Mechanism Design and Kinematics Analysis of Spider-like Octopod Robot

Zihao Yang1,2, Minghai Yuan1,2, Xinhui Shi1, Zenan Yang1,2 and Mengyuan Li1

1 College of Mechanical and Electrical Engineering, Hohai University Changzhou, China
2 Jiangsu Key Laboratory of Special Robot Technology Changzhou, China

Abstract: Based on the study of spider motion, a spider-like Octopod robot is proposed and its forward and inverse kinematics are analyzed. The position of the end of the mechanical leg in space at certain joint angles and the rotation angles of each joint when the end of the mechanical leg is positioned in space can be obtained.

1. Introduction

As the most important branch of robotics, mobile robots are composed of tracked robots, wheeled robots and foot robots [1]. Tracked robots and wheeled robots have the advantages of stable structure and fast speed, but they have high requirements for the ground, poor flexibility, and can not adapt to rough roads and muddy marshes. In some specific working environments, people urgently need a kind of robot which can move stably, flexibly and theoretically reach any point on the ground. From this point of view, people put their research focus on bionics, hoping to inspire design inspiration from animals in nature and develop intelligent, stable and reasonably structured robotic systems by imitating animal motion and control mechanism, thus replacing human beings in various dangerous, complex and unpredictable environments to complete tasks [2]. Foot robots were born and quickly became the focus of academic research.

Octopod robots have great research value. At present, the research on quadruped and hexapod robots by scholars at home and abroad also provides important reference for the research of Octopod robots.

2. Mechanism Design

Mechanism design is the most basic design of the robot. The mechanism design of the spider-like Octopod robot is mainly divided into the overall mechanism design and the foot mechanism design.

2.1. The overall mechanism design

Based on the analysis and simplification of the spider body structure, a spider-like Octopod robot shown in Figure 1 is proposed. The trunk of the robot is a regular octagon, and the eight legs of the robot are located on the eight vertices of the regular octagon. The structure of each foot is exactly the same.
2.2. The foot mechanism design

The structure of the mechanism legs is shown in Figure 2. Each leg consists of three steering engines, three steering gear brackets and an imitation tibia connecting rod. One end of the first steering gear bracket is fixed on the trunk, and the other end is fixed with the first steering engine. The rotation axis of the first steering engine is perpendicular to the plane of the trunk. The rotation axis of the first steering engine is connected with one end of the second steering gear bracket to form a rotating pair, which forms the root joint of the mechanical leg. The other end of the second steering gear bracket is fixed with the second steering gear. The rotation axis of the second steering gear is parallel to the plane of the trunk. The rotation axis of the second steering engine is connected with one end of the third steering gear bracket to form a rotating pair, which forms the hip joint of the mechanical leg. The other end of the third steering gear bracket is fixed to the third steering engine, and the rotation axis of the third steering engine is parallel to the plane of the trunk. The rotation axis of the third steering gear is connected with the imitation tibia connecting rod to form a rotating pair, which forms the knee joint of the mechanical leg. The second steering gear bracket is the root of the mechanical leg. The third steering gear bracket is the femur of the mechanical leg. The imitation tibia connecting rod is the tibia of the mechanical leg.

The degree of freedom of an open kinematic chain is equal to the sum of the degrees of freedom of all the kinematic pairs in the kinematic chain. Each of the legs mentioned above has three joints composed of rotating pairs and is driven by three steering engines. The degree of freedom of the kinematic chain is equal to the number of driving parts, so each of the legs has a definite movement in space.
3. Kinematics Analysis

Kinematics analysis is an important basis for gait planning and stability analysis of spider-like Octopod robot. The proposed spider-like Octopod robot has 24 degrees of freedom, of which each leg has 3 degrees of freedom. The kinematics analysis of the spider-like Octopod robot is essentially to find the relationship between the spatial position of the foot end of each leg and the three joint angles. The eight legs of the spider-like Octopod robot presented in this paper are identical in structure and evenly distributed on the trunk. The kinematics equations of the eight legs are identical in form and structure, but the parameters are different in different spatial positions and motion states. Therefore, only one of the legs needs to be kinematically analyzed.

Kinematics analysis is divided into forward kinematics analysis and inverse kinematics analysis. In order to facilitate the forward and inverse kinematics analysis of the mechanical leg, the D-H coordinate system as shown in Figure 3 is established. \( O_0 - x_0 y_0 z_0 \) is fixed on the trunk, \( O_1 - x_1 y_1 z_1 \) is fixed on the root, \( O_2 - x_2 y_2 z_2 \) is fixed on the femur and \( O_3 - x_3 y_3 z_3 \) is fixed on the tibia. The origins of the coordinate systems are at the heel joint, hip joint, knee joint and foot end, respectively. The X-axis points to the extension direction of the rod, the Z-axis points to the rotation direction of the joint, and the Y-axis is perpendicular to the corresponding X-axis and Z-axis, which constitute the right-hand coordinate system. \( \theta_1, \theta_2, \theta_3 \) are the rotation angles of root joint, hip joint and knee joint, respectively. \( l_1, l_2, l_3 \) are the lengths of root, femur and tibia, respectively.

3.1. Forward kinematics analysis

Forward kinematics analysis refers to solving the space position of the foot end of the mechanical leg and obtaining the forward kinematics equations when the rotation angles of the three joints are known. By analyzing the above D-H coordinate systems, the following homogeneous transformation matrices are obtained:

\[
R_{01} = \begin{bmatrix}
    \cos \theta_1 & 0 & \sin \theta_1 & l_1 \cos \theta_1 \\
    \sin \theta_1 & 0 & -\cos \theta_1 & l_1 \sin \theta_1 \\
    0 & 1 & 0 & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]
Inverse Kinematics Analysis refers to solving three joint rotation angles and obtaining inverse kinematics equations when the spatial position of the foot end of the mechanical leg is known.

The coordinates of the foot end in the coordinate system $O_3x_3y_3z_3$ are $(0, 0, 0)$, so:

\[
\begin{bmatrix}
\cos \theta_1 \cos \theta_2 + \theta_3 & -\cos \theta_1 \sin \theta_2 & \sin \theta_1 (l_1 + l_2 \cos \theta_2 + l_3 \cos(\theta_2 + \theta_3)) \cos \theta_1 \\
\sin \theta_1 \cos \theta_2 + \theta_3 & -\sin \theta_1 \sin \theta_2 & -\cos \theta_1 (l_1 + l_2 \cos \theta_2 + l_3 \cos(\theta_2 + \theta_3)) \sin \theta_1 \\
0 & 0 & l_2 \sin \theta_2 + l_3 \sin(\theta_2 + \theta_3)
\end{bmatrix}
\begin{bmatrix}
x_0 \\
y_0 \\
z_0
\end{bmatrix} =
\begin{bmatrix}
x_0 \\
y_0 \\
z_0
\end{bmatrix}
\]

The solutions are:
\[
x_0 = (l_1 + l_2 \cos \theta_2 + l_3 \cos(\theta_2 + \theta_3)) \cos \theta_1 \\
y_0 = (l_1 + l_2 \cos \theta_2 + l_3 \cos(\theta_2 + \theta_3)) \sin \theta_1 \\
z_0 = l_2 \sin \theta_2 + l_3 \sin(\theta_2 + \theta_3)
\]

The coordinates of the foot end are $x_0$, $y_0$, $z_0$ in the coordinate system $O_0x_0y_0z_0$.

### 3.2. Inverse Kinematics Analysis

Inverse kinematics analysis refers to solving three joint rotation angles and obtaining inverse kinematics equations when the spatial position of the foot end of the mechanical leg is known.

The root, femur and tibia are located in the same plane, so:

\[
\theta_1 = \arctan\left(\frac{y_0}{x_0}\right)
\]

\[
x_0 \cos \theta_1 - l_1 - l_2 \cos \theta_2 = l_3 \cos(\theta_2 + \theta_3)
\]

\[
z_0 - l_2 \sin \theta_2 = l_3 \sin(\theta_2 + \theta_3)
\]

We add formula (1), formula (2) and formula (3) squared, and substitute formula (4), formula (5) and formula (6). There is:

\[
(2x_0l_2(\cos(\arctan(y_0 / x_0))))^{-1} - 2l_1l_2 \cos \theta_2 + 2z_0l_2 \sin \theta_2 = x_0^2 + y_0^2 + z_0^2 - l_1^2 + l_2^2 - l_3^2 - 2x_0l_1(\cos(\arctan(y_0 / x_0)))^{-1}
\]

The solution is:
\[ \theta_2 = \left( x_0^2 + y_0^2 + z_0^2 - l_1^2 + l_2^2 - l_3^2 \right) \left( 2x_0l_2 \left( \cos \left( \arctan \left( y_0/x_0 \right) \right) \right) - 2l_3l_2 + 2z_0l_2^2 \right) \left( 2x_0l_2 \left( \cos \left( \arctan \left( y_0/x_0 \right) \right) \right) - 2l_3l_2 + 2z_0l_2^2 \right)^{1/2} \]

\[ -2x_0l_2 \left( \cos \left( \arctan \left( y_0/x_0 \right) \right) \right) \left( 2x_0l_2 \left( \cos \left( \arctan \left( y_0/x_0 \right) \right) \right) - 2l_3l_2 + 2z_0l_2^2 \right) \left( 2x_0l_2 \left( \cos \left( \arctan \left( y_0/x_0 \right) \right) \right) - 2l_3l_2 + 2z_0l_2^2 \right)^{1/2} \]

\[ -\arctan \left( x_0l_2^{-1}l_3^{-1} \cos \left( \arctan \left( y_0/x_0 \right) \right) \right) - l_1l_2^{-1}l_3^{-1} \]

The formula (6) deformation, have:

\[ \theta_3 = \arcsin \left( \frac{z_0l_3^{-1} - l_2l_3^{-1} \sin \theta_2}{l_2} \right) \theta_2 \]

Acknowledgments
This work was supported by National Innovation Training Program for College Students (No: 201810294059) and the Open Fund of Key Laboratory of Special Robot Technology in Jiangsu Province under Grant number 2017JSJQR03.

References
[1] Klaassen B., Linnemann R and Spenneberg D. Biologically Inspired Robot Design and Modeling[J]. International Conference on Advanced Robotics, 2003:576-581.
[2] Chi Dongxiang and Yan Guozheng. BIOMIMITIC ROBOT RESEARCH AND ITS PERSPECTIVE[J].ROBOT, 2001 (05): 476-480P.
[3] Gou Wenhao and Yuan Lipeng. Strategy of foot trajectory for bionics quadruped robots kinematic analysis and gait planning[J]. Modern Manufacturing Engineering , 2017,7:37-41P.
[4] Ding Kai. Research on Gait Planning and Locomotion Control System for Hexapod Robots[D]. Southeast University, May,2016.
[5] R.b.Mchee and Iswandhi. Adaptive Locomotion of a Multilegged Robot over Rough Terrain[A]. IEEE Transactions on Systems,Man and Cybernetics,1979,9(4):176-182P.
[6] Yin Xiaolin. RESEARCH ON GAIT PLANNING AND CONTROL STRATEGY FOR BIOMIMETIC HEXAPOD ROBOT[D].HarbinInstituteofTechnology,2013,7.
[7] Liu Ze Guo and Ding Xiang Fang . Planning and simulation of the rule-based trotting gait of a bionic quadruped robot[J]. Advanced Materials Research, 2014, 971:624-628P.
[8] Nam and Woochul. Kinematic Analysis and Experimental Verification on the Locomotion of Gecko[J]. Journal of Bionic Engineering,2009, 3(6): 246-254P.
[9] Li Manhong, Zhang Minglu and Zhang Jianhua .Review on key technology of the hexapod robot [J].Journal of Machine Design , 2015,10(32): 1-8P.
[10] Ishikawa and Tomo. Gait motion planning for a six legged robot based on the associatron[J]. Journal of Advanced Computational Intelligence,2014,2(18):135-139P.
[11] Quinn, Sonya ,Gaughran and William .Bionics-An inspiration for intelligent manufacturing and engineering [J],Robotics and Computer-Integrated Manufacturing, 2010,6(26):616-621P.
[12] Nam and Woochul. Kinematic Analysis and Experimental Verification on the Locomotion of Gecko[J]. Journal of Bionic Engineering,2009, 3(6): 246-254P.