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Walking model and planning algorithm of the over-obstacle pipe climbing robot

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Abstract

Effective inspection of pipelines is of significant importance in the industry. In order to reduce human labour, risk and expenses in this area, robots can be applied. The pipe robot should perform not only the linear motion in the axial direction but also the rotary motion in the circumferential direction while working. Meanwhile, in order to achieve reasonable performance and efficiency, these robots should have high enough normal linear motion velocity. They should be able to cross a pipe in one direction to another pipe in a different direction to achieve the over-obstacle function. In this study, a double-joint wheeled robot model is established to fulfil the actions of fast walking, rotation around the pipe and over-obstacle on spatial pipes. Based on the expected position on the pipe for the robot constructed by the proposed model, the precise starting position and control synthesis of the axial and circumferential velocities are initially determined. In order to study the velocity synthesis more accurately, the pipe is unfolded along the axial direction to transform the spatial motion into a plane motion. A novel spatial distribution form of driving wheels is proposed. In addition, based on the initial position of the straight, T-shaped, L-shaped, two-axis '+'-shaped and spatial three-axis '+'-shaped pipes, the posture adjustment of the robot prior, during and after the over-obstacle is investigated. Furthermore, the corresponding planning algorithms are established.

Keywords: pipe climbing robot; spatial velocity synthesis; over-obstacle algorithm; path planning; spatial pipe

1 Introduction

At present, the inspection and maintenance of pipelines are mainly performed by staff who climb up these pipes. The majority of the assigned tasks are repetitive with high labour intensity, low work efficiency and extremely high risk. Moreover, many industrial transport pipes have hazardous features such as high temperature,

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high pressure, high toxicity and radiant fluids, which add to the risk and hazard of the job. If these pipes are not regularly inspected and maintained, significant economic loss, injuries or even human casualty may be caused once a leakage occurs. Therefore, developing climbing robots for outdoor pipelines with specific capabilities, such as climbing and passing over obstacles, is in high demand. It is expected that these robots can replace humans in the task of regular inspection and maintenance of pipes.

Takahiro Fukui et al. [1] proposed autonomous gait transition and galloping over unperceived obstacles of a quadruped robot with central pattern generators (CPG) modulated by vestibular feedback. Laura Hak et al. [2] applied stability margins to better investigate variations of the obstacle crossing strategy. Moreover, Heeseung Hong et al. [3] presented a composite locomotive strategy by estimating the contact angle for a stair-climbing mobile platform. Since then, this strategy has been widely applied for designing and analysing the corresponding performance of many wall-climbing robots [4–8]. Subsequently, the optimal design and kinetic analysis were proposed for stair-climbing mobile robots in different structures [9,10]. Morales et al. [11] studied the obstacle surpassing and posture control of a stair-climbing robotic mechanism. Sorin and Nitulescu [12] studied locomotion over common types of obstacles for a legged mobile robot. Furthermore, Ryosuke Yajima et al. [13] studied the tracked vehicle from different aspects, including the ability to traverse obstacles. Fengyu Xu et al. [14] proposed the obstacle-negotiation capability of rod-climbing robots and improved the design mechanisms. Du Qiaoling et al. [15] designed a microrobot that enables the robot to climb a straight pole with a five-bar linkage. Pfozter et al. [16] proposed an autonomous navigation system for reconfigurable snake-like robots in challenging unknown environments. Adrián Peidr et al. [17] designed compact switchable magnetic grippers for the HyReCRo structure-climbing robot. Ma and Mao [18] used global path planning and local path adjustment for the coal mine robot to avoid obstacles in gas-polluted areas. Recently, Lili Bykerk [19] proposed a method for identifying beam members in truss structures based on the tactile data. Klein and Haugland [20] performed the obstacle-aware optimisation for cable layouts of offshore wind farms.

The literature review performed indicates that numerous investigations have been conducted so far on different aspects of pipeline robots; however, only a few of them are dedicated to the velocity synthesis of robots when walking on three-dimensional (3D) pipes. In addition, posture adjustments of the robot prior to the over-obstacle, processing the over-obstacle and the robot posture after the over-obstacle are rarely studied for 3D pipes.

The over-obstacle out-pipe climbing robot can not only walk fast on the straight pipe but can also rotate around the pipe. Therefore, these types of robots can be effectively applied in diverse configurations of pipes, including the plane two-axis, T-shaped, ‘+’-shaped, L-shaped and spatial three-axis ‘+’-shaped pipes. It is worth noting that these robots require special structural theory models. To this end, it is intended to design a novel robot based on previous achievements and new requirements.

2 Establishment and demonstration of the model

2.1 Model establishment

Figure 1 presents the configuration of the out-pipe climbing robot. It indicates that the robot is generally divided into two parts (A and B), where these parts are hung with an axis. Each part has two legs that can be opened and closed. Moreover, there is a driving assembly at the end of each leg. Figure 1 shows that each part contains two guiding wheels.

2.2 Demonstration of straight movement along the pipe axis and rotation around the pipe axis

In order to study the synthetic velocity direction of the robot walking on the pipe more accurately, the outer circumference of the pipe is expanded along the axis direction. This is schematically illustrated in Figure 2, where W_{A1} and W_{A2} denote the contact points between the guiding wheel and the pipe on part A of the robot, while W_{A3} and W_{A4} are the contact points between the driving wheel and the pipe on part A of the robot. All the

Fig. 1 Configuration of the out-pipe climbing robot. 1 - V-shaped drive assembly on part B; 2 - a leg of part B; 3,10 - guiding wheels of part B; 4 - hinged shaft of parts A and B; 5, 9 - the guiding wheel of part A; 6 - the left leg; 7 - the right leg; 8 - inverted V-shaped drive assembly of part A; O - the intersection of the hinged centre of parts A and B and the left and right symmetrical plane of the whole machine.

points are located on the same circumferential line. Similarly, W_{B1} and W_{B2} are the contact points between the guiding wheel and the pipe on part B of the robot. Moreover, W_{B3} and W_{B4} are the contact points between the guiding wheel and the driving wheel, and the pipe on part B, respectively. All the points are located on the same circumferential line. Points W_{A1} , W_{A2} , W_{B1} , and W_{B2} are collinear and parallel to the axis. The angle between the lines $W_{A1}W_{B2}$ and $W_{A3}W_{B3}$ is $\frac{2\pi}{3}$, which is equal to that between the lines $W_{A1}W_{B2}$ and $W_{A4}W_{B4}$ in the circumferential direction. The dashed-dotted line shows the pipe axis, while the dotted line is the circumferential expansion direction of the pipe. Moreover, L_1 , L_2 , L_3 , L_4 and L_5 denote the distances between the corresponding points in Figure 2. In order to make the robot force uniform, which is imposed on the pipe, the angles between the contact points are set in accordance with the values presented in Figure 2.

Fig. 2 Expanded layout of the driving wheel position on the pipe.

2.2.1 Rotation of driving wheels around the pipe axis

Figure 3 shows the rotation of the driving wheels around the pipe axis. When the velocities of all the driving wheels W_{A3} , W_{A4} , W_{B3} and W_{B4} are to the right, the resultant velocity will also be to the right so that the entire machine walks towards the right, and it rotates forward around the pipe. On the contrary, when the velocities of all driving wheels W_{A3} , W_{A4} , W_{B3} and W_{B4} are to the left, the entire machine walks to the left and performs a reverse rotation around the pipe. The robot stops moving when all the driving wheels stop their movement. Based on the performed analysis, the proposed robot can only rotate around the pipe. In other words, it cannot move straight along the pipe axis with no rotation.

Fig. 3 Rotation of driving wheels around the pipe axis.

2.2.2 Driving wheels walking along the axis

Figure 4 presents the driving wheel axis perpendicular to the pipe axis. When all the velocities of driving wheels W_{A3} , W_{A4} , W_{B3} and W_{B4} are upward, the resultant velocity of the whole robot machine is upward, so that the whole machine walks upwards. On the contrary, when all the velocities of the driving wheels W_{A3} , W_{A4} , W_{B3} , and W_{B4} are downward, the whole machine goes down. Furthermore, the resultant velocity for stationary driving wheels is zero, so that under this circumstance, the robot stops moving. Based on the performed analysis, the proposed robot can only go straight along the pipe axis. In other words, it cannot rotate around the pipe axis.

Fig. 4 The driving wheels walk up or down along the axis.

2.2.3 Driving wheels walking along the double inverted ‘V’-shaped direction

Figure 4(a) shows the paths of the driving wheels along the double inverted V-direction. It is worth noting that in this scheme, driving wheels W_{A3} , W_{A4} , W_{B3} , and W_{B4} are controlled by the electronic control system. When all the front driving wheels (W_{A3} and W_{A4}) and the rear driving wheels (W_{B3} and W_{B4}) move upwards in accordance with the inverted ‘V’-shaped direction, then the resultant velocity will be upward and the whole machine will move upward. On the other hand, when all driving wheels move downwards along the inverted ‘V’-shaped direction, the resultant velocity is downward, and the whole machine moves downwards accordingly. Finally, the whole machine stops for stationary driving wheels. It should be indicated that there are different methods to analyse the resultant velocity. Based on the performed analysis, it is found that the robot can move upward, downward or stay stationary in a certain place, but it cannot rotate around the pipe axis.

Fig. 5 Driving wheels walk along the double inverted V-direction.

2.2.4 Driving wheels walking along the double ‘V’-shaped direction

This case is similar to that of the previous part, where the driving wheels walk along the inverted ‘V’-shaped direction. Based on the performed analysis of the resultant velocity shown in Figure 6(a) and (b), it is concluded that the robot can only move upward, downward or stay stationary in a certain place. In other words, it cannot perform a complete rotation around the pipe axis.

Fig. 6 Paths of the driving wheels along the double V-direction.

2.2.5 Driving wheels walking along the ‘V’-shaped and inverted ‘V’-shaped directions

In this case, the axis of the driving wheels in part A is arranged in a ‘V’-shape, while the axis of the driving wheels in part B is arranged in an inverted ‘V’-shape. Accordingly, the upper driving wheels (W_{A3} and W_{A4}) and the lower driving wheels (W_{B3} and W_{B4}) walk along the ‘V’-shaped and inverted ‘V’-shaped directions, respectively. Moreover, the angles between the upper and lower driving wheels and the axes are equal. Under these circumstances, the resultant velocity of the whole machine is upward, so that the whole machine moves upwards.

Figure 7(b) illustrates that when the upper driving wheels (W_{A3} and W_{A4}) and the lower driving wheels (W_{B3} and W_{B4}) walk downward, the resultant velocity of the whole machine is downward, so that the whole robot moves downward.

As shown in Figure 7(c), the upper driving wheel W_{A3} is downward, while the upper driving wheel W_{A4} moves upward at a constant velocity. The lower driving wheel W_{B3} is upward, while the lower driving wheel W_{B4} walks downward at a constant velocity. Subsequently, the resultant velocity of the whole machine is to the right, so that the whole robot moves to the right along the pipe circumference. Under this circumstance, the robot rotates to the right around the pipe axis.

As shown in Figure 7(d), when the upper driving wheel W_{A3} moves upward, the upper driving wheel W_{A4} moves downward at a constant velocity, the lower driving wheel W_{B3} is downward and the lower driving wheel W_{B4} walks upward at a constant velocity. Therefore, the resultant velocity of the whole machine is to the left, so that the whole robot walks to the left along the circumference. In this case, the robot rotates to the left around the pipe axis.

Based on the performed analysis in different working conditions, it is found that the robot can achieve upward and downward movements, as well as rotation around the pipe axis. Therefore, this scheme is feasible to be applied as a powerful method to design over-obstacle out-pipe climbing robots.

Fig. 7 Velocity vectors of driving wheels walking along the V- and inverted V-directions.

2.2.6 Driving wheels walking along the inverted 'V'-shaped and 'V'-shaped directions

Figure 8(a) indicates that in this scheme, the axes of the driving wheels in parts A and B are set as inverted 'V'-shape and 'V'-shape, respectively. Accordingly, the upper driving wheels (W_{A3} and W_{A4}) walk along the inverted 'V'-shaped direction, while the lower driving wheels (W_{B3} and W_{B4}) move along the 'V'-shaped direction. Moreover, the angles between the upper and lower driving wheels and the axis direction are equal. When all the upper and lower driving wheels move upward, the resultant velocity of the whole machine is upward, so that the whole robot walks upwards.

Figure 8(b) indicates that when all the upper and lower driving wheels walk downward, the resultant velocity of the whole machine is downward, so that the entire robot moves downward.

Figure 8(c) shows that when the upper driving wheel W_{A3} moves downward, the upper driving wheel W_{A4} walks upward at a constant velocity, while the lower driving wheel W_{B3} moves upward and the lower driving wheel W_{B4} walks downward at a constant velocity. Subsequently, the resultant velocity of the whole machine is to the left, so that the whole robot walks to the left along the circumference. In this case, the robot rotates to the

left around the pipe axis.

According to Figure 8(d), it is found that when the upper driving wheel W_{A3} moves upward, the upper driving wheel W_{A4} walks downward at a constant velocity. The lower driving wheel W_{B3} moves downward, while the lower driving wheel W_{B4} walks upward at a constant velocity. Subsequently, the resultant velocity of the whole machine is to the right, so that the whole robot walks to the right along the circumference. Under this circumference, the robot rotates to the right around the pipe axis.

Fig. 8 Velocity vectors of driving wheels walk along the inverted V- and V-directions.

Based on the performed analysis in this section, it is concluded that the robot can achieve downward and upward movements, as well as rotation around the pipe axis. Therefore, this scheme is feasible to be applied as a powerful method to design over-obstacle out-pipe climbing robots.

2.2.7 Determination of the wheel spatial model

Based on the above analysis for the driving wheel velocity synthesis, two feasible schemes are proposed. Considering the control constraints, driving wheels are selected to walk along the ‘V’-shaped and inverted ‘V’-

shaped models.

Fig. 9 Gait analysis of the over-obstacle model.

3 Gait analysis of the over-obstacle model

Figure 8 shows the design model for investigating the over-obstacle performance of the robot. Figure 8(a) illustrates that the robot adjusts its posture by walking and rotating on the horizontal rod to reach the vicinity of the vertical rod. The following is the gait analysis of the robot:

- (1) Adjust the posture by walking and rotating to the plane defined by the horizontal rod axis and the vertical rod axis, as shown in (a).
- (2) Release the pipe-holding mechanism of part A.
- (3) Part A rotates at 90° counterclockwise around point O , as shown in (b).
- (4) Part B remains clamped and approaches the vertical pipe to the position illustrated in (c).
- (5) After reaching the position shown in (c), the pipe-holding mechanism of part A is tightly held, while that of part B is released.
- (6) Starting from (c), the driving wheels on part A rotate, which drives the whole upward to the position shown in (d).
- (7) Part B rotates counterclockwise at 90° around point O to the position shown in (e).
- (8) The pipe-holding mechanism of part B holds the vertical pipe tightly to complete the over-obstacle process.

4 Over-obstacle planning and algorithms

When the entire robot runs on the pipe, all parts of the robot are moving. Moreover, relative positions among the robot body components change due to the rotation. In order to determine the position of the robot in the 3D space and provide a reference for the pose of the robot body joints, a coordinate origin should be determined. Through analysing the structure of the robot without considering the pose of the robot, it is observed that there is only one axis with a constant distance from the pipe centre, which is the axis of the hinge joint of parts A and B of the robot. In order to simplify the investigation, the intersection of the hinge joint axis and the both left and right symmetrical planes of the whole machine are considered to be the coordinate origin, such as point O in Figure 1. It should be indicated that for performing subsequent analyses, several important parameters should be determined before planning. Table 1 defines the corresponding parameters.

According to the robot theory, the corresponding translation and rotation matrices are defined as follows:

- (1) The translation matrix

$$\text{Trans}(a,b,c) = \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where a , b and c denote the translation distance (m) along the x -, y - and z -axes, respectively.

- (2) Rotation matrix around the z -axis

$$\text{Rot}_z(z, \alpha) = \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 & 0 \\ \sin \alpha & \cos \alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where α is the rotation angle (rad) around the z -axis.

- (3) Rotation matrix around the y -axis

$$\text{Roty}(y, \beta) = \begin{bmatrix} \cos \beta & 0 & \sin \beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \beta & 0 & \cos \beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where β is the rotation angle (rad) around the y -axis.

Table 1 Definition of parameters.

R	Outer radius of the pipe, m
r	Minimum distance from the coordinate origin O_1 of the robot body to the pipe axis $x, y, z, r > R$
a	Initial movement distance from the origin O on the x -axis, m
b	Initial movement distance from the origin O on the y -axis, m
c	Initial movement distance from the origin O on the z -axis, m
α	The initial position angle (rad) around the z -axis, whose direction starts with the direction of the x -axis and rotates according to the right-hand rule, and the angle interval is $[0, 2\pi]$.
β	The initial position angle (rad) around the y -axis, whose direction starts with the direction of the z -axis and rotates according to the right-hand rule, and the angle interval is $[0, 2\pi]$.
θ	The initial position angle (rad) around the x -axis, whose direction starts with the direction of the y -axis and rotates according to the right-hand rule, and the angle interval, is $[0, 2\pi]$
A1	Positive trajectory of the robot coordinate origin
B1	Inverse trajectory of the robot coordinate origin.

(4) Rotation matrix around the x -axis

$$\text{Rotx}(x, \theta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta & 0 \\ 0 & \sin \theta & \cos \theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where θ is the rotation angle (rad) around the x -axis.

(5) The homogeneous vector corresponding to the coordinate origin O is defined as follows:

$$O = [0, 0, 0, 1]^T \quad (5)$$

4.1 Determination of the initial position

Considering the objective existence of the pipe radius and the robot spatial size and the achievement of the mutual over-obstacle function between the pipes, the initial positions on different axes are determined as follows:

(1) The initial position with x -axis as the pipe axis

Based on the hypothetical step-by-step method of the robot particle on the pipe, [21] the initial position of the x -axis is determined as the pipe axis

$$\text{Stpx}(\theta, a, r) = \text{Rotx}(x, \theta) \text{Trans}(a, 0, 0) \text{Trans}(0, r, 0)O = [a r \cos \theta \ r \sin \theta \ 1]^T \quad (6)$$

(2) The initial position of the y -axis as the pipe axis is defined as

$$\text{Stpy}(\beta, b, r) = \text{Roty}(y, \beta) \text{Trans}(0, b, 0) \text{Trans}(0, 0, r)O = [r \sin \beta \ b \ r \cos \beta \ 1]^T \quad (7)$$

(3) The initial position of the z -axis as the pipe axis is in the form below:

$$\text{Stpz}(\alpha, c, r) = \text{Rotz}(z, \alpha) \text{Trans}(0, 0, c) \text{Trans}(r, 0, 0) O = \begin{bmatrix} r \cos \alpha & r \sin \alpha & c & 1 \end{bmatrix}^T \quad (8)$$

4.2 Motion planning and the algorithm of the robot

There are many types of pipe combinations in real applications. Therefore, several typical types are considered as the research objects. These research objects include straight pipes, ‘+’-shaped pipes with two-axes in the same plane, T-shaped pipes with two-axes in the same plane, L-shaped pipes with two-axes in the same plane and spatial three-axis ‘+’-shaped pipes.

The complete over-obstacle process of the robot has four aspects, including the posture adjustment before the over-obstacle, robot position after the posture adjustment, over-obstacle process and the robot position after the over-obstacle. In order to simplify the expression of the motion planning, the posture adjustment algorithm is defined as Matrix **A**, over-obstacle algorithm matrix as Matrix **B**, algorithm matrix of the position after the posture adjustment as Matrix **C** and the algorithm matrix of the position after the over-obstacle as Matrix **D**. The planning of the robot on each type of pipe is described in the following sections.

4.2.1 Straight pipe planning

Fig. 10 shows that straight pipes can be placed horizontally, vertically and inclined in space. There are three forms of robot movement on the pipe, which include linear movements along the pipe axis, rotation around the pipe and spiral movement around the pipe axis. Since the sub-movement of the robot studied in the present article is the movement along the pipe axis and rotation around the pipe, the spiral movement around the pipe axis is a step-combined movement of these two movements. The movement on the horizontal pipe is taken as an example to study the different planning methods.

The linear movement on the horizontal pipe is the translational movement from the initial point $\text{Stpx}(\theta, a, r)$ to the destination point, which is described as follows:

$$\text{Trans}(a_1, 0, 0) \text{Stpx}(\theta, a, r) = \begin{bmatrix} a + a_1 & r \cos \theta & r \sin \theta & 1 \end{bmatrix}^T \quad (9)$$

The new position when the initial point $\text{Stpx}(\theta, a, r)$ rotates around the x -axis by $\Delta\theta_1$ is described as follows:

$$\text{Rotx}(x, \Delta\theta_1) \text{Stpx}(\theta, a, r) = \begin{bmatrix} a & r \cos(\theta + \Delta\theta_1) & r \sin(\theta + \Delta\theta_1) & 1 \end{bmatrix}^T \quad (10)$$

There are two paths for the step spiral movement. One is to rotate $\Delta\theta_1$ initially and then perform translation α_1 , which can be mathematically expressed as

$$\text{Trans}(a_1, 0, 0) \text{Rotx}(x, \Delta\theta_1) \text{Stpx}(\theta, a, r) = \begin{bmatrix} a + a_1 \\ r \cos(\theta + \Delta\theta_1) \\ r \sin(\theta + \Delta\theta_1) \\ 1 \end{bmatrix} \quad (11)$$

The other type of step spiral movement initially performs translation α_1 and then rotates $\Delta\theta_1$, that is

$$\text{Rotx}(x, \Delta\theta_1) \text{Trans}(a_1, 0, 0) \text{Stpx}(\theta, a, r) = \begin{bmatrix} a + a_1 \\ r \cos(\theta + \Delta\theta_1) \\ r \sin(\theta + \Delta\theta_1) \\ 1 \end{bmatrix} \quad (12)$$

The results obtained from Equations (11) and (12) are the same, although the process can be very different. When approaching the over-obstacle position, the robot should first rotate and then perform translation to adjust the posture. However, in order to prevent the over-obstacle position, the translation should be initially performed and then the robot should rotate to adjust the posture. This can prevent the robot from interfering with the pipe during the rotation process. Therefore, the robot cannot achieve the expected action.

Straight pipe planning includes vertical, horizontal and inclined pipe planning and is the basis of complicated planning. When the robot is climbing on the pipe, all motion states are synthesised from the basic motions.

Fig. 10 Motion planning for the straight pipe.

4.2.2 Two-axes in the same plane '+'-shaped pipe planning

The '+'-shaped pipe with two-axes in the same plane means that the axis of the '+'-shaped pipe has two axes and the two axes are perpendicular to each other in a plane. It should be indicated that planning mainly includes the transition process planning and over-obstacle planning. The structure of the plane '+'-shaped pipe is relatively complicated in the plane planning with multiple paths and full of information. Therefore, it is also the emphasis of the research.

It should be indicated that the over-obstacle on the two-axis plane '+'-shaped pipe is more complicated than walking on a straight pipe. The out-pipe climbing robot should adjust its posture to perform an over-obstacle at a specific location when climbing the pipe. The specific position refers to the plane defined by the two pipe axes. Figure 11 shows that there are no pipes in the x -axis direction, and only pipes along the y - and z -axes directions exist. Figure 11 shows that principles of the plane '+'-shaped pipe composed of x - and y -axes are the same as that of the plane '+'-shaped pipe composed of z - and x -axes. Therefore, it will not be described further. The y - and z -axes divide the '+'-shaped pipe into four quadrants, and add two working planes so that there are reversible movements in total.

On each projection diagram, the clockwise motion is defined as the forward motion, while the counterclockwise motion is defined as the reverse motion. The over-obstacle from the horizontal pipe to the vertical pipe in the first quadrant is taken as an example. The corresponding motion planning and algorithm are as follows:

- (1) The initial position is the result of Equation (7). This can be expressed as $\text{stpy}(\beta, b, r)$.
- (2) Starting from the initial β , rotate $-\beta$ around the y -axis to the upper edge of the two pipes in the zoy plane, and the corresponding rotation matrix is $\text{Roty}(y, -\beta)$.
- (3) Stretch legs of part A.
- (4) Part A rotates $\frac{\pi}{2}$ clockwise around the hinge joint of the robot.
- (5) Part B advances $r - b_i$ towards O_i to r_i , and its translation matrix is $\text{Trans}(0, b, -r, 0)$.
- (6) The legs of part A hold tight.
- (7) The legs of part B release.
- (8) Part A runs $c - r$ to c along the positive direction of the z_i -axis of Pipe 1, and the corresponding matrix is $\text{Trans}(0, 0, c - r)$.
- (9) Part B rotates $\frac{\pi}{2}$ clockwise around the hinge joint of the robot.
- (10) The legs of part B hold tight.
- (11) Move on the vertical pipe.

Fig. 11 Motion planning for the '+' pipe.

It should be indicated that the over-obstacle planning and algorithms in other quadrants are consistent with the above-mentioned principles.

According to Equations (1) and (3), the posture adjustment matrix before the over-obstacle can be expressed as follows:

$$\text{MatrixA} = \text{Trans}(0, r - b, 0) \text{Roty}(y, -\beta) = \begin{bmatrix} \cos \beta & 0 & \sin \beta & 0 \\ 0 & 1 & 0 & r - b \\ -\sin \beta & 0 & \cos \beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (13)$$

According to Equations (1) and (13), the over-obstacle process matrix approaching from the y -axis to the z -axis is as follows:

$$\text{MatrixB} = \text{Trans}(0, 0, c - r) \text{MatrixA} = \begin{bmatrix} \cos \beta & 0 & \sin \beta & 0 \\ 0 & 1 & 0 & r - b \\ -\sin \beta & 0 & \cos \beta & c - r \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (14)$$

According to Equations (1) and (13), the position after the posture adjustment is as follows:

$$\text{MatrixC} = \text{MatrixAstpy}(\beta, b, r) = [0 \ r \ r \ 1]^T \quad (15)$$

According to Equations and (14), the position algorithm after the over-obstacle is as follows:

$$\text{MatrixD} = \text{MatrixBstpy}(\beta, b, r) = [0 \ r \ c \ 1]^T \quad (16)$$

4.2.3 Plane T-shaped pipe planning

The structure of the T-shaped pipe is also a part of the two-axis '+'-shaped structure. Moreover, its motion planning is included in the '+'-shaped pipe planning. The differences are studied as follows.

Figure 12 shows the planning diagram of the T-shaped pipe. Compared with the '+'-shaped pipe, there is one less branch pipe. Comparing Figure 12 with Figure 11 shows that most of the planning details are the same, while they are different only in some ways. The different parts are introduced in detail in Figure 12.

Fig. 12 Motion planning for T pipe.

Since Pipe 4 does not exist, the second quadrant, the third quadrant, ⑦ and ⑧ of the planning path do not exist. The planning between the second and third quadrants is the same as the planning is in the right view. However, the angles around one or three axes are different.

4.2.4 Plane L-shaped pipe planning

The structure of the L-shaped pipe is a part of the two-axis ‘+’-shaped structure. Therefore, the motion planning is included in the ‘+’-shaped pipe planning. However, they have differences that will be shown in this study.

Figure 13 shows the planning diagram of the L-shaped pipe. Compared with the ‘+’-shaped pipe, it only has two branch pipes. Comparing Figure 13 with Figure 11, it is observed that many of planning is the same, while they are only partly different. The different parts are introduced in detail as follows:

Fig. 13 Motion planning for the L pipe.

Since Pipes 3 and 4 do not exist, the second, third and fourth quadrants, ⑤, ⑥, ⑦, and ⑧ of the planning path do not exist.

4.2.5 Spatial three-axis ‘+’-shaped pipe motion planning

The spatial three-axis ‘+’-shaped pipe means that there are three axes of the pipe, which are perpendicular to each other. This is similar to the three coordinate axes of the spatial coordinate system. The motion planning of this structure is the most complicated planning among all, which should be supported by a plane planning.

Figure 14 illustrates a projection diagram of a spatial three-axis ‘+’-shaped pipe. It is observed that there are six pipes, which are indicated by the corresponding symbols. The front view, the top view and the left view are represented as F_1F_1 , G_1G_1 and H_1H_1 , respectively. There are four quadrants in each projection diagram, which are C_i , D_i , and E_i . Moreover, counter i can take an integer from 1 to 4.

In the spatial three-axis ‘+’-shaped over-obstacle process, the path planning from one pipe to an adjacent pipe is L-type planning. There are 24 planning routes in total. The L-type planning has been studied above, and will not be discussed here.

Figure 14 shows that the over-obstacle planning is complicated between Pipes 2 and 4, 1 and 3, as well as 5 and 6, while these three methods are the same. Therefore, only one of them is studied. For example, planning from Pipes 2–4 is investigated, in which there are numerous motion planings.

Figure 15 shows the detailed path scheme. According to the scheme, there are four planned paths from

Fig. 14 Motion planning for '+' space pipe.

Pipes 2–4. Since the methods are the same, only the planning from Pipes 2–1 and subsequently from Pipes 1–4 is studied. It should be indicated that if the planning from Pipes 2–1 is an L-type positive planning, then the planning from Pipes 1–4 is an L-type inverse planning. It is necessary to rotate 180° around the axis of Pipe 1 between the two 'L'-type plannings. The algorithm of the over-obstacle from Pipes 2–1 and then from 1–4 is described as follows:

$$\text{MatrixBRot}_z(z, \pi) \text{ MatrixB} = \begin{bmatrix} -\sin \alpha \cos \beta & \cos \alpha & \sin \alpha \sin \beta & (b-r) \cos \alpha \\ -\cos \alpha \cos \beta & -\sin \alpha & \cos \alpha \sin \beta & (b-r)(1 - \sin \alpha) \\ \sin \beta & 0 & \cos \beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (17)$$

Fig. 15 The planning principle over the obstacle on the coaxial pipeline of space '+'.

5 Conclusions

The following conclusions are drawn from the present study:

(1) The equivalent method of spatial pipeline expansion is proposed. Therefore, the robot motion is transformed from a space problem study to a plane problem study, which simplifies the analysis process.

(2) The model of pipe climbing robot with obstacle surmounting function is established. Based on the model, the posture analysis of the driving wheel in space and the principle of the velocity synthesis solve the difficult problems of the robot moving straight along the pipe, rotating around the pipe and over-obstacle. Finally, the model showing that the driving wheels walk along the combination of the 'V'-shaped and inverted 'V'-shaped axes is determined.

(3) The present study determines the initial position of the robot on the pipe based on the hypothetical step-by-step method, which provides the theoretical foundation for planning and obstacle crossing analysis.

(4) The present study initially studies the planning methods of the robot on a straight pipe, such as upward, downward, hovering and rotating along the pipe. Then, based on the two-axis '‘'-shaped pipe, it is focused on the path planning, posture adjustment algorithm, over-obstacle algorithm, state algorithm after posture adjustment, and state algorithm after over-obstacle in the four quadrants of the coordinate system and the process of over-obstacle from the side. Moreover, the over-obstacle plannings of the T-shaped pipe and L-shaped pipe are studied, respectively. Furthermore, combined with the double-axis '+'-shaped pipe planning principles and algorithms, the three-axis '+'-shaped spatial pipe planning and algorithm is studied.

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