Gait Planning of Concave Transition for a Wall-climbing Robot*

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Abstract - For a gait planning problem of a wall-climbing robot, an on-line adaptive algorithm to perform concave transition is presented in this paper. The wall-climbing robot has a biped-wheel hybrid locomotion mechanism, which can make itself transit between two different wall surfaces. Firstly, the mechanical structure and the gait of the robot are analyzed respectively. Then, a finite state machine for gait modeling is established. On this basis, the gait planning method is proposed by using the interpolation scheme and the BP neural net. The simulations and the experiments show that for the wall-climbing robot prototype system, the on-line gait planning algorithm is feasible, and can improve the adaptive control ability effectively.

Index Terms – Wall-climbing robot; Finite state machine; Concave transition; Gait planning.

I. INTRODUCTION

Legged wall-climbing robot is a kind of special purposed robot. It is born from the multi-disciplinary crossed realm which involves the bionics, the mechanical design, the control theory and the artificial intelligence, etc. Compared with the wheeled and the tracked wall-climbing robots, the robot with the legged mechanism can not only move in a single wall, but also carry out transition between two adjacent walls, and has strong motor ability and flexibility. Therefore, this kind of climbing robot gets more and more attentions from the scholars in this field [1]. The transition refers to the process that the climbing robot moves from one wall surface to the other. Both of the two wall surfaces are contiguous with each other. According to the range of the angle \( \theta \) between the two wall surfaces, the transition can be classified as concave transition \( (\theta < \pi) \) or convex transition \( (\theta > \pi) \).

According to the special mechanism of the legged wall-climbing robot, how to plan its gait to realize autonomous transition is a difficult problem. A. Alsalam analyzed the feasibility to carry out the concave transition for a quadruped wall-climbing robot, but did not do intensive research about the method of gait planning [2]. Xiao analyzed the gait of concave transition for a micro wall-climbing robot CRAWLER. A gait control method based on multi-sensor data fusion was proposed. However, the further analysis on the relationship between the angle \( \theta \) and the joint variable was not given [3]. Hyungsok Kim studied the gait planning problem in 3D environment for a quadruped wall-climbing robot MRWALLSPECT. By constructing the geometric models of the robot and the environment, an off-line calculation method of various gait parameters for concave and convex transitions was proposed. But, how to realize the on-line gait planning was not given [4].

In this paper, a biped-wheel hybrid climbing robot is introduced. By using the interpolation scheme and the BP neural net, an on-line adaptive algorithm for the robot to realize concave transition is proposed. The simulations and the experiments show that for the wall-climbing robot prototype system, the method is feasible, and can improve the adaptive control ability effectively.

II. WALL-CLIMBING ROBOT

A. Mechanical structure

The wall-climbing robot consists of a negative pressure module, a vacuum module and a planetary gear train, as shown in Figure 1. It applies two adhesion methods to work with the biped-wheel hybrid locomotion mechanism: the negative pressure adhesion method achieved by the negative pressure module and the vacuum adhesion method achieved by the vacuum module [5].

The vacuum sucker is installed at the end of a linear motion guide unit, which has one degree of freedom (DOF). Therefore, the position of the vacuum sucker can be adjusted. A wheeled locomotion mechanism inside the suction chamber has two DOFs, and can perform straight and steering movement by controlling the speed of the two driving wheels.

The structure of the planetary gear train is composed of two half cylindrical gears and a connecting rod. It has one tilting DOF. By using the planetary gear train, the wall-climbing robot can realize the bipedal motion pattern. By using the wheeled locomotion mechanism, the robot can achieve the wheeled motion pattern.

The control system of the wall-climbing robot uses the TI’s TMS320F28335 DSP chip as the central processor. The drives of the joint and the vacuum pump motors adopt the TI’s SN754410 chip. The DC servo motor installed in this robot employs the photoelectric encoder to realize the position and speed closed-loop control for each joint. The sensors used in the robot include a zero position switch, four tactile sensors, two pressure sensors, two infrared distance sensors and two mode sensors. The zero position switch is used to identify the reference zero position; The tactile sensors are used to recognize the posture of the suction cup with respect to the
wall surface; The pressure sensor is used to measure the negative pressure in the gas path; The data detected by the infrared sensors are used to calculate the angle $\theta$ between the two wall surfaces, so as to control the robot to carry out the concave transition; The mode sensor is used to distinguish the motion pattern of the robot. The real-time communication between the robot and the base station is realized by the wireless Bluetooth module.

### III. ROBOT GAIT MODELING

#### A. Gait Analysis of Concave Transition

Through the alternate adsorption of the two suction cups and the coordination with the joints, the wall-climbing robot can flexibly achieve straight and steering movement, like an inchworm, and can realize the concave transition. As shown in Figure 2, the gait process for the robot to across a corner with a given angle $\theta \in [45^\circ,180^\circ]$ between two wall surfaces is as follows.

**Step 1:** Under the wheeled locomotion pattern, the robot moves quickly close to the transitional wall surface.

**Step 2:** The robot arrives at an appropriate location $L_{12}$ with respect to the wall. Then, the vacuum adhesion module is driven to the correct position and posture where the vacuum sucker is roughly parallel to the transitional wall surface.

**Step 3:** The distance $L_{13}$, the posture and position of the vacuum sucker are all adjusted slightly to let the sucker stick the wall surface closely. Then, the adhesion method is switched from the negative pressure module to the vacuum module.

**Step 4:** Drive the negative pressure adhesion module to make its suction chamber touch the wall surface. Then switch the adhesion method again to perform the wheeled locomotion mode.

Two important things that the robot needs to do before concave transition are to calculate the degree of the angle $\theta$ between two adjacent wall surfaces and to locate itself at a proper position $L_{11}$ in front of the transitional wall surface.

The concave transition gait can be expressed as a function:

$$G_g = g(L, \gamma_1, \gamma_2, l), \quad (1)$$

Where, $\beta$ represents the angle between the transitional wall and the adhesion wall; $L$, $\gamma_1$, $\gamma_2$ and $l$ are the undetermined parameters for gait planning.

#### B. Gait Modeling Based on FSM

FSM is composed of a finite number of states and mutual transfer of states. The robot can only be one state at the given states at any time. When receiving an input, FSM produces an output, and also may be accompanied by the transfer of the state.

The gait planning of the FSM model of the wall-climbing robot can be written as:

$$M = (Q, \Omega, \delta, q_0, F), \quad (2)$$

Where: $Q$ represents a finite state set of the movement gait, $\forall q_i \in Q$, as a state of $M$ ; the set of $\Omega$ represents the input state of the robot motion process; $q_0 \in Q$ represents the initial state of the robot; the set of $F \subseteq Q$ represents the terminal state of the robot; the state transition function $\delta : Q \times \Omega \to Q$, $\delta(q_i, a) = q_j$ indicates that when the last input $a \in \Omega$, the state of the robot move from $q_i$ to $q_j$. The state vector FSM model consist of eight elements, which occupy two bytes (16 bits in total, the bits from 15 to 13 are "0"), as shown in Table I.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$LM$</td>
<td>12,11</td>
</tr>
<tr>
<td>$J_1$</td>
<td>10,9</td>
</tr>
<tr>
<td>$J_{2,4}$</td>
<td>8,7,6</td>
</tr>
<tr>
<td>$J_5$</td>
<td>5,4</td>
</tr>
<tr>
<td>$SC_1$</td>
<td>3</td>
</tr>
<tr>
<td>$SC_2$</td>
<td>2</td>
</tr>
<tr>
<td>$AR$</td>
<td>1</td>
</tr>
<tr>
<td>$ST$</td>
<td>0</td>
</tr>
</tbody>
</table>

LM (Locomotion Mode): "00" represents the reference zero position stationary mode, "01" represents the straight mode, "10" represents the steering mode, "11" represents the concave transition mode;
\( J_f \) (state of joint 1): "00" represents rest or suction cup automatic tuning (AR=1), "01" represents that the joint 1 will rotate clockwise, "10" represents that the joint 1 will rotate counterclockwise, "11" represents illegal state;

\( J_{234} \) (state of joint 2, 3, 4) motion state of joint 2, 3, 4: "000" represents rest or suction cup automatic tuning (AR=1), "001" represents the joint 2 will rotate clockwise, "010" represents the joint 2 will rotate counter clockwise, "011" represents the joint 3 will rotate clockwise, "100" represents the joint 3 will rotate counterclockwise, "101" represents the joint 4 elongation, "110" represents the joint 4 contraction, "111" represents illegal state;

\( J_s \) (state of joint 5) motion state of joint 5: "00" represents rest or suction cup automatic tuning (AR=1), "01" represents vacuum sucker adsorption, "10" represents vacuum sucker release, "11" represents illegal state;

\( SC_1 \) (the state of suction chamber): "0" represents suction chamber release, "1" represents suction chamber adsorption;

\( SC_2 \) (the state of vacuum sucker): "0" represents vacuum sucker release, "1" represents vacuum sucker adsorption;

\( AR \) (suction cup adaptive regulate posture): "0" represents the start of self-adjustment program; "1" represents the termination of self-adjustment program;

\( ST \) (the basic gait phases): "0" represents the basic gait in the first stage, "1" represents the basic gait in the second stage.

According to the above definition of the state vector of FSM model for the wall-climbing robot gait planning, the status (hex) of the transfer path of the robot in the wall of the concave transition can be got, as shown in Fig. 3.

Fig. 3 FSM path of concave transition

IV. GAIT PLANNING ALGORITHM

A. The Associated Parameters

The principle of the angle calculation by two infrared sensors is described in below.

\[ \frac{l_1}{\sin (\alpha + \beta)} = \frac{l_2}{\sin \beta} \quad . \quad (3) \]

Where, angle \( \alpha \) is a constant. Ranges \( L_1 \) and \( L_2 \) are the feedback values from the two infrared sensors.

B. Gait Planning Algorithm

By offline gait planning, the wall-climbing robot can autonomously achieve the concave transition when the intersection angle belongs to \( \theta \in \{45^\circ, 75^\circ, 105^\circ, 135^\circ, 165^\circ\} \) .

The available corresponding gait function is expressed as:

\[ G_{\theta i} = g \left( L_{\theta 1}, \gamma_{\theta 1}, \gamma_{\theta 2}, l_{\theta 1} \right) \quad i = 1, 2, 3, 4, 5 \]

For any angle of \( \beta \in \{45^\circ, 180^\circ\} \), the online gait planning algorithm realize the autonomous wall transition is as follows:

Step 1: Determining the adjacent \( \beta \) and \( \theta \), that is \( \theta < \beta < \theta_{\text{start}} \). The corresponding gait functions are

\[ G_{\theta i} = g \left( L_{\theta 1}, \gamma_{\theta 1}, \gamma_{\theta 2}, l_{\theta 1} \right) \]

Step 2: Calculate weighting factors: \( \omega_1 \), \( \omega_2 \);

\[ \omega_1 = \begin{cases} 1 & \beta > \beta \theta \\ \frac{1 - \beta - \theta}{\theta_{\text{start}} - \theta_1} & \beta = \beta \theta \\ 1 + \frac{\theta_{\text{start}} - \beta}{\theta_{\text{start}} - \theta_1} & \beta < \beta \theta \end{cases} \]

\[ \omega_2 = \begin{cases} 1 & \beta > \beta \theta \\ \frac{\beta - \theta}{\theta_{\text{start}} - \theta_1} & \beta = \beta \theta \\ 1 + \frac{\theta_{\text{start}} - \beta}{\theta_{\text{start}} - \theta_1} & \beta < \beta \theta \end{cases} \]

Step 3: Calculation of the rotation angle of the rotary joint 2 and 3:

\[ \gamma_{\beta i} = \frac{\omega_1 \gamma_{\theta 1} + \omega_2 \gamma_{\theta 2,1}}{2} \quad . \quad (7) \]

\[ \gamma_{\beta 2} = 180^\circ - \beta -\gamma_{\beta i} \quad . \quad (8) \]

Step 4: Determine the parameters \( L_{\beta} \) according to the rules;

Step 5: Based on neural network training and learning, curve with a number of BP neural network to the rotation angle of \( \gamma_{\beta i} \), \( \gamma_{\beta 2} \) and prismatic variable \( l_{\beta} \) for piecewise fitting (as shown in Fig. 5), calculated elongation of the prismatic joint \( 4l_{\beta} \), fitting curve is plotted according to the relevant data obtained offline planning.

Step 6: From the above calculation is worth to the gait function to online planning out wall concave transition gait. The gait function is:

\[ G_{\beta} = g \left( L_{\beta}, \gamma_{\beta 1}, \gamma_{\beta 2}, l_{\beta} \right) \]

1286
Add the Rotary Joints 2,3 angle of rotation (°)

Elongation of the Joint 3 (mm)

V. SIMULATION AND EXPERIMENT

Each of the BP neural network has the same structure, as shown in Fig. 6, the two network inputs are the rotation angle $\gamma_1$ and $\gamma_2$ of rotary joint 2 and joint 3, which includes three the hidden neurons. The output network is $l$ that represents the elongation of the prismatic joint 4. The network training samples is from offline planning data.

![BP neural network](image)

Figure 7 shows the trajectory of A (the reference point of negative pressure adhesion module) and B (the reference point of vacuum adhesion module) when $\beta = 3\pi / 4$. $\gamma$ is the angle between the vacuum sucker and the transition surface. The simulation results show that the transition algorithm can accomplish a concave transition fast and reliably, and has a good astringency.

![The trajectory when $\beta = 3\pi / 4$](image)

A prototype of the wall-climbing robot is developed to validate the control method proposed in this paper. The basic specifications are listed in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SPECIFICATION OF THE PROTOTYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>1.9 kg</td>
</tr>
<tr>
<td>Size</td>
<td>298×212×140 mm$^3$</td>
</tr>
<tr>
<td>Noise</td>
<td>50 db$^a$</td>
</tr>
<tr>
<td>Endurance</td>
<td>45 min</td>
</tr>
<tr>
<td>Range of Surface Transition</td>
<td>45°-180° $^a$</td>
</tr>
</tbody>
</table>

$^a$ Noise was measured inside the airplane cabin when the robot moves on the exterior of an airplane.

The concave transition tests for the proposed method are carried out between the two intersecting planes. The experimental environment is built by two sheets of stainless aluminum. The angle between the two intersecting sheets varies from 45° to 180°. Figure 8 shows one of the experiments, and the angel is 143°.

![The transition experiment](image)

The experimental results show that: by using the online gait planning method proposed in this paper, the robot with the biped-wheel hybrid locomotion mechanism can realize concave transition. The simulations and the experiments show that for the wall-climbing robot prototype system, the method is feasible, and can improve the adaptive control ability effectively.

VI. CONCLUSION

In this paper, an on-line adaptive algorithm to perform concave transition is presented for a gait planning problem of
a wall-climbing robot. The wall-climbing robot has a biped-wheel hybrid locomotion mechanism, which can make itself transit between two different wall surfaces. Firstly, the mechanical structure and the gait of the robot are analyzed, respectively. Then, a FSM for gait model is established. An on-line gait planning algorithm for concave transition based on the interpolation scheme and the BP neural net is proposed. By this method, the robot can realize the autonomous concave transition. The simulations and experiments show that the method is effective and feasible.

In the future work, the method to measure the intersection angle will be further studied, and, therefore, the gait planning for convex transition and even more complex environment will be researched.

REFERENCES