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Model design and gait planning of hexapod climbing robot

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Abstract. In this paper, we design a hexapod climbing robot and propose a cross-plane transition gait algorithm to solve the problem that the general walking robot can't perform the work at high altitude and can't realize the autonomous transition between multiple planes. Firstly, we build a simulation control system based on MATLAB and V-REP for algorithm analysis and motion verification. Meanwhile, virtual connection technology is used to design virtual suction sensor to simulate the real adhesion mechanisms. Then, the single-plane walking gait algorithm is designed based on the SS-Shaped interpolation function, which effectively avoid the wear of the adhesion mechanisms. The transition algorithm based on workspace constraints is designed to greatly improve the adaptability of robots in complex environments. Finally, the simulation of rhythmic gait motion and ground-slope transitional motion verify the effectiveness of the gait planning method.

1. Introduction

In recent years, more and more robots have been used in industrial inspection to reduce safety accidents. With the increase of glass curtain wall buildings, the problem of low efficiency detection has become increasingly prominent. In addition, the complex multi-plane environment makes the application of robots more difficult. Therefore, it is meaningful and challenging to research the climbing robot that can span multiple planes.

Multi-legged climbing robots can perform climbing movements, such as Magneto[1], Geckobot[2]. Among them, hexapod climbing robots walk steadily in complex environments. There has been a host of studies in the gait planning of hexapod robots[3-5]. But they only studied the walking gait on single plane. There are many vertical and sloping transition surfaces on the glass curtain wall building, which limit the application of single plane motion gait. The literature[6] gives a transitional gait from the ground to a vertical wall, but it is only suitable for crossing at a specific angle. In this paper, we present a gait algorithm completing the transition to the slope surface at any angle, which greatly improves the autonomy and intelligence of the robot.

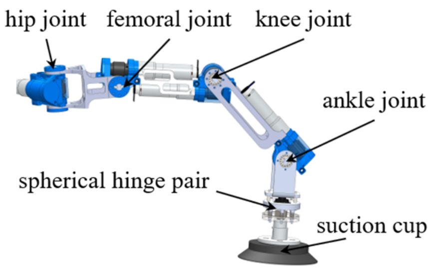
In order to reduce the time of prototype experiments, it is important to develop an effective virtual simulation system. Different simulation software has been applied to robots, such as Gazebo[7], Webots[8], V-REP[9]. However, there is currently a lack of good methods to realize real adhesive motion simulation, and it takes a lot of time and cost to test algorithm. This paper develops a simulation platform based on MATLAB and VREP, and designs a virtual suction sensor which can effectively test climbing motion.

The rest of this paper is organized as follows. Section 2 presents the design of climbing hexapod robot and simulation control system. The gait planning on single-plane and cross-plane is proposed in section 3. The simulation results in section 4 verify the gait algorithm. Section 5 concludes the work.

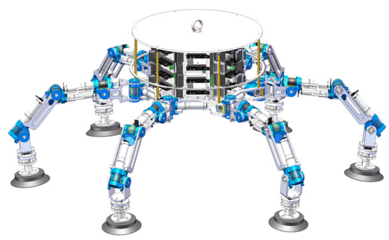
2. Prototype and system description

2.1. Mechanical design

Based on the principles of mechanical and bionics, we design a lightweight and flexible hexapod climbing robot as shown in figure 1. The body adopts a regular hexagon structure. The connecting points between the legs and body uniformly and symmetrically distribute along the circumference, and each leg branch chain that the mechanical design is exactly same radially expands along the circumference. This distribution helps to increase the movement range of legs and reduces the interference between legs. Each leg contains 4 active rotation joints. The hip joint axis is perpendicular to the plane of the body and achieves deflection motion, and the remaining 3 joint axes are parallel to the plane of the body to realize the pitch movement. In addition, link 4 and the foot-end suction cup are linked by a passive spherical hinge pair, and its rotation angles around three perpendicularly intersecting axes are limited within $(-5^{\circ},+5^{\circ})$, providing a small angle of passive compensation, so that the connection between the suction cup and the support surface is more compact.



(a) Single leg model of hexapod robot



(b) Overall design model of hexapod robot

Figure 1. Prototype of the hexapod climbing robot

2.2. Simulation control system design

We build the simulation control system shown in figure 2 based on MATLAB and V-REP. MATLAB calculates and outputs joint positions, and controls the switch of the virtual adhesion mechanism. The communication connection is established between them through the remote API client of V-REP. After receiving the corresponding control instructions, V-REP completes simulation movement and feeds back the motion data to MATLAB.

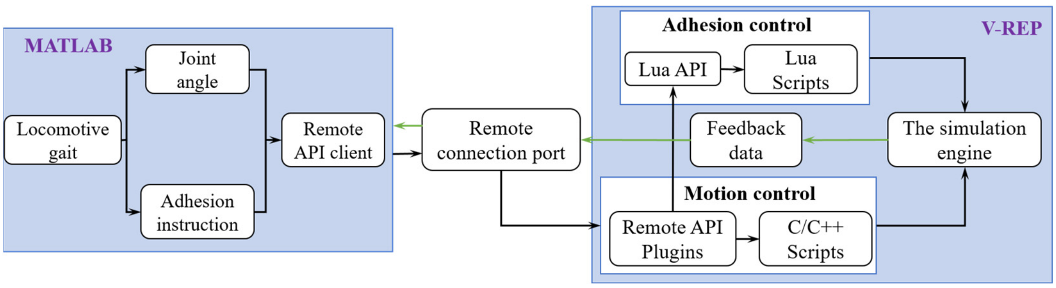


Figure 2. Structure of the simulation control system.

In order to build a simulation model that is more similar to the actual model, we build the overall 3D model in SolidWorks. Some simplifications are needed to reduce the complexity of computations and modeling. The specific methods are as follows:

- The body is simplified into a hexagonal structure, omitting the internal connection and control system hardware.

- Each link of the leg is treated as a part, maintaining the original design and the relative position of each joint.
- The vacuum suction cup is used for the adhesion mechanism, and the deformation of flexible material is ignored.

Figure 3 shows the design of simulation model. The suction sensor shown in figure 4 was built in V-REP based on the principle of virtual connection. Proximity sensor detects objects around them by calculating their surroundings. The embedded script is programmed to implement the adhesion function and provides a signal value for the upper control system to open or close the adhesion mechanism. When the suction sensor is turned on, dummy2 will be transferred to the supporting surface, forming a virtual link between dummy1 and dummy2.

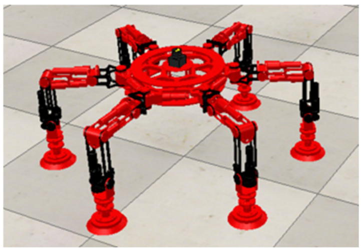


Figure 3. Simulation model in V-REP

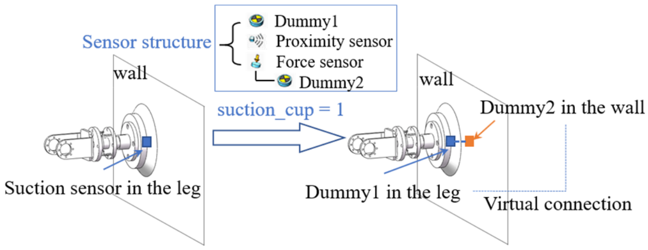


Figure 4. The Structure and principle of suction sensor

3. Gait planning

3.1. Gait planning on Single-plane

The six legs of a hexapod robot are divided into stance phase and swing phase according to the motion state during the robot movement. The switching and coordination of different states form the motion gait. T represents the gait period. The duty factor λ is the ratio of the stance phase in a period. It is calculated as shown in equation (1).

$$\lambda = t_0 T^{-1} \tag{1}$$

where t_0 is the leg stance time within one period.

The basic motion gait of the hexapod robot includes tripod gait, quadripod gait and wave gait. Unlike normal hexapods, the leg ends of hexapod climbing robot need to be lifted and dropped perpendicular to the support surface to reduce wear between the adhesion mechanism and the support surface. Therefore, the SS-shaped function as shown in equation (2) is used for tip trajectory interpolation.

$$\Gamma(t) = \frac{C_1 \cdot \sin(\omega \cdot t + \varphi) + C_2}{1 + \exp(-C_3 \cdot (t - C_4))} \tag{2}$$

where $C_i (i = 1,2,3,4)$, ω , φ are adjustable parameters. In particular, if $C_3 = 0$, then $\Gamma(t) = C_1 \cdot \sin(\omega \cdot t + \varphi) + C_2$ is the standard sine curve equation. If $C_1 = 0$, $\Gamma(t) = C_2 (1 + \exp(-C_3 \cdot (t - C_4)))^{-1}$ is the sigmoid curve equation.

The robust PID controller based on kinematics is adapted to trajectory tracking. Suppose the robot's kinematics model has the form as $\dot{P} = J \cdot \dot{\vartheta} - \omega$, where P and ϑ respectively represent the foot pose and joint variables of a limb; J is the velocity Jacobian matrix; and ω is a bounded random disturbance vector whose upper boundary is assumed to be $W_u = diag(W_{u1}, W_{u1}, ..., W_{um})$. Then the PID controller is designed as follows:

$$\dot{\vartheta} = J^{-1}(P_d + K_p e + K_d \dot{e} + \mu) \tag{3}$$

where P_d is the desired pose trajectory, $e = P_d - P$ denotes the tracking error, and $\mu = [\mu_1, ..., \mu_n]$ with $\mu_i = sign(e) \cdot W_{ui}$.

Based on the above method, a gait planning suitable for single-plane motion of hexapod climbing robot is proposed as shown in figure 5.

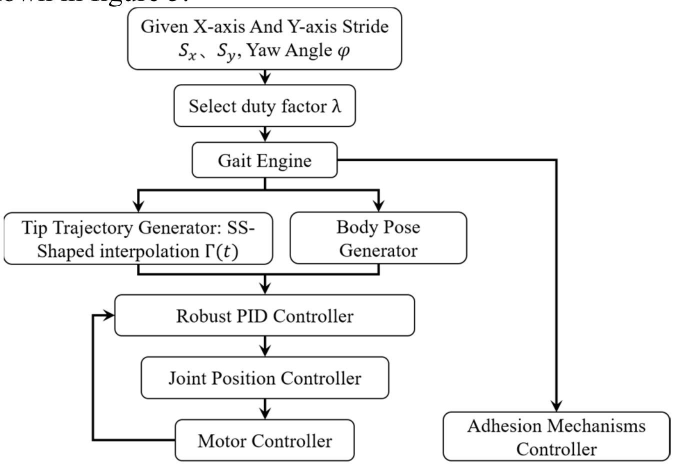


Figure 5. Gait control for single-plane motion.

3.2. Transition gait planning between cross plans

Climbing hexapod robot can not only realize single-plane motion, but also complete complex cross-plane motion. The key of this gait is to plan a feasible path for each leg when swinging across the plane. Figure 6 shows the trajectory planning method based on workspace constraints that is suitable for transition gait.

Our method to solve the transitional gait uses the above algorithm for planning. The entire gait process includes leg posture adjustment, cross plane, body adjustment and forward stepping. Figure 7 shows the specific process. We use lidar data to model the slope surface, and obtain the envelope surface of the workspace by combining polar coordinate and Cartesian coordinate search methods. Finally, the simulation system is used to verify the algorithm.

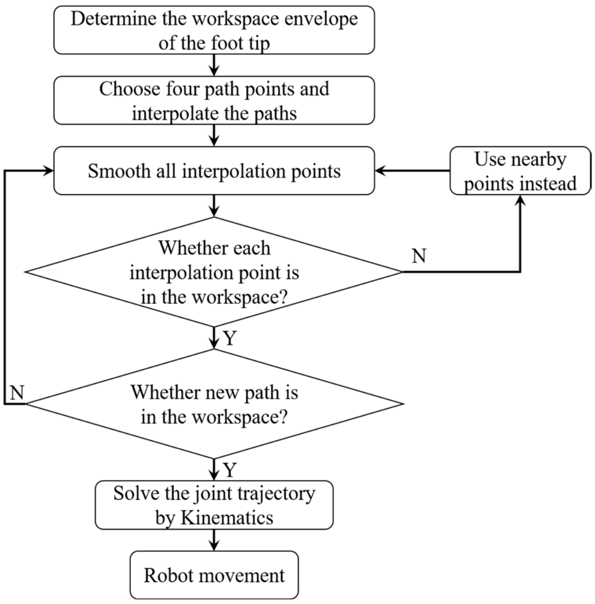


Figure 6. The procedure of generating motion trajectory.

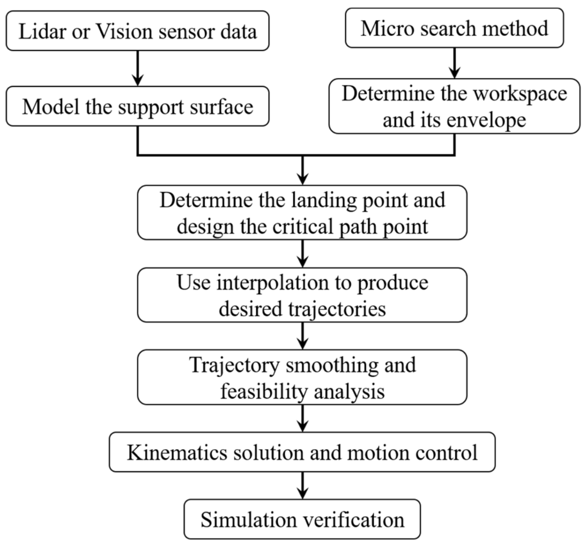
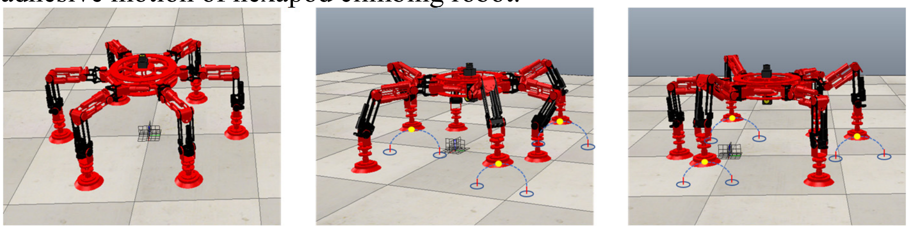


Figure 7. Trajectory planning algorithm for slope transition motion.

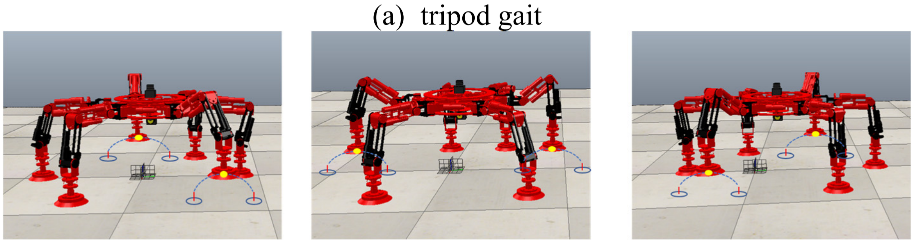
4. Simulation experiment

4.1. Single-plane motion simulation
The simulation environment in V-REP can simulate single-plane motion in the real scene. In the initial stage, the suction sensor is turned on, and the legs of hexapod robot are adsorbed on the ground. Then, the hexapod robot adopts a basic rhythmic gait, such as tripod gait, quadruped gait or wave gait, to complete a single-plane adhesive motion on the ground.

Figure 8 shows the process of tripod gait and quadruped gait simulation. The red lines in figure 8 represent vertical lift and fall. The simulation results show that the simulation system can smoothly simulate the adhesive motion of hexapod climbing robot.



(a) tripod gait



(b) quadruped gait

Figure 8. The single-plane motion simulation.

4.2. Cross-plane transition simulation
A glass curtain wall 45° to the ground is placed as the simulation scene in V-REP. In the simulation, the initial position of the hexapod robot is on the ground. Then the slope is searched by lidar, and the trajectory planning is carried out inside the program. Finally, the hexapod robot transits to the slope surface. The simulation results shown in figure 9 show that the climbing hexapod robot can complete the transition motion across the plane by the adhesion mechanism.

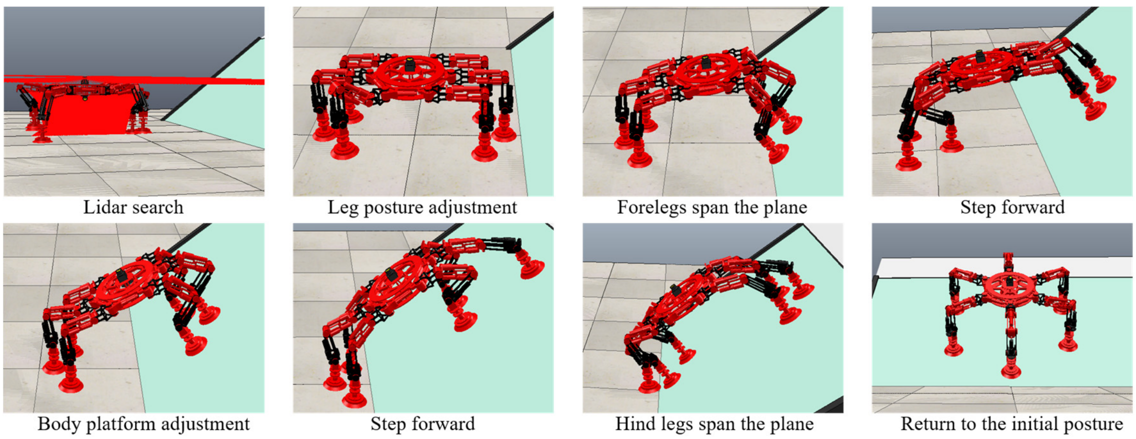


Figure 9. Simulation of climbing the slope.

5. Conclusions
The hexapod climbing robot presented in this work can not only complete the movement of a single plane, but also complete the transitional movement between multiple complex planes. Based on

MATLAB and VREP, we develop a simulation system that can complete the adhesive motion. The simulation results show that the suction sensor proposed in this paper can simulate the adhesive state of the adhesion mechanisms, and the gait planning methods are effective.

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