doi:10.3772/j.issn.1006-6748.2023.01.007

# Analysis on steering characteristics of crawler pipeline robot①

GENG Linkang(耿林康)*, RAO Jinjun*,**, LEI Jingtao②*,**
(*School of Mechatronic Engineering and Automation, Shanghai University, Shanghai 200444, P. R. China)
(**Shanghai Key Laboratory of Intelligent Manufacturing and Robotics, Shanghai 200444, P. R. China)

**Abstract**

In order to improve the elbow passing performance and different diameter adaptability of pipeline robot, a supported crawler pipeline robot is designed, which adopts screw nut mechanism and hinge four-bar mechanism to adapt to the complex environment such as variable diameter pipeline and elbow. The steering characteristics passing through the elbow are studied, the kinematic of pipeline robot bending steering is established, the geometric constraint (GC) and steering constraint (SC) in the elbow are analyzed, and the steering experiment is conducted. The results show that the robot can pass through the elbow by the SC model. The SC model can reduce the motor current and energy consumption when the robot passes through the elbow.

**Key words**: crawler pipeline robot, steering characteristics, geometric constraint(GC), steering constraint(SC)

## 0 Introduction

Pipeline robot is a special robot which can carry a variety of sensors and operating machinery to move along the pipeline[1]. According to the differences in movement modes, pipeline robot can be divided into six categories, i. e. wheel type, crawler type, spiral type, bionic type, walking type and differential pressure type[2-5]. However, the steady operation, detection and maintenance of pipeline robot in special pipelines (such as variable diameter pipelines, elbows, etc.) are still in its infancy[6]. Due to the wide application of special pipelines, the research of pipeline robot is of great significance.

Crawler pipeline robot increases the contact area with the inner surface of the pipeline, and has obvious advantages in terms of stable operation, carrying load capacity and other aspects. It can better adapt to the changes of the pipeline and becomes the research focus of the special pipeline field[7-9]. Ref. [10] proposed a steering algorithm which ensures that the robot can provide enough support in the bend pipe. Refs[11,12] developed a cylindrical crawler robot and proposed a simple steering principle of the crawler robot, which could pass all t-shaped branch paths. Ref. [13] proposed a robot with integrated steering mechanism, which has good load-bearing capacity and adaptability to different pipe diameters and obstacles. Ref. [14] analyzed the influence of the robot's initial attitude on the cornering performance. When the initial attitude angle is 0°, the robot could pass through the L-shaped elbow. With the change of the initial attitude angle, the rotation angle of the robot would change greatly, and the robot could not even pass through the elbow. Refs[15,16] analyzed the varying regularity of the robot's velocity with the pipeline's curvature radius, the robot's axial length and the attitude angle around the pipeline axis. Ref. [17] used speed coordination model to reduce motor torque and energy consumption in the steering process. Ref. [18] verified that when the robot was turning, more accurate dynamic characteristics can be obtained by incorporating the change of relative distance between the centroid and the middle line of the pipeline into the motion analysis equation. Ref. [19] verified that the attitude can be adjusted by adjusting the pressure and speed of each crawler.

Scholars analyzed the parameter changing, motion characteristics and components collaboration of the pipeline robot turning. However, different robot is developed according to the specific working environmental, and the application scene is single[20]. In addition, the existing pipeline robot has complex mechanical structure, which is generally cumbersome and detrimental to lightweight and miniaturization. To ensure the stable movement of pipeline robot, it is necessary

① Supported by the National Natural Science Foundation of China (No. 51775323).
② To whom correspondence should be addressed. E-mail: jtlei2000@163.com.
Received on Mar. 9, 2022

to study the adaptability of the robot to the different pipelines.

Aiming at the problems of poor cornering performance, small diameter adaptability range, complex mechanical structure and inconvenient control of pipeline robot, a kind of crawler pipeline robot is designed, which can adapt to the pipeline diameter of 250 – 400 mm. The radial expansion device of the pipeline robot is designed by using screw nut and hinge four-bar mechanism, which can improve the adaptability of different pipe diameter. The steering characteristics of crawler pipeline robot are studied. The geometric constraint (GC) model and steering constraint (SC) model of crawler pipeline robot is established, and the varying regularity of curvature radius, expansion diameter and velocity of pipeline robot is deduced. The experiment platform of crawler pipeline robot steering is built, and the influence of SC model on the pipeline robot's steering motion is compared and analyzed. The rationality of robot structure design and SC model is verified by experiments.

# 1 Structure design

To pass through the pipeline with different diameter smoothly, the pipeline robot should meet two requirements, which are cornering ability and adapting to different pipe diameter.

To improve the movement ability of the pipeline robot and the interchangeability of components, the robot is designed with three modules, namely the crawler travelling module, the radial expansion module and the basal body, as shown in Fig. 1. The crawler travelling module provides the driving force for the robot to walk. The radial expansion module endows the robot with flexible adaptability to different pipe diameters and ensures that the crawler travelling module is in well contact with the inwall.

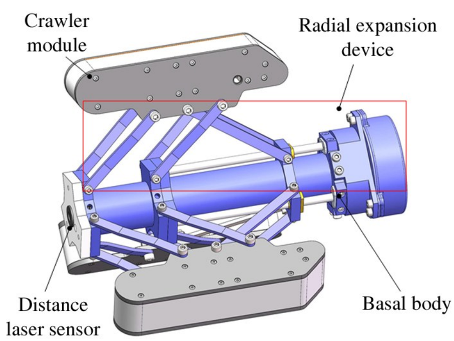


**Fig. 1** Structure composition

## 1.1 Crawler travelling module

Three groups of crawler modules are evenly distributed along the central axis of the robot to enable the robot to enter the pipeline in any posture. As shown in Fig. 2, the three groups of crawler modules are equipped with built-in power drive device, which can realize independent movement of the crawler module. By controlling the synchronous operation of three crawler modules, the robot can move smoothly in the straight pipe. The crawler module is connected with the pipe diameter adaptation module through bolts. By adjusting the rotational speed of each crawler module and the radial expansion of the pipe diameter adaptation module, the pipeline robot can have the ability of obstacle crossing and three-dimensional turning in pitch and yaw directions.

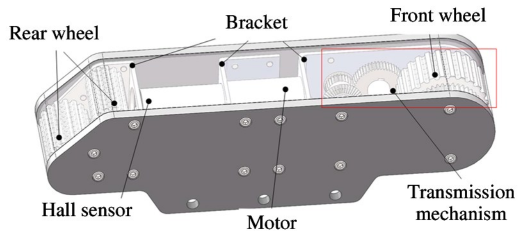
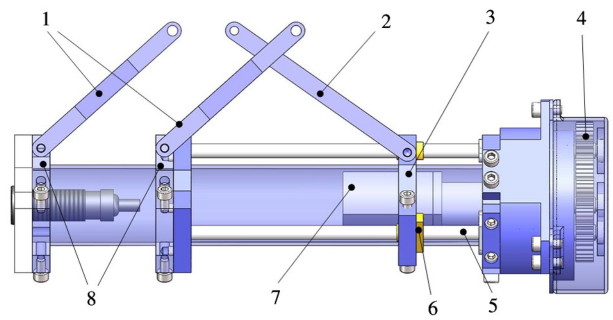


**Fig. 2** Crawler travelling module

## 1.2 Radial expansion module

As shown in Fig. 3, radial expansion module which is designed by screw nut mechanism includes rocker arm, expansion link, sliding disk, lead screw, special-shaped nuts, expansion motor, gear transmission device and other parts.



1 Rocker arm; 2 Expansion link; 3 Sliding disk; 4 Gear transmission device; 5 Lead screw; 6 Special-shaped nuts; 7 Expansion motor; 8 Rocker bracket

**Fig. 3** Radial expansion module

The expansion motor transmits the driving torque to the lead screw through gear transmission device. Three screws are all distributed around the basal body and fixed by sliding disk and special-shaped nuts. The screw rotates and pushes the special-shaped nut to move in a straight line, and then pushes the sliding disk to move back and forth along the axis. The expansion link which is hinged on the sliding disk changes the supporting angle to make the crawler module close to the inner wall of the pipe, so that there is enough positive pressure between the crawler module and the pipe wall to make the robot move smoothly. It can also provide enough adhesion to overcome gravity and all kinds of traveling resistance to realize the pipeline robot moving in vertical pipes. The pipeline robot can adapt to pipes with diameters between 250 – 400 mm by software calculation.

## 2 Steering motion analysis

When the pipeline robot turns, it is necessary to solve the two problems which are the incompatibility between the robot body and the pipeline space, and the influence of pipeline curvature on the motion performance of the robot[21], otherwise, the pipeline robot will be stuck.

### 2.1 Geometric constraint analysis

During turning, to make the pipeline robot pass through the elbow smoothly, the structure size, pipe diameter and curvature radius of the pipeline robot need to meet the specific relationship.

It is most difficult for the robot to navigate in the middle of the pipe elbow (the limit state), so if it can navigate through the middle of the bend, it can navigate the entire pipe section. The pipeline robot is simplified to a cylinder, as shown in the shaded area of Fig. 4 and Fig. 5.

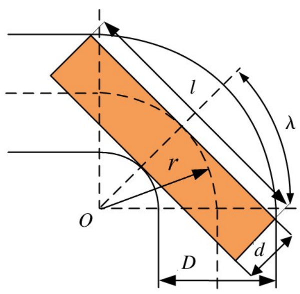



**Fig. 4** $0 \leqslant d \leqslant D/2$

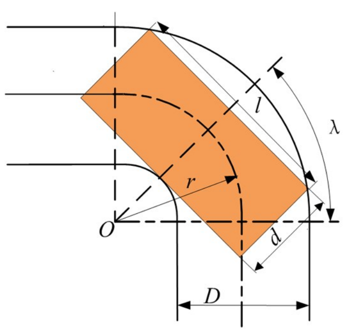



**Fig. 5** $D/2 \leqslant d \leqslant D$

For the different situation of the pipeline robot, the geometric constraint of the pipeline robot can be analyzed as followings.

(1) When $0 \leqslant d \leqslant D/2$, both ends of the pipeline robot are located at the straight pipe in the limit state, as shown in Fig. 4, the size of the pipeline robot should meet

$$\begin{cases} 0 \leqslant d \leqslant (r + \frac{D}{2})\cos\lambda - (r - \frac{D}{2}) \\ l_{\max} = 2\left[\frac{(r + \frac{D}{2})}{\sin\lambda} - (r - \frac{D}{2} + d)\cot\lambda\right] \end{cases} \quad (1)$$

where, $d$ is the robot extension diameter, $l$ is the length of the pipeline robot, $D$ is the diameter of the pipeline, $r$ is the minimum curvature radius of the robot through the elbow, and $\lambda$ is the bending angle.

(2) When $D/2 \leqslant d \leqslant D$, both ends of the pipeline robot are located at the elbow in the limit state, as shown in Fig. 5, the size of the pipeline robot should meet

$$\begin{cases} (r + \frac{D}{2})\cos\lambda - (r - \frac{D}{2}) < d < D \\ l_{\max} = 2\sqrt{(D - d)(2r + d)} \end{cases} \quad (2)$$

Assuming that the robot can pass a right-angle elbow ($\lambda = 45°$) with curvature radius $R \geqslant 1.5D$, the ratio of the robot expansion diameter to the pipeline diameter $k_1$ and the ratio of the robot's length to the pipe diameter $k_2$ are defined, then Eq. (1) and Eq. (2) can be simplified as

$$\begin{cases} k_2 \leqslant 4\sqrt{2} - 2 - 2k_1,\ 0 \leqslant k_1 \leqslant \sqrt{2} - 1 \\ k_2 \leqslant \sqrt{4(1 - k_1)(3 + k_1)},\ \sqrt{2} - 1 \leqslant k_1 \leqslant 1 \end{cases} \quad (3)$$

where $k_1 = d/D$, $k_2 = l/D$.

According to Eq. (3), the relationship between pipe diameter and robot extension diameter that can pass through the elbow can be obtained, as shown in Fig. 6, and the relationship between the length ratio of the robot and the expansion diameter ratio is drawn, as shown in Fig. 7.

The range of $D$ and $d$ in the two cases is shown in the shaded area in Fig. 6, the size range of the robot extension diameter can be solved when the pipe diameter is determined. On the premise of passing the elbow, the robot length ratio will decrease with the increase of the expansion diameter ratio as shown in Fig. 7. When the robot completely shrinks, the expansion diameter of the robot is 250 mm, if the pipe diameter is 310 mm, and the maximum length of the robot is 532 mm, which is larger than the actual length of the robot ($l$ = 338 mm). The results show that the designed pipeline robot satisfies the pipe geometry constraints and can pass through the elbow with $R \geqslant 1.5D$.

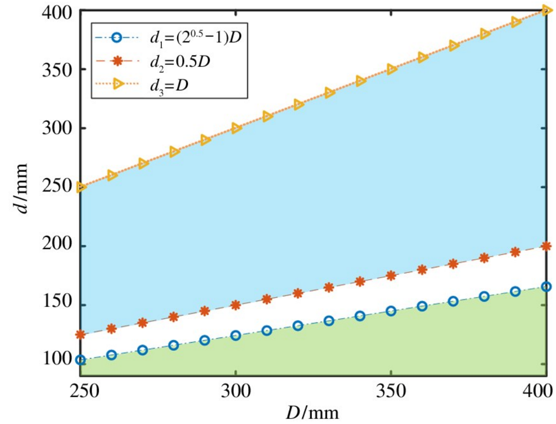



**Fig. 6** The relationship between $D$ and $d$

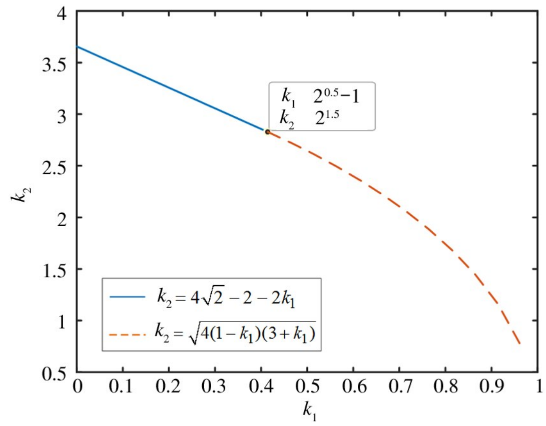



**Fig. 7** The relationship between $k_1$ and $k_2$

## 2.2 Steering constraint analysis

When the pipeline robot passes through the elbow, the displacement of the crawler module is different. Therefore, the pipeline robot should not only satisfy the geometric constraints, but also satisfy the steering constraints. The process through the elbow pipeline is divided into two stages, i. e., transition stage and steering rotation stage.

Taking the curvature center $O$ at the elbow section as the coordinate origin, the $\{O\}$ coordinate system is established. The $x$ axis is parallel to the velocity direction when the pipeline robot enters the elbow, the $z$ axis is perpendicular to the plane formed by the pipeline center axis, and the $y$ axis is perpendicular to the plane $xOy$ according to the right-hand principle.

When the pipeline robot travels, the driving wheel of each crawler module is connected to the contact point of the pipe wall to form an end face perpendicular to the forward direction.

The robot coordinate system $\{O_r\}$ is established by taking the intersection point of the end face and the pipe axis as the origin of coordinates. The $x_r$ is along the central axis of the pipeline robot, and the positive direction is consistent with the forward direction. The $y_r$ axis is perpendicular to the $x_r$ axis, pointing to the central direction of the crawler module 1, and the $z_r$ axis is perpendicular to the $x_rO_ry_r$ plane. The positive direction conforms to the right-hand principle. Moreover, each crawler module does not affect each other, and the robot's motion process of the robot in the elbow can be understood as the rotation of each crawler module around the $z$ axis.

### 2.2.1 Transition stage

In this stage, the pipe robot does planar motion, therefor it can be analyzed by rigid body planar motion as shown in Fig. 8. In the initial state, the contact points between the three groups of crawler modules and the front of the pipeline's inner wall are about to enter the elbow section, and the matrix of the coordinates of the front and back contact points in the robot coordinate system is expressed as (replace cos, sin with $s$, $c$ in the matrix)

$$W_f = \begin{bmatrix} l & l & l \\ \frac{1}{2}Dc\varphi & \frac{1}{2}Dc(\varphi + \frac{2\pi}{3}) & \frac{1}{2}Dc(\varphi - \frac{2\pi}{3}) \\ \frac{1}{2}Ds\varphi & \frac{1}{2}Ds(\varphi + \frac{2\pi}{3}) & \frac{1}{2}Ds(\varphi - \frac{2\pi}{3}) \end{bmatrix} \tag{4}$$

$$W_b = \begin{bmatrix} 0 & 0 & 0 \\ \frac{1}{2}Dc\varphi & \frac{1}{2}Dc(\varphi + \frac{2\pi}{3}) & \frac{1}{2}Dc(\varphi - \frac{2\pi}{3}) \\ \frac{1}{2}Ds\varphi & \frac{1}{2}Ds(\varphi + \frac{2\pi}{3}) & \frac{1}{2}Ds(\varphi - \frac{2\pi}{3}) \end{bmatrix} \tag{5}$$

where, $l$ is the length between the front and the rear contact points of the crawler module; $\varphi$ is the attitude angle of pipeline robot, as shown in Fig. 9.

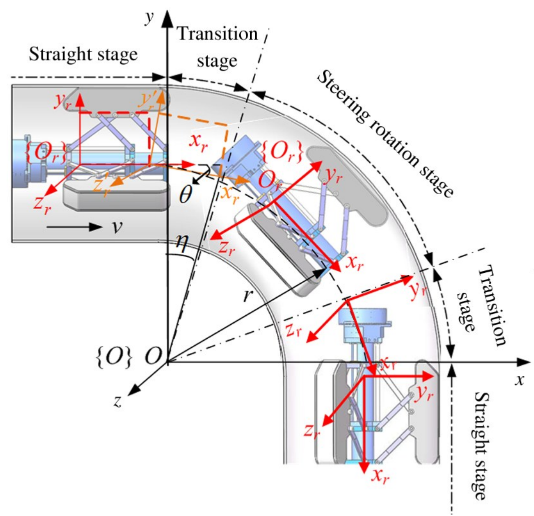



**Fig. 8** The process through the elbow pipeline

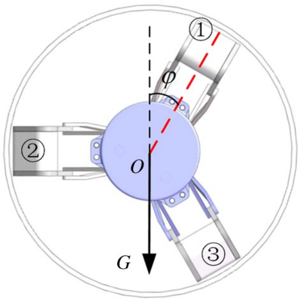



**Fig. 9** Attitude angle of pipeline robot

In a certain state of the transition stage, the translation vector of the robot in the world coordinate system is

$$T = \begin{bmatrix} r\sin\eta - l\cos\theta \\ r \\ 0 \end{bmatrix} \tag{6}$$

where, $\eta$ is the turning angle of the center of the robot's front face in the elbow, $\theta$ is the rotation angle of the robot coordinate system.

According to the position relationship of robot in the transition stage, it can be obtained as

$$r(1 - \cos\eta) = l\sin\theta \tag{7}$$

In the robot coordinate system, the pipeline robot rotation matrix is

$$\boldsymbol{R} = \boldsymbol{Rot}(z,\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{8}$$

In the coordinate system $\{O\}$, the coordinates of the contact point between the robot crawler module and the pipeline's inner wall can be described as

$$\begin{cases} \boldsymbol{W'}_f = \boldsymbol{R} \cdot \boldsymbol{W}_f + \boldsymbol{T} \\ \boldsymbol{W'}_b = \boldsymbol{R} \cdot \boldsymbol{W}_b + \boldsymbol{T} \end{cases} \tag{9}$$

The velocity of the contact point between the robot crawler module and the pipeline's inner wall can be described as the derivation of $\boldsymbol{W'}_b$ and $\boldsymbol{W'}_f$ for time.

$$\frac{d\boldsymbol{W'}_f}{dt} = \begin{bmatrix} v_{f_{x1}} & v_{f_{x2}} & v_{f_{x3}} \\ v_{f_{y1}} & v_{f_{y2}} & v_{f_{y3}} \\ 0 & 0 & 0 \end{bmatrix} \tag{10}$$

$$\frac{d\boldsymbol{W'}_b}{dt} = \begin{bmatrix} v_{b_{x1}} & v_{b_{x2}} & v_{b_{x3}} \\ v_{b_{y1}} & v_{b_{y2}} & v_{b_{y3}} \\ 0 & 0 & 0 \end{bmatrix} \tag{11}$$

where, $v_{f_{xi}}$ and $v_{f_{yi}}$ ($i = 1, 2, 3$) represent the $x$, $y$ direction components of the front-end contact point world coordinate system $\{O\}$; $v_{b_{xi}}$ and $v_{b_{yi}}$ ($i = 1, 2, 3$) are the components of the $x$, $y$ direction of the rear-end contact point world coordinate system $\{O\}$ and the absolute velocity of the back-end contact point is

$$\begin{cases} v_{fi} = \sqrt{v_{f_{xi}}^2 + v_{f_{yi}}^2} \\ v_{bi} = \sqrt{v_{b_{xi}}^2 + v_{b_{yi}}^2} \end{cases} \tag{12}$$

In the robot's transition stage, the velocity ratio of the front and robot's rear contact points should be coordinated and controlled to be equal to the rotational speed ratio, namely

$$n_{f1} : n_{f2} : n_{f3} : n_{b1} : n_{b2} : n_{b3} = v_{f1} : v_{f2} : v_{f3} : v_{b1} : v_{b2} : v_{b3} \tag{13}$$

However, due to the same speed of the crawler robot's front and rear ends, it will inevitably lead to internal friction. Therefore, the robot should slow down in the transition stage to reduce internal friction and increase smoothness.

2.2.2 Steering rotation stage

The steering rotation stage of the pipeline robot is similar to the transition stage, as shown in Fig. 8. The pipeline robot rotates around the $z$ axis of the world coordinate system. To reduce internal friction and increase the operation stability of the robot, the velocity ratio of the front and back contact points between the robot crawler module and the pipeline's inner wall should be equal to the ratio of the radius of curvature corresponding to the contact points, so that the robot can pass through smoothly. Therefore, the motion constraint model of the robot in the rotation stage is

$$n_1 : n_2 : n_3 = R_1 : R_2 : R_3 \tag{14}$$

where, $n_i$ and $R_i$ are respectively the speed of the $i$th crawler module and the radius of rotational curvature of the contact point between the crawler module and the elbow ($i = 1, 2, 3$).

Since the pipeline robot is designed with a modular structure and each crawler module is identical, the three groups of crawler modules' velocity can be coordinated and controlled according to Eq. (14), so that the robot can pass the rotation stage smoothly.

## 3 Experimental study

### 3.1 Control system design

Robot control is a very complicated process, and the control system belongs to nonlinear system. It is impossible to construct a complete and accurate object model because the robot parameters obtained are not very accurate. There are a lot of non-deterministic factors for the specific application environment. To improve the quality of control, proportion integral differential (PID) control, fuzzy control and neural network control are often used. In this paper, the PID algorithm of AQMD2408BLS-M driver is used to realize the speed control of tracked robot. The robot's control system is composed of host computer, sensor, driver and cable, as shown in Fig. 10.

The host computer module controls the AQMD2408BLS-M driver to perform motor drive through

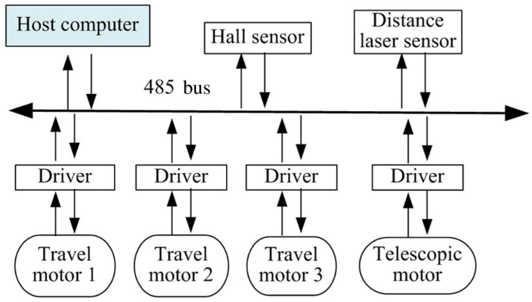



**Fig. 10** Control system structure diagram

the 485 bus output control instruction; at the same time, the hall sensor and the laser ranging sensor perceive the running state and the surrounding environment of the robot, and the motor parameters and the distance from the elbow are transmitted to the driver in real time. The sensor information returned by the sensor module is received through the 485 bus, and the information is fed back to the host computer. The corresponding processing and adjustment of the motor output are carried out to realize the robot's effective motion control in the pipe.

## 3.2 Robot steering motion experiment

As shown in Fig. 11, the cornering performance of the robot is tested by combining two straight pipes and one elbow pipe.

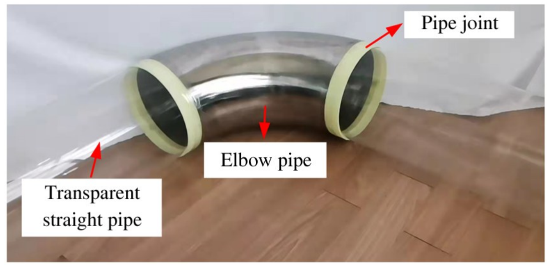



**Fig. 11** Pipeline structure

The parameters of the pipeare shown in Table 1.

Table 1 Parameters of the pipeline

| Pipeline | Parameter | |
|---|---|---|
| Straight | Length | 1500 mm |
| | Inner diameter | 310 mm |
| Elbow | Inner diameter | 319 mm |
| | Curvature radius | 423 mm |
| | Bending angle | 90 ° |

The prototype of the pipeline robot is shown in Fig. 12. Fig. 12(a) shows the pipeline robot in fully extended state and Fig. 12(b) shows the pipeline robot in fully contracted state.

(a) Full extension state (b) Full contraction state (c) Side view

**Fig. 12** Robot prototype

The pipeline robot decelerates and passes in the transition stage, and the steering speed constraint model is adopted in the steering rotation stage, and the attitude angle of entering the elbow is set to 0 °. The pipeline robot steering motion experiment process as shown in Fig. 13 and the six groups of expansion diameter data and experimental results are shown in Table 2. The experiments show that the geometric constraint model of the pipeline robot is effective.

To verify the feasibility of the pipeline robot's steering motion constraint model, the speed of the crawler module is set according to the steering constraint (SC) model and the constant speed (CS) model of the three crawler modules. In the experiment, the speed setting of the robot is shown in Table 3.

Table 2 Extension diameter data and the results

| Extension diameter | Experimental results |
|---|---|
| 270 mm | successful |
| 275 mm | successful |
| 280 mm | successful |
| 285 mm | failed |
| 290 mm | failed |
| 295 mm | failed |

Table 3 Robot speed setting

| Crawler module | Straight pipe stage/(m/min) | Transition stage/(m/min) | Turning stage/(m/min) |
|---|---|---|---|
| C1 | 4 | 3 | 1.37 |
| C2 | 4 | 3 | 2.96 |
| C3 | 4 | 3 | 2.16 |


**Fig. 13** Robot steering motion experiment process

Since the internal friction of the robot is linearly correlated with the current, the average current of the robot crawler travelling module is used to represent the robot's internal friction.

The experimental results show that the current changes of two models is different when robot pass through the elbow, as shown in Figs14 – 16, which are the current comparison diagrams when passing through the elbow at 0 °, 30 ° and 90 ° attitude angles, respectively. It can be found that the peak value and fluctuation degree of the robot motor current increase significantly when CS model passes through the elbow regardless of the attitude, while SC model passes through the elbow and the robot motor current remains stable and the peak value is small in the steering rotation stage. As can be seen from Figs14 – 16, the maximum current of SC model is 1.45 A, while the maximum current of CS model is 2.3 A, and the maximum current of SC model is 36.96% lower than that of CS model. Thus, SC model can effectively reduce the internal friction of motor, which verifies the rationality of SC model.

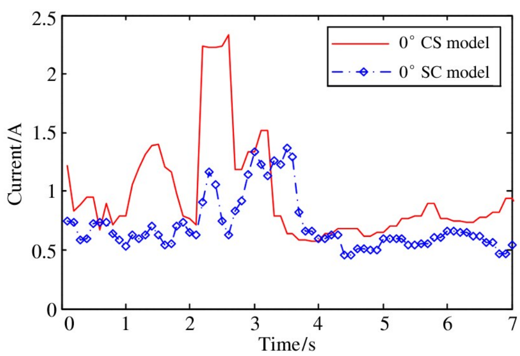



**Fig. 14** Motor current comparison at 0 ° attitude angle

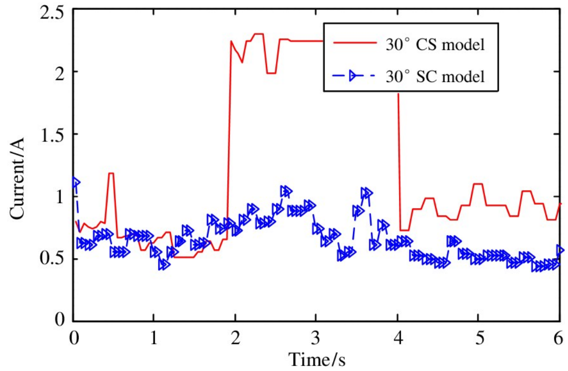



**Fig. 15** Motor current comparison at 30 ° attitude angle

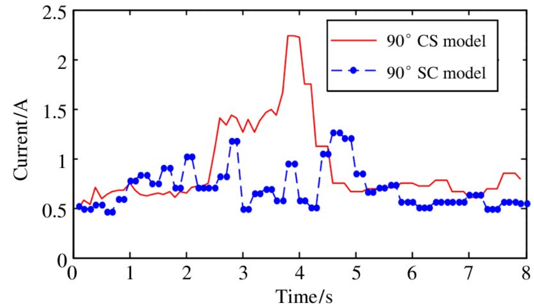



**Fig. 16** Motor current comparison at 90 ° attitude angle

## 4 Conclusions

A supported crawler pipeline robot is designed to adapt to the changing pipeline diameter, which has good cornering performance. A geometric constraint model and a steering constraint model are proposed, and the robot steering motion experiments are performed. When the pipeline robot travels in a straight pipe, the actual current is less than the maximum current of the motor, and the robot travels smoothly; when passing through elbow, the speed of the pipeline robot is set according to the geometric constraint model and the steering speed constraint model, which can smoothly pass through the curved pipe, and at the same time, it can be greatly reduce the motor current, reduce energy consumption. When the pipeline robot turns, the maximum current of crawler module motor with SC model is reduced by 36.96% compared with CS model, which verifies the feasibility of the SC model.

**Reference**

[ 1 ] LIU Q Y. Research status and development tendency of the oil and gas in-pipe robot[J]. Journal of Xihua University (Natural Science Edition), 2016, 35:1-6.

[ 2 ] FENG G, LI W, ZHANG H, et al. Development of a wheeled and wall-pressing type in-pipe robot for water

pipelines cleaning and its traveling capability [J]. Mechanics, 2020, 26(2): 134-145.

[3] RASHID M, YAKUB F, SALIM S, et al. Modeling of the in-pipe inspection robot: a comprehensive review [J]. Ocean Engineering, 2020, 203: 107206.

[4] HABIB M R, AHMED K, REZA A S, et al. An arduino based robot for pipe surveillance and rescue operation [C] // The 22nd International Conference on Computer and Information Technology. Dhaka: IEEE, 2019: 1-5.

[5] SHAO L, WANG Y, GUO B, et al. A review over state of the art of in-pipe robot [C] // IEEE International Conference on Mechatronics and Automation. Beijing: IEEE, 2015: 2180-2185.

[6] XUE Y Y, ZHANG J Z, ZHANG L. Design of pipeline robot adaptive mechanism and analysis of crossing obstacle [J]. Manufacturing Automation, 2018, 40(6): 29-32.

[7] REN T, ZHANG Y, LI Y, et al. Driving mechanisms, motion, and mechanics of screw drive in-pipe robots: a review [J]. Applied Sciences, 2019, 9(12): 2514.

[8] JANG H, KIM T Y, LEE Y C, et al. Autonomous navigation of in-pipe inspection robot using contact sensor modules [J]. IEEE/ASME Transactions on Mechatronics, 2022, 27(6): 1-10.

[9] WOO J M, MYUNGSOO J, HAHM J, et al. Development of high traction in-pipe robot adjustable 500 ~ 800 mm pipe and verification of the capability [J]. Journal of Power System Engineering, 2021, 25(4): 52-61.

[10] XU L, ZHANG L, ZHAO J, et al. Cornering algorithm for a crawler in-pipe inspection robot [J]. Symmetry, 2020, 12(12): 2016.

[11] NAGASE J, FUKUNAGA F, ISHIDA K, et al. Steering system of cylindrical elastic crawler robot [J]. IEEE Journal of Industry Applications, 2018, 7(5): 441-442.

[12] FUKUNAGA F, NAGASE J. Cylindrical elastic crawler mechanism for pipe inspection inspired by amoeba locomotion [C] // IEEE International Conference on Biomedical Robotics and Biomechatronics. Singapore: IEEE, 2016: 424-429.

[13] ALLEN J, RUTAN-BEDARD S, FEKRMANDI H. Robotic inspection crawler for small diameter complex piping [C] // USCToMM Symposium on Mechanical Systems and Robotics. Rapid City: Springer, 2020: 298-309.

[14] ZHANG L, WANG X. Stable motion analysis and verification of a radial adjustable pipeline robot [C] // IEEE International Conference on Robotics and Biomimetics. Qingdao: IEEE, 2016: 1023-1028.

[15] KAKOGAWA A, MA S, HIROSE S. An in-pipe robot with underactuated parallelogram crawler modules [C] // IEEE International Conference on Robotics and Automation. Hong Kong: IEEE, 2014: 1687-1692.

[16] KAKOGAWA A, MA S. Speed analysis for three driving modules of an in-pipe inspection robots for passing through bent pipes [C] // IEEE International Conference on Robotics and Biomimetics. Bali: IEEE, 2014: 1731-1736.

[17] CHEN X, WU Z P, HE S Y, et al. Passing property design of adaptive support pipeline detection robot [J]. Journal of Central South University, 2018, 49(12): 2953-2962.

[18] YAN H W, WANG Y, MA J Q, et al. Analysis of dynamic characteristics of wheeled pipeline robot bending [J]. Journal of Xi'an Jiaotong University, 2018, 52(8): 87-94.

[19] ZHAO W, ZHANG L, KIM J. Design and analysis of independently adjustable large in-pipe robot for long-distance pipeline [J]. Applied Sciences-Basel, 2020, 10(10): 3637.

[20] SURYAVANSHI K, VADAPALLI R, VUCHA R, et al. Omnidirectional tractable three module robot [C] // 2020 IEEE International Conference on Robotics and Automation. Paris: IEEE, 2020: 9316-9321.

[21] XIE T Y, LI Q, DING Y W, et al. Design and analysis of a multi-module snake shaped pipeline grinding robot [J]. Robot, 2020, 42(6): 672-685.

**GENG Linkang**, born in 1997. He received his B. S. degree from Shandong University of Science and Technology in 2019. Now he is a postgraduate student in School of Mechatronic and Engineering Automation, Shanghai University. His research interest is pipeline robot technology.