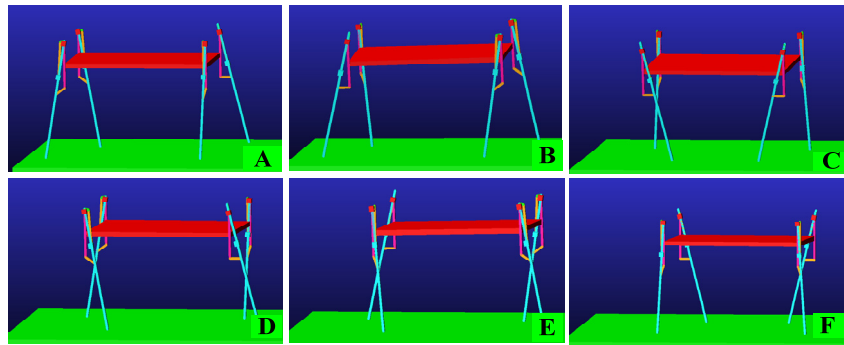


Figure7. Crawling gait simulation screenshot

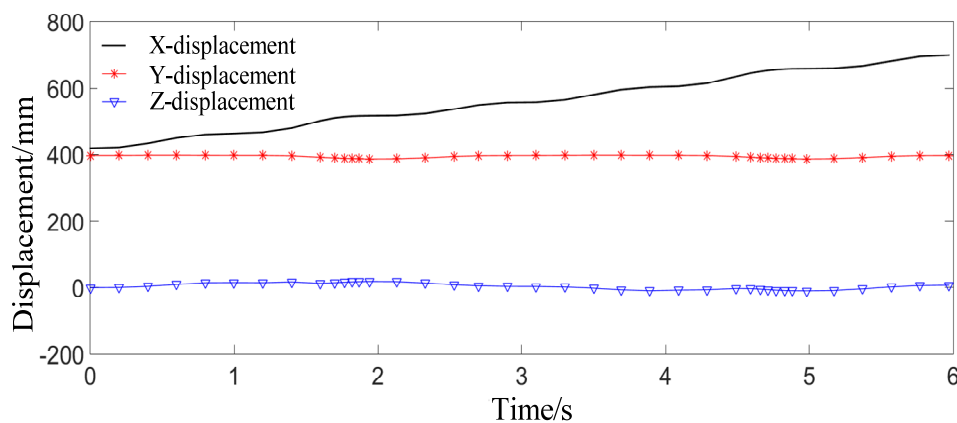


Figure 8. The XYZ direction displacement of body centroid

The displacement fluctuation of the body center in the  $y$  direction directly reflects the stability of the robot motion. The displacement data of the center of mass in the  $y$  direction are extracted and analyzed separately. As can be seen from figure 9, the center of mass fluctuates periodically in the vertical direction, the maximum value is about 398mm, the minimum value is about 387mm, and the wave momentum is about 11mm, accounting for 2.75% of the total height of the robot. This shows that the robot has a certain fluctuation in the process of motion, but it remains stable in general.

According to the displacement data of xyz in three directions, we can see that the robot can keep the stability of the body and the accuracy of movement in the course of crawling.

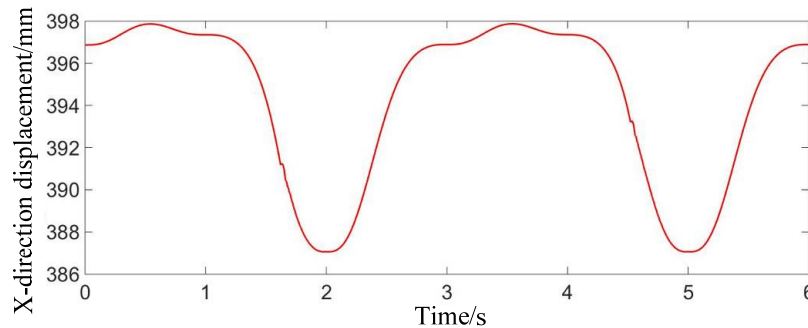


Figure 9. The y-direction displacement curve of the body centroid at the time of crawling

By extracting the velocity of the centroid in the three directions of xyz, the curve graph is obtained, as shown in figure 10. The velocity of robot xyz fluctuates periodically in all three directions, which is consistent with the six sub-cycles of crawling gait programming. The average velocity of the center of mass X direction (forward direction) is 45.7 mm/s, which belongs to slow walking. It can be seen from the figure that the high frequency fluctuation of the velocity in the three directions of xyz occurs at the time of 1.5s~2.0s. Through the observation of the simulation process, this is due to the impact phenomenon of the robot's front legs during landing, which causes the overall vibration of the body. However, because the foot trajectory of the leg mechanism is decelerated at the joint of the support phase and the swing phase, and the impact distance between the foot and the ground is relatively short, the velocity change caused by the impact does not exceed the overall motion speed of the robot, so the impact on the overall motion of the robot is relatively small.

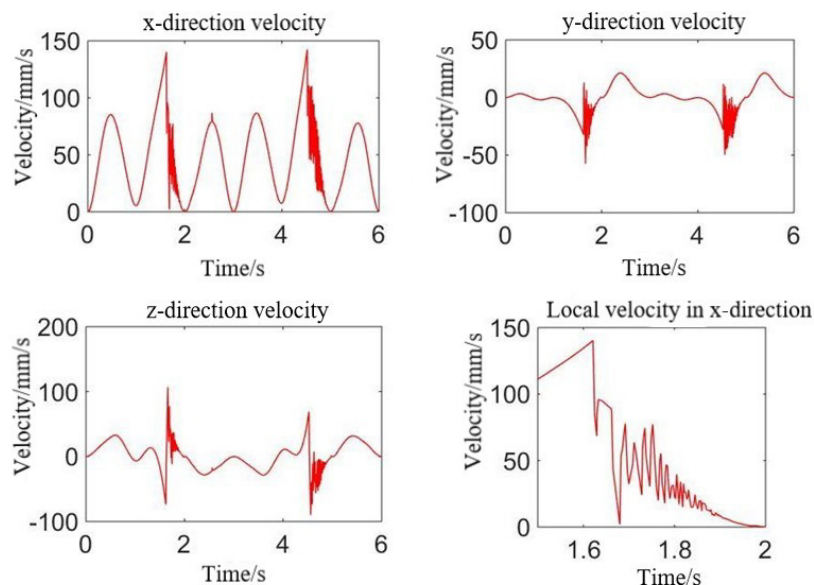


Figure 10. Velocity in the centroid of the body in the direction of xyz

After the crawling simulation, we analyze the trajectory and velocity of the foot end of the robot, which is helpful to improve the configuration of the foot end in the later stage. The left hind leg is taken as an example to study the foot end trajectory and foot end velocity. The data of foot end trajectory is extracted from ADAMS software. The trajectory curve of the crawling foot in figure 11 is

in the global coordinate system, so the trajectory curve is a composite trajectory of the foot relative to the body motion and the body self-motion. The foot end trajectory of two crawling cycles is shown in figure 11. According to the curve data, the distance of the foot moving in the forward direction is about 276 mm in each cycle, and the height of the foot is about 81 mm. It can be found in figure 11 that there is a small transverse displacement of the foot end in each initial stage, which is caused by the vibration of the foot landing during the crawling process of the robot, which is consistent with the vibration generated during the crawling process obtained from the previous analysis.

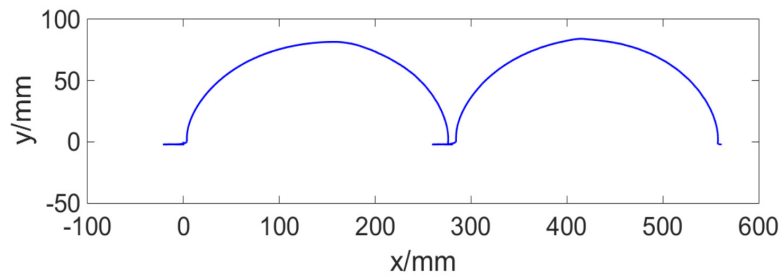


Figure 11. Foot end trajectory

From Figure 12, we can see that the speed of the foot is basically kept at 0. During the period of 4~5s, the speed of the foot changes greatly, but eventually returns to 0. This is consistent with our planned crawling gait, with the foot end swinging at 4~5s and supporting at other times. However, in the period of 1.5~2s and 4.5~5s, the foot end velocity changes frequently and irregularly, which is caused by the vibration of the unstable foot landing during the crawling process. The result is consistent with the motion analysis of the body.

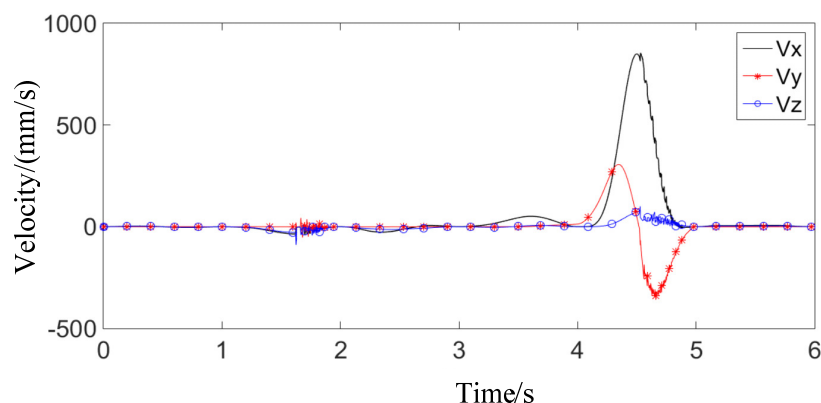


Figure 12. The xyz direction velocity at the foot end

## 5. Conclusion

Based on the principle of four-bar mechanism, a kind of double closed-chain leg mechanism is proposed in this paper. On this basis, a quadruped robot is constructed, and the crawling gait of the robot is planned. According to the crawling gait planning, the virtual prototype model of the quadruped robot is established, and the motion simulation experiment of the robot is carried out by using ADAMS to obtain the centroid and foot end trajectory of the robot. The simulation results show that the crawling process of the quadruped robot with double closed-chain leg mechanism is smooth.

## Acknowledgments

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