# Analysis and Experiment of a Bioinspired Multimode Octopod Robot 

Hongzhe Sun ${ }^{1}$, Chaoran Wei ${ }^{2}$, Yan-an Yao ${ }^{1}$ and Jianxu Wu ${ }^{1 *}$


#### Abstract

Legged robots use isolated footholds to support, which have the merit of good terrain trafficability but lack speed ability. In contrast, wheeled robots have the advantages of high speed and efficiency but only run on flat roads. To improve the moving speed and terrain adaptability of the legged robot, this paper proposes a bioinspired multimode octopod robot with rolling, walking, and obstacle-surmounting modes. First, inspired by the multimode locomotion of the Cebrennus rechenbergi spider, the high-speed mobility of the legged robot is realized in involute kick-rolling mode through the extendable appendages. Then, the foot and appendage trajectories are analyzed by kinematic method and optimized for walking stability. Based on the static and the kinematic analyses, the terrain adaptability is improved by adhesive obstacle-surmounting mode with the assistance of the appendages affiliated to the main feet. The deformable trunk with one DoF is designed to switch between three modes. Finally, a series of dynamic simulations and experiments are carried out to verify the theoretical analyses of the adhesive obstacle-surmounting mode and the mobility of the involute kick-rolling mode. It is shown that the multimode octopod robot can integrate the advantages of high speed and good terrain trafficability from different types of robots and is suitable for performing tasks in unstructured terrains.


Keywords Octopod robot, Bioinspired robot, Close-chain leg mechanism, Adhesive obstacle-surmounting strategy, Involute kick-rolling strategy

## 1 Introduction

In complex working environments, wheeled and legged robots are gradually playing two important roles. The former have the merits of high moving efficiency, simple structure, light weight, and low energy consumption [1], and are often used in structured roads for highspeed transportation. Legged robots adopt isolated footholds to provide support and traction [2, 3], which endow them with two advantages: high mobility and terrain adaptability. For instance, the leg of BigDog is characterized by four active DoFs and a passive DoF

[^0][4]. HyQ and its upgraded version HyQ2Max have three DoFs per leg which are actuated by large torque motors and have wide range motion with joints $[5,6]$. Baby elephant robot adopts motor-combined hydraulic actuators and three passive DoFs on the ankle to support a bigger payload and adapt to complex terrains $[7,8]$. However, complicated structures also bring the problems of high curb weight, control difficulty, and failure rate. Compared with open-chain legged robots, closed-chain legged robots are more suitable for reducing weight and simplifing the drive system [9-11]. Wu et al. [12] proposed an eight-legged vehicle with a simple control system to improve the obstacle-surmounting ability through its reconfigurable legs.
In the field of the obstacle-surmounting, openchain legged robots can lift their legs to walk above the obstacle. Au-Spot is motivated by exploring the extreme environment and is capable of surmounting the obstacle
of 400 mm ( 0.5 times body height) [13]. ANYmal Beth and its posterity ANYmal B have fully rotary joints, which enable their feet to rise high above the ground for crossing large obstacles of 350 mm ( 0.5 times body height) [14-16]. In our previous researches, robots with closed-chain leg mechanism are designed to surmount obstacles through geometric variation methods of the leg or trunk mechanism. Wu et al. [17] proposed a novel sixteen-legged vehicle with a reconfigurable leg mechanism to heighten the foot trajectory for surmounting. Ruan et al. [18] developed a multi-legged robot with pitch adjustive units that can lift the front legs in obstacle-surmounting mode.
However, the obstacle-surmounting ability can be further improved from the mechanism, and the obstaclecrossing strategy of wheeled vehicles is to convert the contact force with the ground into traction force. Sun et al. [19] studied the obstacle-surmounting performance of sand milling vehicles, and found that whether the vehicle can cross the step depends on the traction force of the wheels. Zhou et al. [20] developed an all-terrain eight-wheel robot that can climb the vertical obstacle higher than itself through rotatable waist and traction force. Xu et al. [21] designed a magnetic adhesion robot with passive suspension and 6 wheels that is able to run on magnetic walls with different dip angles and cross 5 mm weld seam. He et al. [22] proposed a horse-inspired eight-wheeled vehicle driven by distributed hydraulic motors that can climb the obstacle like a horse with the help of four-swing arms and the friction of the wheels.
In the field of high-speed movement, wheeled robots have better performance [23-25]. Unlike many robots whose wheels are arranged on the sides of the trunk, some novel robots can deform the entire body into a cylinder and roll on the ground. Kim et al. [26] proposed a spherical mobile robot with an elastic external frame, and it is driven by a pendulum placed in the center. Lee et al. [27] built a robot that is actuated by an unbalanced mass-shifting mechanism rotated by two motors, and the imbalance induced by the weight makes the robot roll. Wait et al. [28] proposed a spherical robot driven by a novel deformable pneumatic method consisting of many inflatable rubber bladders covering the sphere. Inspired by Cebrennus rechenbergi spider, Prof. Rechenberg and his team developed four generations of robots that have a cylindrical shape and can roll by kicking the ground quickly with legs [29].
In order to combine the merits of legged and wheeled robots, many researchers proposed a series of multimode robots that can both roll and walk by switching the modes. Phipps et al. [30, 31] developed a bipedal planar robot that complements its walking and climbing capabilities with rolling. He et al. [32, 33] designed a
wheel-legged rover that uses four wheels instead of the feet, and can switch different actuating strategies to adapt to regular or irregular terrains. A low-cost quadruped robot proposed by Wang et al. [34] is able to walk in complex terrains and use backflip strategy for self-recovery. Sun et al. [35] designed a robot with walking, scrolling, and crawler modes that can be actively switched. Based on the reconfigurable 8-bar trunk, Zhao et al. $[36,37]$ proposed a multi-mimicry quadruped robot that can transform between reptile-, arthropod-, and mammal-like modes. BionicWheelBot, designed by the Festo company in Germany, is a representative model as an example of the combination of the wheeled and legged robots [38]. It has eight legs, six for crawling and two multi-link legs for rolling powered by wire ropes.
To better integrate the advantages of wheeled and legged robots, and reduce the complexity of the mode switching process, based on a closed-chain legged mechanism, a bioinspired multimode octopod robot with three modes is proposed. In terms of obstaclesurmounting ability, the maneuvering performance is further improved by the adhesive obstacle-surmounting strategy and the attachment mechanism. That is, the robot can climb the obstacles higher than itself with the help of the surface friction force of the obstacles and its appendages. On the other hand, to achieve a high-speed movement, the involute kick-rolling gait through the appendages was proposed and inspired by the flic-flac spider [39].

The remaining part of the paper is organized as follows. Section 2 describes the layout of the robot and presents three motion modes. Section 3 carries out the kinematic analysis and the optimization of the leg and appendage trajectories. The theoretical analyses of two motion modes are discussed in Section 4 to verify the feasibility. A series of dynamic simulations of the robot are conducted in Section 5 to test the adhesive obstaclesurmounting and the involute kick-rolling strategies. Subsequently, an experimental prototype is fabricated in Section 6 to verify the practicability and performance of the proposed robot. Finally, Section 7 concludes the research.

## 2 Mechanism Design

In this section, the layout design of the robot and its deformable trunk are discussed and presented. To exert the linkage advantages, the closed-chain leg and the appendage mechanisms with one actuated degree of freedom are proposed.

### 2.1 The Layout Design of the Robot

To significantly reduce the DoF of the robot, the whole closed-chain legged octopod robot is proposed, and the
modes switching is designed to correspond with the trunk deformation. As displayed in Figure 1, the robot consists of a single DoF deformable trunk (4-bar linkage), eight planar close-chain legs (6-bar linkage) and four appendages (4-bar linkage). Each pair of adjacent legs is a legged unit with a crank phase difference of $180^{\circ}$. Fourlegged units are driven by one drive motor arranged in the middle of the rear trunk. The pitch angles of legged units will be adjusted with the trunk deformation simultaneously by two planar 4-bar linkages to switch different modes. To achieve the kick-rolling mode, the trunk and the front-legged units are equipped with roll cages, which assist in deforming the whole robot into a cylinder.
The legged units of the rear trunk can move together with four appendages, which are fixed on the links of the legs group as submodules. The appendages can improve the obstacle-surmounting ability and achieve kickrolling ability by kicking on the ground. The appendages are divided into two types: the interior type and the exterior type. Both types are used to walk in the
obstacle-surmounting mode, but only the exterior type is used in the kick-rolling mode.

### 2.2 Deformable Trunk Design

The robot can switch into different modes by using the electric pushing rod to adjust the pitch angle of the trunk. The lengths of the pushing rod are $340 \mathrm{~mm}, 299.32$ mm , and 220 mm , respectively, corresponding to the obstacle-surmounting mode, walking mode, and kickrolling mode. The maximum range of the pitch angle is $150^{\circ}$. Three modes are illustrated in Figure 2, and the leg mechanism is simplified as one link in the schematic diagram of the mechanism.
The angle between the front-legged units and trunk and the angle between the rear-legged units and trunk can be adjusted with the deformation of the robot through two designed planar 4-bar mechanisms. In walking mode, the values of $\theta_{b}, \theta_{p}$ and $\theta_{f}$ are $90^{\circ}, 180^{\circ}$ and $90^{\circ}$, respectively. In obstacle-surmounting mode, the front legs are raised to walk on the vertical wall, so the values of the three angles


Figure 1 Layout design of the robot


Figure 2 Three modes of the robot: $\mathbf{a}$ Walking mode, $\mathbf{b}$ Obstacle-surmounting mode, $\mathbf{c}$ Kick-rolling mode
are $60^{\circ}, 240^{\circ}$ and $150^{\circ}$, respectively. The values of the three angles are $120^{\circ}, 90^{\circ}$ and $72^{\circ}$, respectively, to make the whole robot curls up into a cylinder in kick-rolling mode.

## 3 Kinematic Analysis and Optimization Design

In this section, the kinematics analysis of the leg mechanism and the appendage mechanism are taken through vector loop method. Then the optimized foot trajectory and the appendage extension trajectory are obtained by dimensional synthesis and inverse kinematic methods, respectively.

### 3.1 Leg Mechanism Kinematic Analysis and Optimization

The Watt-I linkage [40], as a planar 6-bar closed-chain mechanism, is designed to be the leg mechanism. Its vector loop diagram is illustrated in Figure 3b, and $r_{i}$ represents the link vector. The coordinate frame $O-x y$ is established at the crank's rotation center, and $x$-axis coincides with the horizontal direction.
The vector loops of the leg mechanism are formulized as Eqs. (1) and (2):

$$
\begin{align*}
& \boldsymbol{r}_{0}+\boldsymbol{r}_{2}+\boldsymbol{r}_{5}+\boldsymbol{r}_{1}=0  \tag{1}\\
& \boldsymbol{r}_{7}+\boldsymbol{r}_{8}+\boldsymbol{r}_{6}+\boldsymbol{r}_{4}=0 \tag{2}
\end{align*}
$$

In the two ternary links composed of $r_{2}, r_{3}, r_{4}$ and $r_{8}, r_{9}$, $r_{10}$ :

$$
\begin{equation*}
\theta_{i j}=\cos ^{-1} \frac{r_{i}^{2}+r_{j}^{2}-r_{j+1}^{2}}{2 r_{i} r_{j}},(i, j)=(2,3),(8,9) \tag{3}
\end{equation*}
$$

In Eq. (3), $\theta_{i j}$ represents the angle between $r_{i}$ and $r_{j}$. $\theta_{i}(i=1,2 \ldots, 10)$ represents the angle between $r_{i}$ and the horizontal direction of the $x$-axis, and they can be obtained by solving the Eqs. (4) to (6):


$$
\begin{align*}
& \theta_{i}=2 \tan ^{-1}\left(\frac{p_{i 2}+\sqrt{p_{i 1}^{2}+p_{i 2}^{2}-p_{i 3}^{2}}}{p_{i 1}-p_{i 3}}\right) i=2,7,  \tag{4}\\
& \theta_{i}=2 \tan ^{-1}\left(\frac{p_{i 2}-\sqrt{p_{i 1}^{2}+p_{i 2}^{2}-p_{i 3}^{2}}}{p_{i 1}-p_{i 3}}\right) i=5,8,  \tag{5}\\
& \theta_{i}=\theta_{j}+\theta_{i j}(i, j)=(3,2),(9,8) . \tag{6}
\end{align*}
$$

The related intermediate variables are shown in Eqs. (7) and (8):

$$
\left[\begin{array}{lll}
p_{21} & p_{22} & p_{23}  \tag{7}\\
p_{51} & p_{52} & p_{53} \\
p_{71} & p_{72} & p_{73} \\
p_{81} & p_{82} & p_{83}
\end{array}\right]=\left[\begin{array}{ccc}
2 r_{5} q_{21} & 2 r_{5} q_{51} & q_{21}^{2}+q_{51}^{2}-q_{71} \\
-2 r_{2} q_{21} & -2 r_{2} q_{51} & q_{21}^{2}+q_{51}^{2}+q_{71} \\
2 r_{8} q_{22} & 2 r_{8} q_{52} & q_{22}^{2}+q_{52}^{2}-q_{72} \\
-2 r_{7} q_{22} & -2 r_{7} q_{52} & q_{22}^{2}+q_{52}^{2}+q_{72}
\end{array}\right],
$$

$$
\left[\begin{array}{ll}
q_{21} & q_{22}  \tag{8}\\
q_{51} & q_{52} \\
q_{71} & q_{72}
\end{array}\right]=\left[\begin{array}{cc}
r_{0} \cos \theta_{0}-r_{1} \cos \theta_{1} & r_{4} \cos \theta_{4}-r_{6} \cos \theta_{6} \\
r_{0} \sin \theta_{0}-r_{1} \sin \theta_{1} & r_{4} \sin \theta_{4}-r_{6} \sin \theta_{6} \\
r_{2}^{2}-r_{5}^{2} & r_{7}^{2}-r_{8}^{2}
\end{array}\right] .
$$

Then the trajectory of foot-point $H$ can be calculated in Eq. (9):

$$
\left[\begin{array}{l}
x_{H}  \tag{9}\\
y_{H}
\end{array}\right]=\left[\begin{array}{llll}
\cos \theta_{0} & \cos \theta_{3} & \cos \theta_{7} & \cos \theta_{9} \\
\sin \theta_{0} & \sin \theta_{3} & \sin \theta_{7} & \sin \theta_{9}
\end{array}\right]\left[\begin{array}{l}
r_{0} \\
r_{3} \\
r_{7} \\
r_{9}
\end{array}\right]
$$

Based on kinematics analysis, the initial foot trajectory can be obtained. The two-dimensional optimization of the initial trajectory can be regarded as a nonlinear optimization problem. The trajectory that satisfies the walking demands should be generated, and the walking characteristics are listed below: (1) the lower part of the supporting phase should be as straight as possible; (2) the stride length of the supporting phase should be as long as possible; (3) the vertical variation during the supporting phase should be as small as possible. As shown in Table 1, eight pre-assigned points are used to limit the trajectory. The points of $i=3,4,5$ have the same altitudes, so that the trajectory in the supporting phase can be smooth. The points of $i=1,7,8$ are set to control the height of the foot trajectory. The points of $i$ $=2,6$ are set to control the length of the foot trajectory.
The maximum approximation of the initial points to the pre-assigned points can be obtained by the objective function shown in Eq. (10):

$$
\begin{equation*}
f(x)=\sum_{i=1}^{8}\left[\left(X_{i}-X_{H i}\right)^{2}+\left(Y_{i}-Y_{H i}\right)^{2}\right] \tag{10}
\end{equation*}
$$

Figure 3 a Leg mechanism, and $\mathbf{b}$ vector loop diagram

Table 1 Coordinates of pre-assigned points

| $\boldsymbol{i}$ | $\mathbf{1}$ | $\mathbf{2}$ | $\mathbf{3}$ | $\mathbf{4}$ | $\mathbf{5}$ | $\mathbf{6}$ | $\mathbf{7}$ | $\mathbf{8}$ |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| $\Delta \theta_{0}\left({ }^{\circ}\right)$ | $0^{\circ}$ | $45^{\circ}$ | $90^{\circ}$ | $135^{\circ}$ | $180^{\circ}$ | $225^{\circ}$ | $270^{\circ}$ |  |
| $X_{H i}(\mathrm{~mm})$ | 100 | 110 | 95 | 65 | 18 | -20 | -5 | $-15^{\circ}$ |
| $Y_{\text {Hi }}(\mathrm{mm})$ | -125 | -140 | -150 | -150 | -150 | -140 | -125 | -125 |

Table 2 Optimum values of design variables

| Variables | $r_{0}(\mathrm{~mm})$ | $r_{1}(\mathrm{~mm})$ | $r_{2}(\mathrm{~mm})$ | $r_{3}(\mathrm{~mm})$ | $r_{4}(\mathrm{~mm})$ | $r_{5}(\mathrm{~mm})$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Initial value | 24.17 | 83.21 | 71.20 | 27.03 | 66.36 | 52.06 |
| Optimal value | 25.23 | 76.37 | 67.61 | 23.84 | 61.89 | 52.02 |
| Variables | $r_{6}(\mathrm{~mm})$ | $r_{7}(\mathrm{~mm})$ | $r_{8}(\mathrm{~mm})$ | $r_{9}(\mathrm{~mm})$ | $r_{10}(\mathrm{~mm})$ | $\theta_{1}(\mathrm{rad})$ |
| Initial value | 32.43 | 59.46 | 59.29 | 72.85 | 119.52 | 0.69 |
| Optimal value | 31.93 | 60.15 | 60.09 | 72.92 | 123.75 | 0.79 |



Figure 4 The optimized foot trajectory
where $\left(X_{H i}, Y_{H i}\right)$ represent the pre-assigned coordinate points of the trajectory. Accordingly, link lengths ( $r_{0}, r_{1} \ldots$, $\left.r_{10}\right)$ and link angle $\left(\theta_{1}\right)$ are the variables of the optimization function Eq. (10).
The initial values and optimal values of link lengths and link angles are listed in Table 2. After optimization, the vertical fluctuation reduces to 12.28 mm , and the stride length increases to 124.15 mm , as displayed in Figure 4.

### 3.2 Appendage Walking Trajectory Kinematic Analysis

As a submodule, the appendage frame is fixed on the $r_{7}$ link of the leg mechanism. The exterior appendage connects to the appendage frame through a link and a revolute joint, shown in Figure 5a, and its kinematic diagram


Figure 5 a Appendage mechanism, b Kinematic diagram of appendage, c Appendage walking trajectory
is displayed in Figure 5b. The whole appendage submodules move with legs together in walking mode, and in obstacle-surmounting mode, they substitute for legs to walk.

In the second stage of obstacle-surmounting mode (described in Section 4.1), the robot uses its extended appendages to walk on the ground. In this mode, the appendages have two main tasks: one is to walk on the ground, and the other one is to put the legged units of the rear trunk above the vertical wall. Therefore, there are two constraints of the appendage trajectory optimization: (1) the stride length should be as long as possible; (2) the extension length of the appendages should be longer than the vertical wall's height. Meanwhile, the mechanical design of the appendages should meet two necessary conditions: (1) the supporting phase should be at the back of the center of gravity; (2) there is a moment when appendages are behind the feet of the rear trunk. The purposes of the two conditions are to prevent the robot from tumbling backward and enable the appendages to put the legged units above the vertical wall without interfering.
The appendage is fixed on $r_{7}$ link so that the foot point $K$ can be defined by parameters $x_{1}, y_{1}$, and $\theta_{k}$, shown in Figure 5 c . The value of $\theta_{k}$ is $48.5^{\circ}$, which is the angle between $r_{7}$ link and the negative direction of $y$-axis when $\theta_{0}$ is $0^{\circ}$. The initial $x_{1}$ and $y_{1}$ are 100 mm and 450 mm , respectively. According to the leg mechanism kinematic


Figure 6 Appendage trajectory

analysis, the appendage trajectory can be established in Eq. (11):
$\left[\begin{array}{l}x_{K} \\ y_{K}\end{array}\right]=\left[\begin{array}{llll}\cos \theta_{0} & \cos \theta_{3} & \cos \left(\theta_{7}-\theta_{k}\right) & \cos \left(\theta_{7}-\theta_{k}+\frac{\pi}{2}\right) \\ \sin \theta_{0} & \sin \theta_{3} & \sin \left(\theta_{7}-\theta_{k}\right) & \sin \left(\theta_{7}-\theta_{k}+\frac{\pi}{2}\right)\end{array}\right]\left[\begin{array}{l}r_{0} \\ r_{3} \\ x_{1} \\ y_{1}\end{array}\right]$.

Based on the four conditions above, the optimal values are $x_{1}=89 \mathrm{~mm}$ and $y_{1}=457 \mathrm{~mm}$. The stride length of the appendage trajectory is 253.80 mm , and the vertical fluctuation is 32.52 mm , as shown in Figure 6.

### 3.3 Appendage Extension Trajectory Kinematic Analysis

During the kick-rolling mode, the robot deforms into a cylinder and uses its extendable exterior appendages to kick on the ground for getting the moving force. The DoF of the rigid appendage mechanism can be determined as follows: $F_{D}=3 w-2 P_{l}-P_{h}-F^{\prime}=1$, where $w, P_{l}, P_{h}$, and $F^{\prime}$ denote the numbers of moving links $(w=4)$, low pairs $\left(P_{l}=5\right)$, high pairs $\left(P_{h}=0\right)$, and local DoFs $\left(F^{\prime}=1\right)$, respectively. In order to achieve excellent rolling performance, the appendage extension trajectory is designed to fit an involute curve. The diagram is shown in Figure 7a.
The appendage kinematic parameters are illustrated in Figure 7 b , and $r_{i}(i=13,14, \ldots, 21)$ represents the link vector. The mechanism is actuated by the extendable link $r_{16}$, which varies from -164.4 mm to 26.6 mm . The $r_{16}$ and $r_{19}$ are associated links, explained in Section 6.2, and their vector difference is 137.8 mm .
The coordinate frame $C-x y$ is set at the roll cage center. The kinematic analysis of this planar mechanism is carried out by using the vector loop method:

$$
\begin{equation*}
\boldsymbol{r}_{13}+\boldsymbol{r}_{14}+\boldsymbol{r}_{15}+\boldsymbol{r}_{16}+\boldsymbol{r}_{17}+\boldsymbol{r}_{18}=\mathbf{0} \tag{12}
\end{equation*}
$$

where $\theta_{i}(i=13,14, \ldots, 21)$ represents the angle between $r_{i}$ and the positive direction of the $x$-axis. The appendage extension trajectory can be calculated as Eq. (13):

$$
\left[\begin{array}{l}
x_{K}^{\prime}  \tag{13}\\
y_{K}^{\prime}
\end{array}\right]=\left[\begin{array}{l}
x_{D} \\
y_{D}
\end{array}\right]+\left[\begin{array}{cc}
\cos \theta_{14} & \sin \theta_{14} \\
\sin \theta_{14} & -\cos \theta_{14}
\end{array}\right]\left[\begin{array}{c}
r_{14}+r_{16}+r_{19}+r_{21} \\
r_{15}+r_{20}
\end{array}\right],
$$


(b)

Figure 7 The diagram of a the extendable appendage and its $\mathbf{b}$ vector loop
where:

$$
\begin{array}{r}
\theta_{13}=\tan ^{-1} \frac{y_{D}-y_{E}}{x_{D}-x_{E}}+2 \pi, l_{D F}=\sqrt{\left(r_{14}+r_{16}\right)^{2}+\left(r_{17}-r_{15}\right)^{2}}, \\
\theta_{14}=\theta_{13}-\cos ^{-1} \frac{l_{D F}^{2}+r_{13}^{2}-r_{18}^{2}}{2 l_{D F} r_{13}}-\tan ^{-1} \frac{r_{17}-r_{15}}{r_{14}+r_{16}} .
\end{array}
$$

According to the scale and the parts of the appendage mechanism, most links' lengths are determined. The position of point $D$ is determined by the length of the appendage and the position of the involute. Then we calculate the length of $r_{18}$ and the coordinate of point $E$. To fit the trajectory with the desired curve, three preassigned points shown in Table 3 are set on the standard involute, used to calculate the unknown variables.
Through pre-assigned points and the appendage's scale, the coordinate of point $F_{i}$ can be obtained as Eqs. (14) and (15):
$\left\{\begin{array}{l}r_{16}+r_{19}=\sqrt{\left(x_{D}-x^{\prime}{ }_{K i}\right)^{2}+\left(y_{D}-y_{K i}^{\prime}\right)^{2}-\left(r_{15}+r_{20}\right)^{2}}, \\ r_{19}-r_{16}=138,\end{array}\right.$


Then, we can obtain the unknown variables ( $r_{18}$ and coordinate of point $E$ ) as Eqs. (16) and (17):

$$
\begin{equation*}
r_{18}=\sqrt{\frac{B^{\prime 2}+C^{\prime 2}-4 A^{\prime} D^{\prime}}{4 A^{\prime 2}}} \tag{16}
\end{equation*}
$$

Table 3 The coordinate of pre-assigned points

| $\boldsymbol{i}$ | $\mathbf{1}$ | $\mathbf{2}$ | $\mathbf{3}$ |
| :--- | :--- | :--- | :--- |
| $x_{K i}^{\prime}(\mathrm{mm})$ | -205.85 | -207.45 | -58.17 |
| $y_{{ }_{K i}(\mathrm{~mm})}$ | -140.68 | -358.57 | -526.93 |

$$
\left[\begin{array}{l}
x_{E}  \tag{17}\\
y_{E}
\end{array}\right]=\left[\begin{array}{l}
-\frac{B^{\prime}}{2 A^{\prime}} \\
-\frac{C^{\prime}}{2 A^{\prime}}
\end{array}\right]
$$

where,

$$
\begin{gathered}
A^{\prime}=\left|\begin{array}{lll}
x_{F 1} & y_{F 1} & 1 \\
x_{F 2} & y_{F 2} & 1 \\
x_{F 3} & y_{F 3} & 1
\end{array}\right|, B^{\prime}=-\left|\begin{array}{lll}
x_{F 1}^{2}+y_{F 1}^{2} & y_{F 1} & 1 \\
x_{F 2}^{2}+y_{F 2}^{2} & y_{F 2} & 1 \\
x_{F 3}^{2}+y_{F 3}^{2} & y_{F 3} & 1
\end{array}\right|, \\
C^{\prime}=\left|\begin{array}{lll}
x_{F 1}^{2}+y_{F 1}^{2} & x_{F 1} & 1 \\
x_{F 2}^{2}+y_{F 2}^{2} & x_{F 2} & 1 \\
x_{F 3}^{2}+y_{F 3}^{2} & x_{F 3} & 1
\end{array}\right|, D^{\prime}=-\left|\begin{array}{lll}
x_{F 1}^{2}+y_{F 1}^{2} & x_{F 1} & y_{F 1} \\
x_{F 2}^{2}+y_{F 2}^{2} & x_{F 2} & y_{F 2} \\
x_{F 3}^{2}+y_{F 3}^{2} & x_{F 3} & y_{F 3}
\end{array}\right| .
\end{gathered}
$$

The variables' values are calculated and shown in Table 4. The appendage extension trajectory is drawn in Figure $8 . \Delta h$ is the deviation between the trajectory and the standard involute curve, whose maximum value is 1.85 mm .

In the walking mode, the appendage extension mechanism will move together with the movement of the rear-legged unit. Therefore, before the kick-rolling motion, we should rotate the crank to a specified angle $\left(343^{\circ}\right)$ to make the base circle of the extension involute coincide with the roll cage.


Figure 8 Appendage extension trajectory

Table 4 Values of design variables

| Variables | $r_{13}$ | $r_{14}$ | $r_{15}$ |  | $r_{17}$ |  | $r_{18}$ | $r_{20}$ | $r_{21}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Value (mm) | 172.97 | 210.50 | 18.00 |  | 40.00 |  | 134.46 | 18.00 | 210.50 |
| Variables | $x_{D}$ | $y_{D}$ |  | $X_{E}$ |  | $y_{E}$ |  | $r_{16}$ | $r_{19}$ |
| Value (mm) | -100.84 | 84.44 |  | 24.42 |  | -34.84 |  | $\begin{aligned} & -164.4 \\ & \text { to } 26.6 \end{aligned}$ | $\begin{aligned} & -26.6 \\ & \text { to } 164.4 \end{aligned}$ |

## 4 Multimode Motion Analysis

In this section, the force and dynamic analyses of the two modes are developed to verify their feasibility. The analysis results determine the structure and control system design.

### 4.1 Adhesive Obstacle Surmounting Strategy

In our previous work, the obstacle-surmounting strategy of the closed-chain legged robots adopted the geometric variation method to adjust the pitch angle of the legged units [20]. In this method, the robot is capable of surmounting the obstacle of 0.5 times its height without the aid of the obstacle's friction.
To further improve the obstacle-surmounting ability, the adhesive obstacle-surmounting strategy is proposed, which can be divided into two stages as shown in Figure 9. The first stage (states 1 to 3 ) is the adhesive obstacle-surmounting stage. The robot lifts the front legs perpendicular to the vertical wall, and then the drive motor starts to work. The front legs are pressed on the vertical wall through the friction between the ground and the rear legs so that the front legs can walk upward along the vertical wall until it is higher than the wall. In this stage, the pitch angle of the robot will increase by $12^{\circ}$ to $15^{\circ}$. The stride of the two steps will decrease from 248.3 mm to 189.8 mm , and the height of the leg raise will increase from 22 mm to 42 mm under this condition.
In the second stage (states 4 to 7 ), the appendages gradually extend to lift the trunk and then substitute for the rear legs to walk on the ground. Meanwhile, the front legs are walking on the vertical wall with an inevitable slippage due to stride difference and the position of the robot's centroid, which is located on the rear trunk. Because the appendages' length is longer than the vertical wall's height, the rear legs can be put on the wall when
appendages come to the wall. Then the robot contracts its appendages, and walks on the vertical wall.
Next, the feasibility study of the first stage is carried out to analyze the influence of the robot's centroid in the obstacle-surmounting process. To simplify the model, we assume that the sliding between the feet and the ground, the deformation of the feet, and the effects of the feet impulse can be ignored. The force model is established and shown in Figure 10. The rear legs of the robot contact the ground at point $P$, and the front legs contact the vertical wall at point $Q$. The coordinate frame $P$-xy is set, and the $x$-axis coincides with the $P Q$ 's line segment.
In Figure $10, N_{1}$ and $N_{2}$ denote the supporting forces on the rear legs and front legs, respectively. $T_{1}, T_{2}$ and $F_{f 1}, F_{f 2}$ represent the traction forces and rolling resistances of the rear legs and front legs, respectively. $G$ is the total gravity of the robot, whose coordinate is $\left(L_{x}, L_{y}\right) . L_{d}$ is the length of line segment $P Q$, and $\beta_{p}$ is the angle between it and the ground, which gradually increases with the progress of the first stage. The whole motion is slow, so the force model can be analyzed through a static equilibrium equation as Eq. (18):

$$
\begin{cases}\sum F_{x}=0, & T_{1}-N_{2}-F_{f 1}=0,  \tag{18}\\ \sum F_{y}=0, & T_{2}+N_{1}-F_{f 2}-G=0, \\ & \left(T_{1}-F_{f 1}\right)\left(L_{x} \sin \beta_{p}+L_{y} \cos \beta_{p}\right) \\ & +\left(T_{2}-F_{f 2}\right)\left[\left(L_{d}-L_{x}\right) \cos \beta_{p}+L_{y} \sin \beta_{p}\right] \\ \sum M_{G}=0, & -N_{1}\left(L_{x} \cos \beta_{p}-L_{y} \sin \beta_{p}\right) \\ & +N_{2}\left[\left(L_{d}-L_{x}\right) \sin \beta_{p}-L_{y} \cos \beta_{p}\right]=0 .\end{cases}
$$

The rolling resistance $F_{f i}$ can be expressed as Eq. (19):

(g) State 7

Figure 9 Adhesive obstacle-surmounting strategy


Figure 10 Force analysis of state 1

$$
\begin{equation*}
F_{f i}=N_{i} f_{i} \tag{19}
\end{equation*}
$$

where $f_{i}$ is the rolling resistance coefficient between legs and the ground. Effective traction $T_{i}$ should be satisfied:

$$
\begin{equation*}
T_{i} \leq N_{i} \varphi_{i} \tag{20}
\end{equation*}
$$

where $\phi_{i}$ is adhesion coefficient. According to Eq. (20), another form of effective traction $T_{i}$ can be written as follows:

$$
\begin{equation*}
T_{i}=\delta_{i} N_{i} \varphi_{i} \tag{21}
\end{equation*}
$$

where $\delta_{i}$ is effective traction coefficient, $\delta_{i} \in[0,1]$.
Substituting Eqs. (19) and (21) into Eq. (18), then we can reach Eq. (22) after rearranging in matrix form:

$$
\begin{equation*}
L U N=M \tag{22}
\end{equation*}
$$

where,

$$
\begin{gathered}
\boldsymbol{L}=\left[\begin{array}{cc}
1 & 0 \\
0 & 1 \\
L_{x} \mathrm{~S} \beta_{p}+L_{y} \mathrm{C} \beta_{p} & \left(L_{d}-L_{x}\right) \mathrm{C} \beta_{p}+L_{y} \mathrm{~S} \beta_{p} \\
0 & -1 \\
1 & 0 \\
& \cdots \\
& -\left(L_{x} \mathrm{C} \beta_{p}-L_{y} \mathrm{~S} \beta_{p}\right) \\
\boldsymbol{U}= & \left(L_{d}-L_{x}\right) \mathrm{S} \beta_{p}-L_{y} \mathrm{C} \beta_{p}
\end{array}\right], \\
{\left[\begin{array}{cc}
\delta_{1} \varphi_{1}-f_{1} & 0 \\
0 & \delta_{2} \varphi_{2}-f_{2} \\
1 & 0 \\
0 & 1
\end{array}\right], \boldsymbol{N}=\left[\begin{array}{l}
N_{1} \\
N_{2}
\end{array}\right], \boldsymbol{M}=\left[\begin{array}{l}
0 \\
G \\
0
\end{array}\right] .}
\end{gathered}
$$

For convenience calculation, we assume that $\delta_{1}=\delta_{2}$ $=\delta, \phi_{1}=\phi_{2}=\phi, f_{1}=f_{2}=f$. To achieve the motion, the torque of the anticlockwise direction of the robot should be greater than or equal to the torque in the clockwise direction, so Eq. (22) can be solved as an inequality:

$$
\begin{equation*}
L_{x}-L_{y} \tan \beta_{p} \leq \frac{(\delta \varphi-f)^{2}+(\delta \varphi-f) \tan \beta_{p}}{(\delta \varphi-f)^{2}+1} L_{d} \tag{23}
\end{equation*}
$$

It can be seen from Eq. (23) that the parameters containing forces such as $G, N$, and $T$ can be eliminated.

Therefore, whether the adhesive obstacle-surmounting mode can be achieved has nothing to do with the robot's gravity, but relates to the centroid's position, pitch angle, and influence coefficients. The value of $\delta$ can be obtained from the Adams ${ }^{\text {TM }}$ simulation. Because of the vertical fluctuation, it varies between 0.8 and 1, which is calculated as 0.9 in the formula. On dry roads, the rolling resistance coefficient $f$ is 0.01 [41]. The adhesion coefficient $\phi$ is the main influence coefficient, which is determined by the materials of the robot's feet, road surface, and other factors.
When the line segment $P Q$ takes the unit length $L_{d}=1$, and $\phi=0.9$, the boundary conditions of the robot's pitch angles $\beta_{p}$ relative to the centroid position are illustrated in Figure 11a. We can see that when the pitch angle $\beta_{p}$ is $0^{\circ}$, the area on the left side of the vertical line can satisfy the condition of the centroid position, and when $\beta_{p}$ is $50^{\circ}$, the area on the left side of the oblique line can satisfy the condition. In order to satisfy the position condition of centroid at any pitch angle, the feasible region should be


Figure 11 The boundary conditions of a robot's pitch angles $\beta_{p}$ relative to centroid position and $\mathbf{b}$ the adhesion coefficients $\varphi$ between the feet and the obstacle relative to robot's centroid position


Figure 12 Force analysis of the involute kick-rolling strategy
selected as the intersection of all areas, which is the area on the left side of the line of $0^{\circ}$.
Then we draw the boundary conditions of the adhesion coefficients $\phi$ between the feet and the obstacle relative to robot's centroid position in the case of $L_{d}=1$ and $\beta_{p}=0^{\circ}$, as shown in Figure 11b. According to modelling analysis, the coordinate of the robot's centroid is $(0.32,0.25)$, so the adhesion coefficient $\phi$ should meet the condition of greater than 0.72 to enable the robot to complete the adhesive obstacle-surmounting stage. Therefore, the feet of the robot are made of rubber material to increase the adhesion coefficient.
robot's centroid determine the size of the acceleration torque. The other is the actuation duration of the force $F_{k}$, determining the final speed of the robot.

Considering the above factors, the involute kick-rolling strategy in Figure 12 is designed. We assume that the appendages extend along the involute and the robot takes a pure rolling movement. In that case, the appendages will contact with the ground at a fixed point, and cause static friction. During the process, the appendages cannot kick the ground from the starting point of the involute, but should kick from the middle of the involute. Because the driving torque can be generated only when point $K$ is to the left of point $G$. The acceleration of the robot can be controlled by adjusting the force $F_{k}$.
Next, the force analysis model of the robot is developed to calculate the value of the force $F_{k}$ under the designated acceleration and the translational velocity of the appendage Bowden cable (described in Section 6.2).
The robot is simplified as a cylindrical rigid body with radius $R$. The coordinate frame is set at the robot's center $C$, and the $x$-axis is oriented horizontally. Point $G$ is set at the centroid of the robot. Value $e$ and $\theta_{e}$ denote the eccentric distance and initial angular of point $G$, respectively. The robot and the appendages contact the ground at points $B$ and $K$, respectively. The robot will make a pure rolling motion under the actuation of the kicking force $F_{k}$ from the appendage. Establish the dynamic equations of the model as Eq. (24):

$$
\left\{\begin{array}{l}
m \ddot{x}=\sum F_{x}, m\left[a_{c}+\omega^{2} e \sin \left(\theta_{e}+\theta_{a}\right)-\alpha_{c} e \cos \left(\theta_{e}+\theta_{a}\right)\right]=F_{S 1}+F_{S 2}  \tag{24}\\
m \ddot{y}=\sum F_{y}, m\left[\omega^{2} e \cos \left(\theta_{e}+\theta_{a}\right)+\alpha_{c} e \sin \left(\theta_{e}+\theta_{a}\right)\right]=F_{k}+F_{N}-m g \\
I \ddot{\theta}=\sum M_{G}, I_{G} \alpha_{c}=F_{k}\left[l_{1}-e \sin \left(\theta_{e}+\theta_{a}\right)\right]-\left(F_{S 1}+F_{S 2}\right)\left[R-e \cos \left(\theta_{e}+\theta_{a}\right)\right]
\end{array}\right.
$$

### 4.2 Involute Kick-rolling Strategy

In involute kick-rolling mode, the robot can curl up into a cylinder, and then roll by extending the appendages to kick the ground. The appendages should keep touching the ground for a while until the robot rolls for a distance. During this process, the rolling driving force comes from the ground friction.
The kicking force $F_{k}$ can be divided into a torque and a force act at the centroid of the robot. There are two main factors that can affect the rolling performance. One is the force $F_{k}$, whose value and distance from the
where $a_{c}=\ddot{x}_{a}, \alpha_{c}=\ddot{\theta}_{a}$, and $\omega=\dot{\theta}_{a}$ are the horizontal acceleration, angular acceleration, and angular velocity, respectively. $F_{k}$ and $F_{N}$ are the supporting forces of the ground. $F_{S 1}$ and $F_{S 2}$ are the frictions on the appendages and the robot, respectively. $l_{1}$ is the distance between point $B$ and point $K . I_{G}$ is the moment of inertia of the robot rotating around point $G$. From the pure rolling motion, there should be:

$$
\left\{\begin{array}{l}
I_{G}=m \rho^{2}  \tag{25}\\
a_{c}=\alpha_{c} R
\end{array}\right.
$$

where $\rho$ is the inertia radius. The acceleration of the robot can be obtained as Eq. (26):

$$
\begin{equation*}
a_{c}=\frac{\left(F_{k} / m\right)\left[l_{1}-e \sin \left(\theta_{e}+\theta_{a}\right)\right]-\omega^{2} e \sin \left(\theta_{e}+\theta_{a}\right)\left[R-e \cos \left(\theta_{e}+\theta_{a}\right)\right]}{\rho^{2}+\left[R-e \cos \left(\theta_{e}+\theta_{a}\right)\right]^{2}} R . \tag{26}
\end{equation*}
$$

The kicking force can be obtained as Eq. (27):
Next, we calculate the linear velocity of the appendage

$$
\begin{equation*}
F_{k}=m \frac{\omega^{2} e \sin \left(\theta_{e}+\theta_{a}\right)\left[R-e \cos \left(\theta_{e}+\theta_{a}\right)\right]+\alpha_{c}\left\{\rho^{2}+\left[R-e \cos \left(\theta_{e}+\theta_{a}\right)\right]^{2}\right\}}{l_{1}-e \sin \left(\theta_{e}+\theta_{a}\right)} \tag{27}
\end{equation*}
$$

The supporting force $F_{N}$ should be greater than or equal to zero. Substitute into Eq. (26), we can get the initial length of $l_{1}$ has a minimum value as Eq. (28). According to the friction formula $F_{S 1}+F_{S 2} \leq \mu\left(F_{k}+F_{N}\right)$, where $\mu$ is the static friction coefficient, we can get the robot's acceleration has a maximum value as Eq. (29). The robot will slip if it moves beyond this acceleration.

Bowden cable. Firstly, the length of $l_{1}$ is computed as Eq. (30) and shown in Figure 13a.

$$
\begin{equation*}
l_{1}=l_{0}+x_{a}=l_{0}+\frac{1}{2} a_{c} t^{2} \tag{30}
\end{equation*}
$$

Secondly, the other form of appendage foot $K$ coordinate

$$
\begin{equation*}
l_{1} \geq \frac{\alpha_{c}\left\{\rho^{2}+\left[R-e \cos \left(\theta_{e}+\theta_{a}\right)\right]^{2}\right\}+\omega^{2} e \sin \left(\theta_{e}+\theta_{a}\right)\left[R-e \cos \left(\theta_{e}+\theta_{a}\right)\right]}{g+\omega^{2} e \cos \left(\theta_{e}+\theta_{a}\right)+\alpha_{c} e \sin \left(\theta_{e}+\theta_{a}\right)}+e \sin \left(\theta_{e}+\theta_{a}\right) \tag{28}
\end{equation*}
$$

$$
\begin{equation*}
a_{c} \leq \frac{\mu g+\omega^{2} e\left[\mu \cos \left(\theta_{e}+\theta_{a}\right)-\sin \left(\theta_{e}+\theta_{a}\right)\right]}{R-e\left[\cos \left(\theta_{e}+\theta_{a}\right)-\mu \sin \left(\theta_{e}+\theta_{a}\right)\right]} R . \tag{29}
\end{equation*}
$$

According to the modelling analysis, we can obtain that $\rho=0.63 R, e=0.045 \mathrm{~m}, \theta_{e}=92.30^{\circ}$. Based on the scale and mechanical design of the robot, the values of other variables are $R=0.24 \mathrm{~m}, m=12.87 \mathrm{~kg}, l_{0}=0.10 \mathrm{~m}$, and we set a constant value of the acceleration $a_{c}=0.5 \mathrm{~m} / \mathrm{s}^{2}$.


Figure 13 Curves of $\mathbf{a} l_{1}$ and $V_{L^{\prime}} \mathbf{b} F_{k}$ and its power
can be expressed as Eq. (31):

$$
\left[\begin{array}{l}
x^{\prime}{ }_{K}  \tag{31}\\
y_{K}^{\prime}
\end{array}\right]=\left[\begin{array}{cc}
\sin \theta_{a} & -\cos \theta_{a} \\
-\cos \theta_{a} & -\sin \theta_{a}
\end{array}\right]\left[\begin{array}{l}
R \\
l_{1}
\end{array}\right] .
$$

Finally, according to Figure 7b and Eq. (31), the linear velocity of the Bowden cable $\left(V_{L}\right)$, which is also the derivative of $r_{16}$ length to $t$, can be calculated as Eq. (32) and illustrated in Figure 13a. We should pull the cable to obey the $V_{L}$ velocity to make the robot roll at the designated acceleration $a_{c}$.

$$
\begin{equation*}
V_{L}=\frac{d r_{16}}{d t}=\frac{d \sqrt{\left(x_{K}^{\prime}-x_{D}\right)^{2}+\left(y_{K}^{\prime}-y_{D}\right)^{2}-\left(2 r_{15}\right)^{2}}}{2 d t} \tag{32}
\end{equation*}
$$

The kicking force $F_{k}$ can be computed based on Eq. (27) and shown in Figure 13b with its power, which can be obtained as Eq. (33):

$$
\begin{equation*}
P_{F k}=F_{k} l_{1} \omega=F_{k} l_{1} \frac{a_{c} t}{R} \tag{33}
\end{equation*}
$$



Figure 14 Force analysis in rolling phase

After the kick-rolling process, the robot will continue to roll with an initial velocity. However, due to the deviation of the centroid, the robot's velocity would not change steadily. To calculate its velocity curve, the force analysis of the rolling phase is established, as shown in Figure 14.
At this stage, the kinetic energy theorem is used to calculate the robot's velocity. The rolling kinetic energy of the robot can be decomposed into the translational kinetic energy and the rotational kinetic energy around the center point C, calculated in Eq. (34):

$$
\begin{equation*}
E_{k}=\frac{1}{2} I_{c} \omega^{2}+\frac{1}{2} m v_{c}^{2}=\frac{1}{2} m \omega^{2}\left(\rho^{2}+e^{2}+R^{2}\right) \tag{34}
\end{equation*}
$$

Taking the horizontal height of point $C$ as the potential energy zero, the gravity potential energy of the robot is obtained as Eq. (35):

$$
\begin{equation*}
E_{p}=-m g e \cos \theta \tag{35}
\end{equation*}
$$



Figure 15 The velocity image of the kick-rolling mode's whole process

According to the initial velocity of the robot, the initial mechanical energy possessed by the robot can be calculated as follows: $E_{0}=E_{k 0}+E_{p 0}$. So, the kinetic energy theorem formula is established as Eq. (36):

$$
\begin{equation*}
\frac{1}{2} m \omega^{2}\left(\rho^{2}+e^{2}+R^{2}\right)=E_{0}+m g e \cos \theta \tag{36}
\end{equation*}
$$

By solving Eq. (36), the angular velocity can be calculated as Eq. (37):

$$
\begin{equation*}
\omega=\sqrt{\frac{2\left(E_{0}+m g e \cos \theta\right)}{m\left(\rho^{2}+e^{2}+R^{2}\right)}} . \tag{37}
\end{equation*}
$$

Order $\theta$ takes 360 values for every interval $\Delta \theta=1^{\circ}$ starting from $\theta_{0}$, which are named $\theta_{i}(i=0,1, \ldots, 359)$, then the $\omega_{i}(i=0,1, \ldots, 359)$ can be calculated through Eq. (37). Because the angle difference corresponding to two adjacent $\omega_{i}$ is $1^{\circ}$, the time interval can be calculated from the quotient of angle and angular velocity, as shown in Eq. (38):

$$
\left\{\begin{array}{c}
t_{0}=0  \tag{38}\\
t_{i+1}=t_{i}+\frac{1^{\circ}}{\omega_{i}},
\end{array} \quad i=0,1 \ldots, 359 .\right.
$$

Then the time $t_{i}$ corresponding to the angular velocity $\omega_{i}$ can be obtained. Finally, the robot's velocity $v_{c i}$ in the rolling phase corresponding to time $t_{i}$ can be calculated through the formula $v_{c i}=\omega_{i} r,(i=0,1, \ldots, 359)$. For a more accurate calculation result, the value of interval angle $\Delta \theta$ can be taken as $0.1^{\circ}$ or less. The speed-time graph combining the kicking and rolling phases is illustrated in Figure 15.

## 5 Dynamic Simulation

In this section, we constructed a dynamic model in Adams ${ }^{\text {TM }}$ to verify the theoretical analysis and performance characteristics. The model was 755 mm


Figure 16 Adhesive obstacle-surmounting simulation


Figure 17 a Contact force of front legs and $\mathbf{b}$ Rear legs (or appendages), c Crank torque and $\mathbf{d}$ Pitch angle, e Pushing force of rod and $\mathbf{f}$ Actuating force of appendages
long, 590 mm wide, and 340 mm high, and the weight was 12.87 kg . The simulation parameters included gravity coefficient ( $9.8 \mathrm{~m} / \mathrm{s}^{2}$ ), contact stiffness ( $30 \mathrm{~N} /$ $\mathrm{mm})$, contact damping ( $1.5 \mathrm{Ns} / \mathrm{mm}$ ), dynamic coefficient (0.7) and static coefficient (0.72). The contact force, pitch angle, and motor torque were measured in adhesive obstacle-surmounting mode. The speeds and kicking forces in different accelerations were calculated in involute kick-rolling mode.

### 5.1 Adhesive Obstacle Surmounting Simulation

To test the obstacle-surmounting ability, a 350 mm high stair was set in the simulation, which was higher than the robot itself. The process is shown in Figure 16, consistent with the theoretical analysis. It can be seen that the platform can overcome obstacles successfully. The vertical projection of the centroid on the ground is always located in the convex polygon formed by touchdown points of the front and rear legs or appendages.

The front and rear legs are driven simultaneously by rotational motion act on the crank, and the motion speed is set as $30 \mathrm{r} / \mathrm{min}$. The appendages and the trunk deformation are controlled by linear motion. As shown in Figure 16, the robot deformed its trunk to obstaclesurmounting mode during 2 to 4 s .4 to 6.6 s is the first stage described in Section 4.1, and the robot surmounted
the stairs by the traction force between the legs and the ground. In the second stage ( 6.6 to 10 s ), the robot walked with appendages instead of rear legs. The timing of the extension of the appendages is essential, and it needs to coordinate with the timing of the trunk deformation. Eventually, the robot contracted its appendages during 10 to 12 s . The contact force between legs (or appendages) and ground (or obstacle) are illustrated in Figures 17a, b. At the same time, the crank torque and


Figure 18 The pitch angles under different adhesion coefficients $\varphi$
the pitch angle of the robot are illustrated in Figures 17c, d. The pushing force of the rod and the actuating force of appendages are also displayed in Figures 17e, f. It can be seen that the contact forces and motor torque increased a lot in the first and second stages. From the test, the maximum height that the robot can surmount is 352 mm , depending on the lengths of the appendages and trunk. The robot can also surmount the wall below 352 mm , and the appendages only need to extend to a suitable length according to the height of the wall to assist the obstaclesurmounting motion.
Then, we tested the robot's obstacle-surmounting performance under different adhesion coefficients and recorded the pitch angles of the front trunk. They started from about $30^{\circ}$ due to the trunk deformation before the climbing stage. As depicted in Figure 18, the increase of the pitch angle curves slows down with the reduction of the adhesion coefficient $\phi$. Consistent with the result in the motion analysis, only if the adhesion coefficient is greater than 0.70 can the robot cross the obstacle.

### 5.2 Involute Kick-rolling Simulation

To explore a high-speed movement strategy, the involute kick-rolling mode is put forward and test the performance. The robot is tested in different designated accelerations by adjusting the Bowden cable velocity, which is explained in Section 4.2. As shown in Figure 19, the robot deforms into a cylinder and rolls by pushing off the ground with its appendages. After one acceleration, the drag spring quickly contracts the appendages, and the robot still rolls for a distance. To consecutive rolling, the robot needs to kick the ground again to get another acceleration after rotating for a circle. It is significant to kick at the appropriate timing. The speed curves and kicking forces of each acceleration test are shown in Figures 20a, b.
From the speed curves, we can see that the robot can move faster than walking. But this mode can only act on relatively smooth terrains. We also tested the robot to roll on the slopes. On downward slopes whose angle is greater than $3^{\circ}$, the robot can roll continuously without pushing off the ground repeatedly. In terms of the upslopes, the maximum angle that the robot can roll is $5^{\circ}$.


Figure 19 Involute kick-rolling simulation


Figure 20 Curves of $\mathbf{a}$ speeds and $\mathbf{b}$ kicking forces


Figure 21 Experimental prototype

Table 5 Parameters of the prototype

| Parameter | Value |
| :--- | :--- |
| Dimensions $\left(\mathrm{mm}^{3}\right)$ | $755 \times 590 \times 340$ |
| Weight $(\mathrm{kg})$ | 12 |
| Voltage $(\mathrm{V})$ | 24 |
| Drive motor speed (r/min) | 30 |
| Pushing rod force (N) | 1100 |
| Main material | Carbon fiber |
| Foot material | Rubber |

## 6 Prototype and Experiment

Based on the mechanical structure design, a prototype was designed to verify its mobility, and the parts processing, component, and testing instrument selection were completed. Meanwhile, the experiments of the two modes were finished to test the robot's performance.

### 6.1 The Layout Design of the Prototype

As shown in Figure 21, the prototype consists of four closed-chain legged units. For lightweight design, the trunk frame, the legged units, and the appendages are made of carbon fiber. The feet and the roll cage are made of rubber to increase the friction. The drive system contains a DC reduction motor (DH-03X-38Nm) installed on the rear trunk, five synchronous belts, and two cardan shafts, which connect the drive motor and the cranks. A DC electric pushing rod (BORSB-1100N-120mm) is installed between the front and the rear trunk to control the deformation and modes switching. In addition, we installed a steering engine (GX3345BLS) to control the robot turning, which can rotate the front-legged units $17^{\circ}$ left and right. The robot cannot turn in the rolling mode because the left and right roll cages and the appendages are designed symmetrically. In terms of the control system, a microcontroller (Arduino ${ }^{\circledR} \mathrm{UNO}$ ) was installed in the middle of the rear trunk to control the drive motor, the electric pushing rod, the steering engine, and two servo motors (GX3380BLS), which are used to adjust the


Figure 22 a Mechanism design of appendage, $\mathbf{b}$ Appendage control module design and $\mathbf{c}$ Appendage model
extension of the appendages. The whole robot is powered by a lithium battery ( $6 \mathrm{~s}-3300 \mathrm{mah}$ ) fixed on the rear trunk. The parameters of the prototype are illustrated in Table 5.

### 6.2 The Mechanical Design of the Appendage

The mechanism of the appendage consists of the first, the second, and the third sections, which are connected through two sliders and two slide rails, as shown in Figure 22a. A steel rope, which wounds around four pulleys installed on both ends of the second section, links the first and third sections to realize the associated motion of the three sections. The exterior appendage extension trajectory is an involute curve. The interior appendage does not participate in the kick-rolling mode, and its extension trajectory is a straight line. To reduce the mass of the appendage mechanism, the control module, which is composed of two servo motors and two capstans, is placed on the rear trunk shown in Figure 22b. It could extend the appendage by pulling the Bowden cable, including a wire and a tube. Two ends of the tube are fixed on the first section and the tube fixture, respectively, and two wire ends are fastened on the second section and the capstan, respectively. In obstacle-surmounting mode, the first servo motor's shaft connects the capstan and spins around twice clockwise or anticlockwise to extend or contract four appendages. In kick-rolling
mode, the second servo motor drives the actuating arm to push the passive block fixed on the other capstan around for extending the exterior appendages. Because of the ball screw, the capstan will move away from the motor, and the passive block will dislocate with the actuating arm after rotating one circle. As a result, the capstan will immediately turn back to the initial angle under the pulling force from a drag spring whose two ends are fixed on the second and third sections of the appendage, respectively.

### 6.3 Adhesive Obstacle-surmounting Experiment

In this experiment, we verified the robot's obstacle-surmounting ability. As depicted in Figure 23, a 350 mm high block was set in front of the robot on the PVC floor, which is the maximum obstacle-surmounting height in theoretical analysis. Then we used the remote control to manipulate the robot switch into obstacle-surmounting mode. The front trunk of the robot will not touch the ground in state two because two rollers are installed on the rear trunk, as shown in Figure 2b. It can be seen that the robot can lift its front legs to climb the vertical obstacle through the friction, and use its appendages to walk and support the trunk. The whole motion is the same as it performed in the simulation.


Figure 23 Adhesive obstacle-surmounting experiment


Figure 24 Involute kick-rolling experiment


Figure $\mathbf{2 5}$ Curves of $\mathbf{a}$ speeds and $\mathbf{b}$ kicking forces

### 6.4 Involute Kick-rolling Experiment

In this experiment, we verified the robot's kick-rolling ability on the PVC floor. As depicted in Figure 24, the robot deformed into a cylinder through its roll cage and front legs, and then extended its appendages to push off the ground for rolling. The cylinder's cross-section is not a complete circle because it uses the gap to determine the starting and ending posture. It means that the robot touches the ground by the gap before rolling, and after the robot rolls for one circle, it will end rolling because of the resistance from the gap.
However, if the robot extends its appendages again at appropriate timing, it can continue rolling. During the rolling, we measured the kicking force between appendages and ground with a thin-film pressure sensor (FSR406) and recorded the speed of the robot with a nine-axis gyro sensor (BWT901CL). The data are shown in Figure 25, and we can see the comparison with theoretical analysis and simulation. In the experiment, the robot can roll $0.8 \mathrm{~m} / \mathrm{s}$ on average, which is 1.06 times the length of the body and much faster than walking ( 0.12 $\mathrm{m} / \mathrm{s}$ ).

## 7 Conclusions

(1) To combine abilities of high-speed movement and adaptability in rough terrain, this paper proposed a bioinspired multimode octopod robot with walking, obstacle-surmounting, and rolling modes switched by the trunk deformation. To improve the control simplicity and integral rigidity, the robot uses the planar closed-chain linkage as the trunk and leg mechanism.
(2) The involute kick-rolling mode was proposed inspired by the Cebrennus rechenbergi spider that enhances the robot's moving speed on flat ground.
(3) The adhesive obstacle-surmounting mode, which can help the robot climb vertical obstacles through the friction of the obstacle, was put forward to improve the terrain adaptability.
(4) As the submodule of the main foot, the appendage mechanism with one DoF is designed. It can extend along the involute to kick the ground or substitute for the rear legs to walk, which assists the robot in completing two proposed modes.
(5) The kinematic analyses of the leg and appendage mechanisms were carried out. The feasibility of two motion modes was verified by establishing the mathematical models. The dynamic simulations were conducted to obtain the contact force, motor torque, and pitch angle of the obstacle-surmounting mode and the moving speed and kicking force of the rolling mode.
(6) Finally, an experimental prototype, including the mechanical, drive, and control system, was fabricated and tested to verify practicability and performance. The results show that the robot can roll $0.8 \mathrm{~m} / \mathrm{s}$, which is 1.06 times the length of the body, and can surmount the obstacle of 350 mm , which is higher than itself.

## Acknowledgements

Not applicable.

## Author contributions

HS was in charge of the whole mechanical design, assembly and drafted the manuscript. CW and HS were in charge of the prototype experiments. JW provided the core idea and modified the manuscript with CW and YY. YY also
provided the necessary equipment and sites for experiments. All authors read and approved the final manuscript.

## Authors' Information

Hongzhe Sun, born in 1996, is currently a MPhil candidate at Beijing Jiaotong University, China. He received his bachelor's degree from Shenyang Agriculture University, China, in 2019. His research interests include mechanical design and mobile robotics.
Chaoran Wei, born in 1994, is currently a researcher at Beijing Institute of Contro Engineering, China. He received his PhD degree from Beijing Jiaotong University, China, in 2022. His research interests include mechanisms and mobile robotics. Yan-an Yao, born in 1972, is currently a professor and a PhD candidate supervisor at Beijing Jiaotong University, China. He received his PhD degree from Tianjin University, China, in 1999. His research interests include mechanical design and robotics.
Jianxu Wu, born in 1989, is currently a lecturer at Beijing Jiaotong University, China. He received his PhD degree from Beijing Jiaotong University, China, in 2019. His research interests include mechanism design and robotics.

## Funding

Supported by National Natural Science Foundation of China (Grant No. 52205007).

## Declarations

## Competing Interests

The authors declare no competing financial interests.

Received: 23 September 2022 Revised: 12 October 2023 Accepted: 19 October 2023
Published online: 28 November 2023

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[^0]:    *Correspondence:
    Jianxu Wu
    wujx@bjtu.edu.cn
    ${ }^{1}$ School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China
    ${ }^{2}$ Beijing Institute of Control Engineering, Beijing 100190, China

