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Motion Simulation of Bionic Hexapod Robot Based on ADAMS/MATLAB Co-simulation

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Motion Simulation of Bionic Hexapod Robot Based on ADAMS/MATLAB Co-simulation

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Abstract. This paper mainly studies the kinematic simulation of hexapod robot when going straight, turning and climbing stairs based on MATLAB and ADAMS. First, the kinematic model of the robot was established based on the D-H method. On this basis, the compound cycloid and half-wave sine function were used to plan the foot trajectory of the robot during straight and turning. Through ADAMS/ MATLAB co-simulation, the hexapod robot has completed the tasks of straight, turning and climbing the stepped terrain. The simulation results show that the planned gait can be more flexible to complete the turning and climbing the stepped ground, and the related results can help the small hexapod robot to quickly verify the gait algorithm and reduce the design development cycle.

1. Introduction

In recent years, small electric-powered hexapod robots have gradually become popular in the civilian consumer field[1]. In the design and development process of hexapod robot, it is the key to shorten the development cycle and reduce cost as much as possible. ADAMS/MATLAB co-simulation can make full use of the strengths of the two in the field of control and dynamics simulation, and it can carry out rapid iteration of robot structures and algorithms[2].

Some scholars have made researches on these situations. Scholars of Shandong University carried out the trot gait simulation of quadruped robot based on ADAMS and MATLAB[3]. L. Angel used PID control to simulate tracking control for a robotic manipulator[4]. Fenghui Xu of Army Engineering University has simulated and verified the straight gait of the hexapod based on the CPG model[5]. Dariusz Grzelczyk of Lodz University of Technology[6] proposed a simple gait generator based on sine function to control the mammal-like octopod robot.

However, at present, most of the research involves the straight gait of the robot, and there are few studies on turning in situ and climbing. For consumer-level hexapod robots without force feedback, how to properly plan the gait period through complex terrain as much as possible is a problem worthy of study.

2. Hexapod robot prototype and kinematic model

As shown in Figure 1, the CAD model of the bionic hexapod robot in this paper was created in SolidWorks and imported in ADAMS. Dimensions of the robot are about 420mm×380mm×160mm (length×width×height). The terrain consists of three parts, first a straight road, then a right-angle curve to the left, and finally a stepped ground. The normal contact force between the feet and the ground adopts the collision force model in ADAMS, and the tangential friction force adopts the coulomb friction model. The detailed parameters are listed in Table 1.

Table 1. Contact force parameter in ADAMS

Parameters	**value**	**Parameters**	**value**
Rigidity	2855	Coefficient of Static Friction	0.7
Force Exponent	1.1	Coefficient of Kinetic Friction	0.55
Damping	0.57	Depth of Penetration	0.1

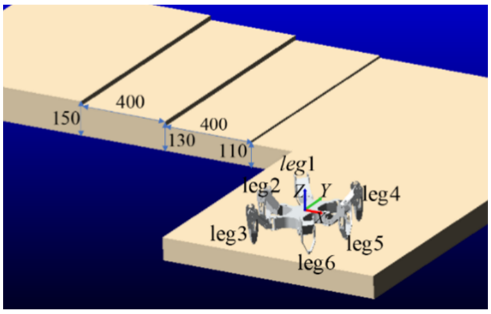

Figure 1 Hexapod robot prototype and terrain

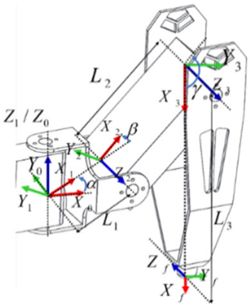
Figure 2 Coordinate system of leg5

Taking leg5 as an example, single-leg kinematics modelling was performed based on standard D-H notations. As shown in Figure **2**, define the fixed coordinate system $\sum_0(X_0Y_0Z_0)$, root joint coordinate system $\sum_1(X_1Y_1Z_1)$, hip joint coordinate system $\sum_2(X_2Y_2Z_2)$, knee coordinate system $\sum_3(X_3Y_3Z_3)$, foot coordinate system $\sum_f(X_fY_fZ_f)$.

Because all the legs have the similar mechanical structure, the coordinate system of leg1-6 is exactly the same. Therefore, the transformation matrix from the coordinate system to the fixed coordinate system of each leg is the same. The homogeneous transformation matrix is:

$$ {}_f^0\boldsymbol{T}=\begin{bmatrix} \cos(\beta+\gamma)\cos\alpha & -\cos\alpha\sin(\beta+\gamma) & \sin\alpha & \cos\alpha\left(L_1+L_3\cos\left(\beta+\gamma\right)+L_2\cos\beta\right) \\ \cos(\beta+\gamma)\sin\alpha & -\sin\alpha\sin(\beta+\gamma) & -\cos\alpha & \sin\alpha(L_1+L_3\cos(\beta+\gamma))+L_2\cos\beta \\ \sin(\beta+\gamma) & \cos(\beta+\gamma) & 0 & L_2\sin\beta+L_3\sin(\beta+\gamma) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where α, β, γ represent the angle of root joint, hip joint and knee joint respectively, L_1, L_2, L_3 represent the length of root link, hip link and knee link respectively.

Based on the forward kinematics analysis, according to the fourth column of the rotation matrix, the position of the foot end in the fixed coordinate can be expressed as follows:

$$ {}_f^0\boldsymbol{P}=\begin{bmatrix} \cos\alpha(L_1+L_2\cos\beta+L_3\cos(\beta+\gamma)) \\ \sin\alpha(L_1+L_2\cos\beta+L_3\cos(\beta+\gamma)) \\ L_2\sin\beta+L_3\sin(\beta+\gamma) \end{bmatrix} \tag{2}$$

The position vector of the foot in the fixed coordinate system is defined as $\left[x,y,z\right]^T$ .Then we can get a system of equations about the position of the feet, which can be expressed as follows:

$$\begin{cases} x=\cos\alpha(L_1+L_2\cos\beta+L_3\cos(\beta+\gamma)) \\ y=\sin\alpha(L_1+L_2\cos\beta+L_3\cos(\beta+\gamma)) \\ z=L_2\sin\beta+L_3\sin(\beta+\gamma) \end{cases} \tag{3}$$

In order to control the robot to track the planned foot trajectory well, we need to derive the inverse kinematics according to the equations (3). By eliminating the unqualified inverse solution, the inverse kinematics formulas can be obtained as:

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$$\begin{cases} \alpha = \arctan(\frac{y}{x}) \\ \beta = \pi + \arcsin\frac{z}{\sqrt{(L_3\cos\gamma + L_2)^2 + (L_3\sin\gamma)^2}} - \arctan\frac{L_3\sin\gamma}{L_3\cos\gamma + L_2} \\ \gamma = \arccos\left[\frac{(\sqrt{x^2+y^2} - L_1)^2 + z^2 - L_3^2 - L_2^2}{2L_3L_2}\right] \end{cases} \tag{4}$$

Note that the atan2 function is needed to replace the atan function in MATLAB to avoid quadrant problems.

3. Gait planning method

When walking on a flat road, hexapod robot usually adopts an insect-like gait. Small hexapod robot has low inertia and can achieve high walking speed by using triangular gait. As shown in figure 1, the triangular gait divides the six legs into two groups, one for leg1, leg3, leg5, and the other for leg2, leg4, leg6. The two groups alternate between supporting phase and swing phase, each accounting for half of the motion cycle. Triangular gait is adopted in this paper to simulate the hexapod robot.

3.1. Foot trajectory planning - straight

The interaction between the foot and the ground depends on the trajectory of the foot end. The appropriate maximum lifting height should be selected in the swing phase, which can not only meet the obstacle crossing requirements but also reduce energy consumption. The support phase should be close to the ground, and the body should move forward smoothly. Commonly used foot end trajectory curves include semi-ellipse, cycloid, parabola, etc.[7] Foot-ground contact slip phenomenon is a major problem to be considered in foot end trajectory planning of small hexapod robots. Therefore, the composite cycloidal foot trajectory planning method proposed in [8] is adopted in this paper. Establish the foot end trajectory constraint equation:

$$x = x_0 \tag{5}$$

$$y = \begin{cases} S\left[\frac{t}{T_t} - \frac{1}{2\pi}\sin\left(\frac{2\pi t}{T_t}\right)\right] + y_0 & 0 \le t \le T_t \\ S\left[1 - \frac{t - T_t}{T_s} + \frac{1}{2\pi}\sin\left(\frac{2\pi(t - T_t)}{T_s}\right)\right] + y_0 & T_t < t \le T \end{cases} \tag{6}$$

$$z = \begin{cases} \frac{H}{2}\left(1 - \cos(\frac{2\pi t}{T_t})\right) + z_0 & 0 \le t < T_t \\ z_0 & T_t < t \le T \end{cases} \tag{7}$$

where T_s is the period of swing phase, T_t is the period of stance phase, H is the stride height, S is the stride length, $[x_0, y_0, z_0]^T$ is the initial position vector of the foot. Take S=95, H=25, Tt=2, Ts=2, $x_0 = 96$, $y_0 = 0$, $z_0 = -77$ and the planned foot trajectory is shown in the figure3.

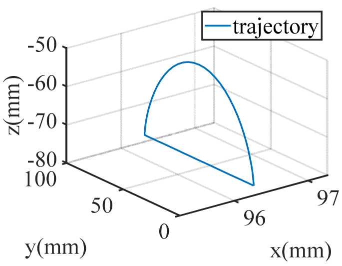


Figure 3 Foot trajectory

3.2. Foot trajectory planning - turning

In this paper, a triangular gait is adopted to realize the robot's fixed-point turning. The realization steps of turning gait are as follows:

First, both sets of legs are in the supporting phase in the initial position of the robot. Then, leg1,3,5 turns to the left and becomes the supporting phase, ready to rotate the body. Finally, leg2,4,6 changed from supporting phase to swinging phase, while leg1,3,5 drove the body to turn to the left. In this process, the heel and hip joint of each leg play a major role, so the half-wave sine function is used as the joint control function. The control rules of each joint during the turn are shown in equation (8).

$$\begin{cases} \alpha = A\left|\sin(\omega t)\right| \\ \beta = \begin{cases} B\sin(2\omega t) & 0 \le t < T_t \\ 0 & T_t < t \le T \end{cases} \\ \gamma = 0 \end{cases} \tag{8}$$

Where A and B represent the maximum angle of the heel joint and the hip joint in each cycle. In this paper, A= $5\pi/27$, B= $\pi/6$.

4. Co-simulation and result analysis

In order to verify the proposed straight and turning gait planning, a co-simulation was carried out based on MATLAB and ADAMS. In ADAMS, the input state variables of the hexapod robot are 18 joint rotation angles, and the output variables are the robot's center of mass displacement, velocity, attitude angle and foot force. As is shown in Figure **4**, by executing the “adams_sys” command, a block containing model information will be created and loaded into the MATLAB/simulink environment.[9]

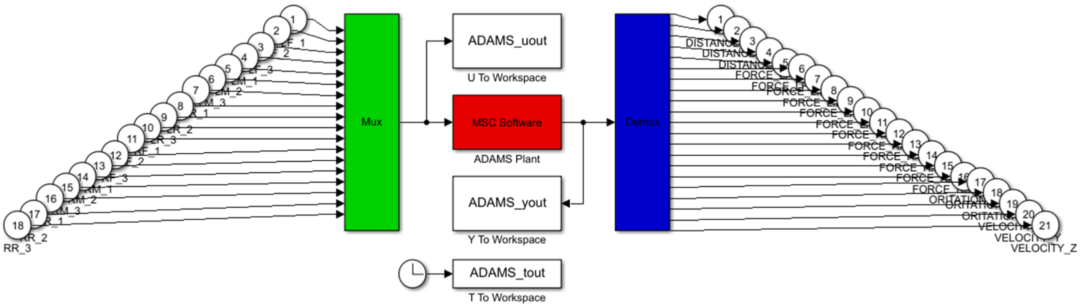


Figure 4 Configured ADAMS-sub block

According to the established terrain, the walking plan can be determined in table2. The first phase is to go straight through a track. The second phase is to make a 90-degree turn to the left at the end of the straight. The third stage is to climb a ladder with a maximum height of 20mm to the left. According to the planned foot trajectory, taking leg5 as an example, the joint angle obtained by the kinematics model is shown in Figure **5**, and the joint angle can be imported into ADAMS to realize the robot walking. The simulation results are shown in figure 6-10.

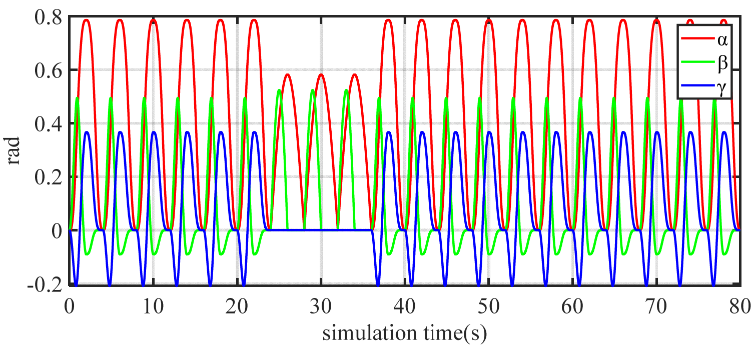
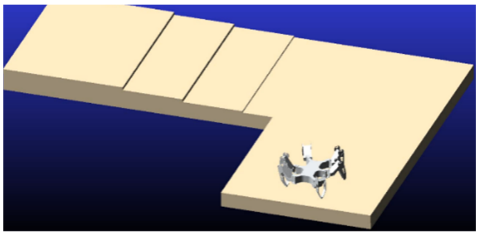
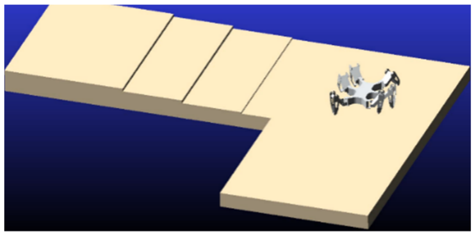


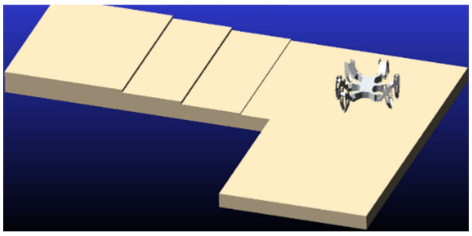
Figure 5 Joint angle of leg5

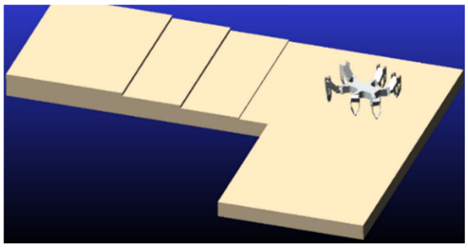
Table 2. Walking plan.

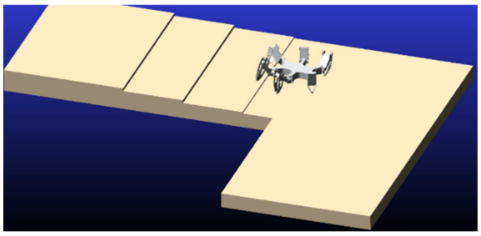
Phase	Detail	Parameters	Duration
1	Straight	1200mm	24s
2	Turn	90degree	12s
3	Climb	1600mm	44s


a) Start of the first phase


b) End of the first phase


c) Start of the second phase


d) End of the second phase


e) Start of the third phase

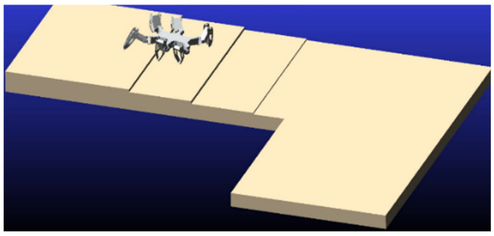

f) End of the third phase

Figure 6 Screenshots of co-simulation at different phase

It can be seen from the simulation screenshots that the robot starts from the initial position and passes the terrain in a regular triangular gait, which proves the correctness and feasibility of this method.

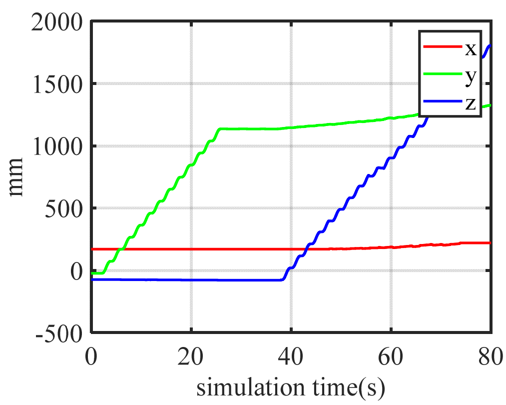


Figure 7 Displacement of body centroid

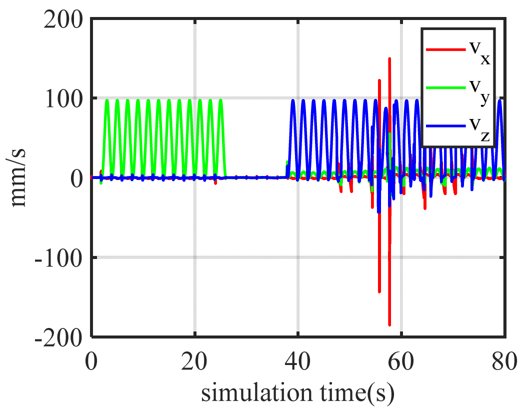


Figure 8 Velocity of body centroid

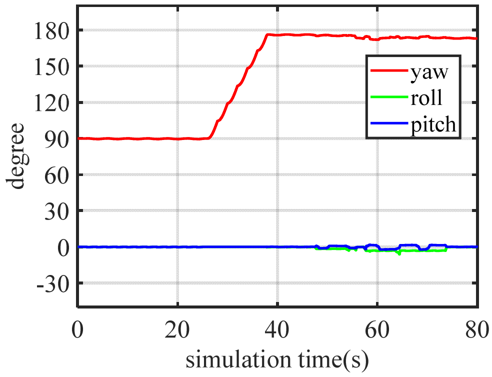


Figure 9 Attitude angle of body centroid

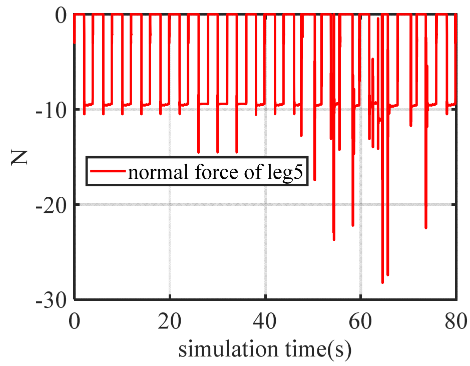


Figure 10 Normal force of leg5

As can be seen from Figure 6 and 9, during 0-24s, the robot displacement mainly occurs in the Y direction, which corresponds to the straight gait of the robot. The roll angle and pitch angle fluctuate little, which means that the posture of the robot is stable. During 24-36s, the yaw angle increases by 90 degrees, and the robot head turns to the left, corresponding to the in-situ turning gait of the second stage. After the robot enters the climbing gait, and the main displacement occurs in the z direction. From the simulation screenshot, it can be seen that the robot has passed the stepped terrain, which verifies the feasibility of the foot trajectory planning on the stepped ground in the straight gait.

5. Conclusions

A biologically inspired model of a hexapod robot was considered to study the kinematic of the robot locomotion on a complex terrain. The model was implemented in ADAMS, and the robot gait was produced by MATLAB/simulink. The co-simulation results show that the proposed gait planning can well complete straight running, turning and climbing stairs on flat ground. This advantage is desirable when implementing control algorithms in development of small consumer-grade hexapod robot.

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