Development of an In-Pipe Robot With Differential Screw Angles for Curved Pipes and Vertical Straight Pipes

The in-pipe robots based on screw drive mechanism are very promising in the aspects of pipe inspecting and maintaining. The novel design of an in-pipe robot with differential screw angles is presented for the curved pipes and vertical straight pipes. The robot is mainly composed of the screw drive mechanism, adaptive linkage mechanism, and the elastic arm mechanism. The alternative adjusting abilities of the mobile velocity and traction, and the adaptive steering ability in curved pipes, are achieved by the special designs. A parameter design approach in consideration of the climbing and steering abilities is proposed in detail for the springs and length of the elastic arms. The results are applied to the prototype design of the robot. In several groups of experiments, the proposed robot is competent to pass through curved pipes and vertical straight pipes. The results prove that the proposed mechanism and parameter design approach are both valid. [DOI: 10.1115/1.4037617]

Keywords: screw drive, in-pipe robot, parameter design

1 Introduction

Kinds of pipelines have been applied to transportation of petroleum or natural gas for decades. In the industrial and urban systems, pipelines are also the most economical and efficient transportation facilities. However, many accidents have been occurred due to the failure of aged pipes. Therefore, it is necessary for regular inspections of the pipes [1,2]. The way of manual inspection is time-consuming and impracticable, especially when the pipes cannot be accessed by workers. Therefore, many kinds of in-pipe robots are developed for inspecting pipes. These robots can carry cameras, ultrasonic or magnetic sensors to detect and feedback fault messages [3]. In recent years, the in-pipe robots of the active wheeled type, the crawler type, the worm type, and the screw drive type have attracted much attention [4–6]. The active wheeled in-pipe robots have better mobile speed and efficiency [7–9]. The crawler in-pipe robots with the caterpillar mechanism can output large traction force [10]. The worm in-pipe robots move by expanding and contracting the chambers alternately [11]. The screw drive in-pipe robots have a simple mechanism and can drive forward by only one motor [12].

Many robots have been developed based on the screw drive mechanism in consideration of the good motion efficiency and simple mechanism. Iwashina et al. developed an early micro
screw drive in-pipe robot that can move inside a pipe of 20 mm in diameter [13]. The simple transmission principles of the screw drive mechanism are beneficial to miniaturization. In the later researches on screw drive in-pipe robots, more attention has been focused on the traction capacity and the steering capacity. Hirose et al. developed an in-pipe robot with the load-sensitive continuously variable transmission that can adjust the traction force passively [14]. However, the adjustment ability is unidirectional. Li et al. proposed an in-pipe robot based on an adaptive mobile mechanism [15]. Although this robot has two output paths of power transmission that can adaptively adjust traction force based on the environmental resistance, this traction adjusting capacity is also unidirectional. In order to obtain a bidirectional traction adjusting capacity, Li et al. proposed an in-pipe robot whose screw angles are controllable [16]. Liu et al. developed an in-pipe robot based on the active screw drive mechanism that can provide a big tractive force [17].

As respects for the steering capacity, Horodinca et al. developed several robots whose modules are connected by the passive universal shaft [18]. This design can decrease the collisions between the body and the inner wall of the pipes, and then the steering capacity of the robot is improved. Yabe et al. developed an in-pipe robot capable of inspecting pipes with different diameters [19]. This robot is composed of units and connecting links with active universal shaft. Therefore, the robot can steer in curved pipes. Kakogawa et al. developed a screw drive in-pipe robot based on the pathway selection mechanism [20]. This robot can pass through bent and branch pipes. The steering mechanism designs mentioned by the earlier researches have improved the steering capacity of the screw drive in-pipe robots. However, when the robot turns in the curved pipes, the motion interference probably occurs between the screw rollers of the robot and the inner wall of the pipes. This is because that the speeds of the screw rollers are not adjusted adaptively based on the respective steering radius. The motion interference maybe bring the roller slipping and the useless power consumption. As for active wheeled robots, the steering is usually realized by the complex differential control methods which is based on the robot’s pose estimating relative to its environment from sensor data [21]. Moreover, the steering capacity and the traction capacity are not carefully considered together. It is important for the robot to have the adaptive steering ability in curved pipes and the active adjusting ability of traction force.

Therefore, in this paper, a screw drive in-pipe robot is proposed, which can pass through varied curved pipes, and actively adjust traction force bidirectionally. The mechanism design and the key parameter design method are both considered. A reliable and fast design approach is necessary in different application situations where the diameters of the pipe are different or the demands of the traction force are different.

For the parameter design, we mainly focus on the design methods of the spring parameters and the elastic arm length. The spring stiffness and preload force that is generated by the rollers pressing on the wall determine the maximum traction force. So, it is important to choose the suitable values for the spring stiffness and preload force. When the robot moves inside a curved pipe, the cross section of the screw rollers is similar as an egg [22]. The length of each elastic arm is changeable real-timely with the rotation of the body. Therefore, the initial length and the minimum length of the elastic arm should satisfy the maximum elongation amount and compression amount when the robot turns in curved pipes. Otherwise, the screw rollers of the robot may lose contact or collide with the inner wall of the pipe.

This paper is organized as follows: Section 2 presents the mechanism design of the screw drive in-pipe robot based on the adaptive linkage mechanism. In Sec. 3, the design method of the spring stiffness, the preload force and the elastic arm length is proposed in consideration of the kinematic model and the statics model. In Sec. 4, the experiments are conducted to verify the validation of the design method. The conclusions are listed in Sec. 5.

2 Mechanism Design

2.1 Structure Overview and Motion Principles. The core idea of the mechanism improvement is to realize the smooth movement in straight and curved pipes and the adjustment of traction force of the robot simultaneously with some simple and novel ways. Generally, the speeds of screw rollers on the screw drive in-pipe robots are controlled synchronously by the driving motor. This is why the motion interference occurs in the curved pipes. As shown in Fig. 1(a), the speed $V_{\text{out}}$ of outside roller should be faster than the speed $V_{\text{in}}$ of inside roller just as the smooth steering of cars. Therefore, it is necessary to change each roller’s speed $v_i$ in order to avoid motion interference and power wasting. It means that each roller’s speed $v_i$ can be adjusted not only independently but also harmonically for a common forward speed of the robot. In Fig. 1(b), the mobile relation is established as Eq. (1) which reveals that $v_i$ can be adjusted independently only by $z_i$ and $R_i$, and $\dot{\theta}$ changes all of the rollers’ speeds simultaneously.

\[
v_i = \frac{\partial R_i \tan z_i}{R_i} - a_i \quad (1)
\]

where $v_i$, $\dot{\theta}$, $R_i$, and $z_i$, respectively, denote the forward speed of the $i$th roller, rotational speed of the driving motor, rotational radius, and screw angle of the $i$th roller.

In the steering, the cross section of the screw rollers is similar as an egg and the length of the arms should change adaptively to avoid losing contact as shown in Fig. 1(c). Therefore, it is an infeasible way to adjust $v_i$ by changing $R_i$.

As shown in Fig. 2, if the speeds of the rollers are adjusted by changing the screw angles properly, the robot can smoothly pass through the straight and curved pipes. Moreover, the traction force and mobile speed of the robot can also be adjusted by the screw angles without controlling driving motor [13]. Based on these ideas, an in-pipe robot with differential screw angles is designed for curved pipes and vertical straight pipes.

As depicted in Fig. 3(a), the proposed screw drive in-pipe robot is mainly composed of four parts: screw drive mechanism, adaptive linkage mechanism, rotational elastic arms, and supporting elastic arms. The screw drive mechanism provides rotational driving torque for the adaptive linkage mechanism through a rotational joint. The elastic arms are arranged circularly around the body of the robot. The rollers can be tightly pressed onto the inner wall of the pipes. Thus, the robot can move continuously by converting the rational torque into the axial propulsion force. The screw angles can be actively and passively changed by the adaptive linkage mechanism. The detailed mobile principles are listed as follows:

(a) The robot can move straight forward when the three screw angles are equal to each other.
(b) The traction force and mobile speed of the robot can be changed by controlling the screw angles. When the screw angles increase, the mobile speed increases, but the traction force decreases. When the screw angles decrease, the traction force increases, but the mobile speed decreases.
(c) The robot moves backward by decreasing the screw angles to the opposite direction.
(d) When the robot moves inside curved pipes, the screw angles are adjusted mechanically adaptively by the reactive force from the pipe. The adjusted screw angles can change the speeds of the rollers in proportion to the respective steering radius.

2.2 Screw Drive Mechanism. The screw drive mechanism serves as a power unit and a stator and its mechanism design is shown in Fig. 3(b). The driving motor is fixed onto the cage. The output shaft of the driving motor is connected with the spur gear $s_j$ by the coupling. The teeth of spur gear $s_j$ engage with those of
spur gear $s_2$. Then, the driving torque from the driving motor is amplified and transmitted to the adaptive linkage mechanism. In order to avoid cable twisting, a slip ring and a cable passageway are designed for the cables of power supply, controller, and data collection that run through the whole body of the robot.

2.3 Adaptive Linkage Mechanism. The design of the adaptive linkage mechanism is the kernel of the proposed robot. As shown in Fig. 3(c), it mainly consists of a servo motor and a set of triaxial differential gear transmission mechanism. The adaptive linkage mechanism can work in two modes.

2.3.1 Active Control Mode. When the servo motor increases the input angle of the adaptive linkage mechanism, all the three screw angles increase, and vice versa.

2.3.2 Adaptive Adjustment Mode. When the external forces acting on the screw rollers are not equal to each other, the three screw angles are adjusted differentially in order to obtain suitable mobile speeds.

The mechanism is designed symmetrically, and its schematic diagram is shown in Fig. 4. The output shaft of the servo motor is fixed with the planet carrier $H_1$ of the planetary gear train $a$. The output ring gear $g_{ts}$ of the planetary gear train $a$ is connected with the input planet carrier $H_2$ of the planetary gear train $b$. The two planetary gear trains form a tridifferential mechanism. The sun gear $g_{sa}$, ring gear $g_{SA}$, and sun gear $g_{sa}$ are the three outputs. In order to convert these outputs to the screw angles, the circular symmetrical output gear transmissions are designed. For example, the rotation motion of sun gear $g_{sa}$ is transferred to spur gear $g_{st}$ by its coaxial spur gear $g_{st}$. Then, the transmitting direction is changed by two bevel gears $g_{st}$ and $g_{sb}$. The new direction of spur gear $g_{st}$ is vertical to the original direction. Finally, $g_{so}$ is engaged with spur gear $g_{so}$ that is fixed on the end of the elastic arm.

The angle and rotational speed relationship between the input angle $\theta_H$ of the servo motor and the screw angles $\alpha_i$ can be, respectively, expressed as

$$\alpha_1 + \alpha_2 + \alpha_3 = 3\theta_H i_i = 3\theta_0$$  \hspace{1cm} (2)

$$\dot{\alpha}_1 + \dot{\alpha}_2 + \dot{\alpha}_3 = 3\omega_H i_i = 3\dot{\theta}_0$$  \hspace{1cm} (3)

where $i_i$ represents the transmission ratio of the adaptive linkage mechanism, and $\omega_H$ is the rotational speed of the servo motor.

As shown in Fig. 4, when the robot is moving inside a curved pipe, the forces acted on the rollers by the inner wall would be different due to the different speed demands. Taking the planar situation, for example, the force $F_{w1}$ on the outward screw roller will be larger than the force $F_{w2}$ on the inner screw roller, if the screw angles still remain the same. Therefore, unbalanced torques act on the gears of the triaxial differential mechanism, and then the mechanism adjusts the screw angles adaptively without any active control until the speed and force come to a new balance. In pipes of different curvature radius, the reasonable screw angles can be always found adaptively.

2.4 Elastic Arm Mechanism

(a) Supporting elastic arms. As shown in Fig. 5(a), the supporting elastic arm is mainly composed of the pedestal, spring, casing, slider bar, and two rollers side-by-side. It can be compressed or extended due to the flexibility of the internal spring. The axis of the roller is intersecting with
the axis of the slider bar. This feature is advantaged for the robot to move forward and backward. Compared to one roller, two rollers arranged side by side can make the robot move more steadily.

(b) Rotational elastic arms. The elastic arm can rotate with the output of the adaptive linkage mechanism. Therefore, the screw angles are adjusted. As shown in Fig. 5(b), the elastic arm is fixed onto the shell of adaptive linkage mechanism by the pedestal. It obtains a rotational freedom by the bearing. The rotational freedom is controlled by the spur gear. The other spur gear is designed for the feedback to the potentiometer that can measure the screw angles. The spring is placed outside the slider bar in order to obtain better extension and compression amount. The cantilever bar is designed for environmental acting force feedback to the adaptive linkage mechanism. As shown in Fig. 5(c), the
environmental acting force $F_p$ with its moment arm $L$ forms a torque transmitting to the spur gear of the adaptive linkage mechanism. If a centered roller is utilized in the point $Q$, $F_p$ will act on $Q$, the moment arm $L$ becomes zero. Then, the environmental acting force cannot be fed back to the adaptive linkage mechanism.

3 Conservative Design Approach for Spring and Arm Length

For the robot design in different dimensions, the parameters of springs and arm lengths are difficult to be determined by intuition or experience. Therefore, a conservative design approach is proposed based on the simple kinematic and statics models. The preload force of the spring is first decided by the robot’s gravity that is regarded as the minimum resistance force in the vertical straight pipes. Then the maximum and minimum arm length can be obtained by the numerical analysis of the steering model. The spring stiffness is determined by the spring stiffness formula. In the design process, the actual selected parameters are determined conservatively in consideration of the mobile ability assurance and engineering constraints.

3.1 The Preload Force of Spring. The preload force $F_0$ of the spring inside the rotational elastic arm is relative to the robot’s traction force that is along the axial direction. In order to make sure the motion ability in the vertical pipes, the preload force $F_0$ is determined in consideration of the gravity force $G_r$ of the robot. As shown in Fig. 6, the static model of the proposed robot in the vertical pipe is established. The normal friction force $f_n$ and the tangential friction force $f_t$ acted on the screw roller. $f_t$ belongs to the rolling friction force. Therefore, $f_t$ is ignored due to its tiny value in the analysis below. The screw angle is denoted as $\alpha_i$ ($i=1,2,3$). The gravity force $G_r$ is the main resistance force that the robot needs to overcome. $\tau$ is the driving torque from the screw drive mechanism. In the direction of $Y_s$-axis, the component $F_Y$ of the total normal friction force whose value is equal to that of the robotic traction force can be expressed as

$$F_Y = 3f_n \cos \alpha_i$$

(4)

The normal friction force $f_n$ is related with $F_Y$. When $\alpha_i$ is selected, $F_Y$ is determined by the maximum normal friction force $f_{n,max}$. Therefore, the robot can climb up in the vertical pipe only when the relationship below is satisfied. That is, to say, the value of the traction force is equal to $G_r$,

$$G_r \leq 3f_{n,max} \cos \alpha_i$$

(5)

$\tau$ is the source of the driving force. The value of $\tau$ should be selected by
\[ \tau \geq 3R_qf_{n_{\text{max}}} \sin \alpha \]  

(6)

where \( R_q \) is the radius of the pipe.

The top view of the static model is shown in Fig. 7. The length of the elastic arm is \( l_0 \), \( F_0 \) is the pressure force from the spring. The inner wall of the pipe has a normal pressure force \( N_1 \) on the roller. The direction of \( N_1 \) passes through the axis of the roller and the axis of the pipe. \( N_1 \) determines the maximum normal friction force \( f_{n_{\text{max}}} \)

\[ f_{n_{\text{max}}} = \mu N_1 \]  

(7)

where \( \mu \) is the frictional coefficient between the roller and the inner wall of the pipe, which is related to the materials.

The relationship between \( F_0 \) and \( N_1 \) can be expressed as

\[ F_0 = N_1 \cos \beta \]  

(8)

where \( \beta \) is the included angle between \( F_0 \) and \( N_1 \). \( \beta \) can be calculated by

\[ \beta = \arctan \left( \frac{e \cos \alpha}{l_0} \right) \]  

(9)

where \( e \) denotes the eccentric distance of the cantilever bar.

The radius of the screw roller is \( r_a \). Through the Pythagoras’s theorem, the length \( l_0 \) can be expressed as

\[ l_0 = \sqrt{(R_q - r_a)^2 - (e \cos \alpha)^2} \]  

(10)

Substitute Eqs. (5) and (7) into Eq. (8). The preload force of the spring \( F_0 \) can be obtained by

\[ F_0 \geq \frac{G_0 \cos \beta}{3 \mu \cos \alpha} \]  

(11)

3.2 The Arm Length in Curved Pipes. In curved pipes, the cross-sectional view of the screw rollers is similar as an egg rather than a circle. Therefore, the maximum length \( l_{\text{max}} \) and the minimum length \( l_{\text{min}} \) of the elastic arm should be designed reasonably. If \( l_{\text{max}} \) is not long enough, the rollers are easily to lose contact with the inner wall of the pipes. The robot may not move forward successfully. If \( l_{\text{min}} \) is not short enough, the rollers probably collide with the inner wall stiffly. As shown in Fig. 8, the steering of the robot can succeed only if the following constraints are satisfied.

\[ \text{(1) The rollers are in contact with the inner wall of the pipes.} \]

The coordinates of the contact points should satisfy the geometric constraint equation of the curved pipes

\[ \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} R \cos \phi + R_a \cos \phi \cos \beta \\ R \sin \phi \\ R \sin \phi + R_a \sin \phi \cos \beta \end{bmatrix} \]  

(12)

where \( R \), \( \phi \), and \( \beta \) denote the curvature radius of the curved pipe, the steering angle, and the rotation angle in the radial section, respectively.

\[ \text{(2) The forward speed component } v_i \text{ (} i = 1, 2, 3 \text{)} \text{ of each screw roller should be proportional to the steering radius } R_i \text{ (} i = 1, 2, 3 \text{). Then, the robot can steer smoothly} \]

\[ v_1 : v_2 : v_3 = R_1 : R_2 : R_3 \]  

(13)

When the rollers of the robot are all in the curved pipe, the deformations of the elastic arms are the most severe. Therefore, it is reasonable to design the arm length in consideration of the situation where the robot is completely in the curved pipe. As shown in Fig. 9, the simplified kinematic model in the curved pipe is established in the global coordinate system \( O-XYZ \). The distance between the elastic arm section \( A \) of the adaptive linkage mechanism and the elastic arm section \( B \) of the screw drive mechanism is \( L \). The center point of the adaptive linkage mechanism in plane \( A \), and the center point of the screw drive mechanism in plane \( B \) are denoted as \( O_A \) and \( O_B \), respectively. Assuming that \( O_A \) and \( O_B \) are both on the axis line of the curved pipe when the robot moves. The coordinates of \( O_A \) and \( O_B \) can be calculated by

\[ O_A = \begin{bmatrix} R \cos (\phi_1 + 45) \\ 0 \end{bmatrix} \]  

(14)

\[ O_B = \begin{bmatrix} R \cos (45 - \phi_1) \\ 0 \end{bmatrix} \]  

(15)

where \( \phi_1 = \arcsin(0.5L/R) \).

The coordinate of \( O_1 \), that is, the midpoint of \( O_A \) and \( O_B \), can be calculated by

\[ O_1 = \begin{bmatrix} R \cos \phi_1 \cos 45^\circ \\ 0 \end{bmatrix} \]  

(16)

Rotate \( O-XYZ \) around \( Y \)-axis by 45 deg and move the original point to \( O_1 \). Then, the local coordinate system \( O_1-\hat{X}_1\hat{Y}_1\hat{Z}_1 \) is obtained. \( \theta_1 \) is the rotation angle of the \( i \)th elastic arm around \( Z_1 \). \( O_1-\hat{X}_1\hat{Y}_1\hat{Z}_1 \) is rotated by \( \theta_1 \) around \( Z_1 \) and \( O_1 \) is moved to \( O_2 \). Then, the local coordinate system \( O_2-\hat{X}_2\hat{Y}_2\hat{Z}_2 \) is established. The length of the \( i \)th elastic arm and the corresponding screw angle are denoted as \( l_i \) and \( \alpha_i \), respectively. The coordinate of \( O_3 \) in the \( O_2-\hat{X}_2\hat{Y}_2\hat{Z}_2 \) is \( (l_1, 0, 0) \). The coordinate system \( O_3-\hat{X}_3\hat{Y}_3\hat{Z}_3 \) is obtained by rotating \( O_2-\hat{X}_2\hat{Y}_2\hat{Z}_2 \) around \( X_2 \)-axis. The included angle of \( Y_2 \)-
axis and \(Y\)-axis is \(z_i\). In \(O_3X_3Y_3Z_3\), the coordinate of the contact point \(O_{wi}\) between the \(i\)th screw roller and the inner wall can be expressed as
\[
O_{wi} = \begin{pmatrix} r_w & -e & 0 \end{pmatrix}^T
\] (17)

The homogeneous transformation matrixes are calculated by
\[
^0T = \begin{bmatrix}
cos 45^\circ & 0 & -sin 45^\circ & R \cos \phi_i \cos 45^\circ \\
0 & 1 & 0 & 0 \\
sin 45^\circ & 0 & cos 45^\circ & R \cos \phi_i \sin 45^\circ \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (18)
\[
^{1/2}T = \begin{bmatrix}
cos \theta_i & -sin \theta_i & 0 & 0 \\
sin \theta_i & cos \theta_i & 0 & 0 \\
0 & 0 & 1 & L/2 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (19)
\[
^{1/3}T = \begin{bmatrix}
1 & 0 & 0 & l_i \\
0 & cos x_i & -sin x_i & 0 \\
0 & sin x_i & cos x_i & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (20)

where \(\theta_i = \theta + 2(i-1)\pi/3\), \(i = 1, 2, 3\). \(\theta\) is the rotation angle of the adaptive linkage mechanism.

The coordinate of \(O_{wi}\) in the global coordinate system \(O-XYZ\) can be calculated by
\[
\begin{pmatrix} \dot{O}_{wi} \end{pmatrix}^T = ^0T^{1/2}T^{1/3} \begin{pmatrix} r_w & -e & 0 \end{pmatrix}^T, \quad i = 1, 2, 3
\] (21)
\[
^0O_{wi} \quad \text{meets the geometric constraint of the pipe and substitute} \quad ^0O_{wi} \quad \text{into Eq. (12)}
\]
\[
^0O_{wi} = \begin{bmatrix}
R \cos \phi_i + R_p \cos \phi_i \cos \beta_i \\
R_p \sin \phi_i \\
R \sin \phi_i + R_p \sin \phi_i \cos \beta_i
\end{bmatrix}, \quad i = 1, 2, 3
\] (22)

The forward speed component \(v_i\) can be obtained by
\[
v_i = e_i \cdot e_{2z}(l_i + r_w)\dot{\theta} \tan x_i = (l_i + r_w)\dot{\theta} \tan x_i \cos(\phi_i - 45^\circ)
\] (23)

where \(e_i\) and \(e_{2z}\) denote the unit vectors of the forward direction and the \(Z_2\)-axis
\[
R_i = R + R_p \cos \beta_i
\] (24)

In order to obtain the length of the elastic arms and the changing tendency, an equation set is established by 12 equations, including Eqs. (2), (13) and (21). Simultaneously, there are 12 variables \((l_1, l_2, l_3, x_1, x_2, x_3, \phi_1, \beta_1, \phi_2, \beta_2, \phi_3, \beta_3)\). The equation set can be solved through Newton–Raphson method. When changing the initial value of \(l_i\) the curves of \(l_i\) and \(x_i\) can be drew by the numerical results. Then, the theoretical maximum and minimum length of the elastic arms are obtained.

The stiffness of the springs can be chosen by
\[
k = F_0/(l_{max} - l_0)
\] (25)

3.3 Design Approach and Implementation. The parameter design process of the spring and elastic arm length is summarized below in details.

Step 1. Initialize the basic parameters of the robot, including the gravity force \(G_r\), the eccentric distance \(e\), the radius of the screw roller \(r_w\), the frictional coefficient \(\mu\), the radius of the pipe \(R_p\), the curvature radius \(R\), and the screw angle \(\phi_i\).

Step 2. Calculate theoretical minimum value \(F_{0, min}\) of the preload force \(F_0\) of the spring by Eq. (11).

Step 3. Solve the equation set established by Eq. (2), Eq. (13), and Eq. (21), and obtain the theoretical maximum length \(l_{max}\) and minimum length \(l_{min}\) of the elastic arms, respectively.

Step 4. Select conservative values of \(l_{max}\) in case that the rollers lose contact with the inner wall of pipes. Renew the values by
\[
l_{max} = l_{max} + \Delta l_{max}
\] (26)

where \(\Delta l_{max}\) denotes the extension compensation amount of the arm length and its value is restricted by the engineering design space.

Step 5. Calculate spring stiffness \(k\) by Eq. (25) and decide it in consideration of the engineering constraints.

In the actual design of the proposed robot by above mentioned steps, the initial parameters are \(G_r = 20.5\ \text{N},\ e = 20\ \text{mm},\ r_w = 11\ \text{mm},\ \mu = 0.5,\ R_p = 104.5\ \text{mm},\ R = 313\ \text{mm},\ \phi_1 = 15\ \text{deg}\). In step 2, \(F_{0, min}\) is calculated by Eq. (11), and its value is 13.9 N. Through the simulation results of step 3, the theoretical values of \(l_{max}\) and \(l_{min}\) are obtained as 91.5 mm and 99 mm, respectively. As shown in Fig. 10, the length \(l_i\) \((i = 1, 2, 3)\) changes all along when the rotator rotates around \(Z_2\)-axis. The screw angles \(x_i\) are changing around 15 deg in Fig. 11. If the value of \(l_{max}\) is exactly selected as 99 mm, the roller will be at the risk of losing contact with the inner wall of the pipe. Therefore, the value of \(l_{max}\) is compensated by \(\Delta l_{max}\) whose value is 6 mm. In step 4, \(l_{max}\) is finally designed conservatively as 105 mm. \(k\) is obtained by step 5 and its value is designed as 2 N/m.

By the earlier design approach, the key parameters of the elastic arms are all obtained, that is \(k = 2\ \text{N/m},\ l_{max} = 105\ \text{mm},\ \text{and}\ l_{min} = 91.5\ \text{mm}.

4 Experiments

4.1 Robotic System Design. As shown in Fig. 12, the prototype of the proposed robot is designed based on the calculated results from the proposed design approach, and the detailed parameters of the robot are listed in Table 1. The maximum length of elastic arm is compensated and extended to 105 mm, which ensures that the robot’s rollers maintain contact with the inner wall of the pipe. The preload force of springs \(F_0\) is 23 N, which is large enough to provide a stable traction force even in vertical straight pipes.

In order to control the robotic in-pipe movement, a small-sized control board by Fujitsu microcontroller is developed. As shown in Fig. 13, a double-layer control system is built. On the laptop,
changed by the screw angles due to the special structure of the robot. Therefore, operators can not only control the movement but also observe the state of pipes and robot. 

Several groups of experiments are conducted to verify the design validity of the mechanism and parameter design approach.

4.2 Movement Speed Tests. As shown in Fig. 14(a), the robot moves smoothly in a straight pipe whose inner diameter is 209 mm. The robot has two modes to adjust the robot’s mobile velocity. One mode is that the mobile velocity is adjusted by the rotational speed of the driving motor; the other mode is that the mobile velocity is adjusted by the screw angles. As shown in Figs. 14(b)–14(d), the mobile direction of the robot can only be changed by the screw angles due to the special structure of the elastic arms. In order to observe and verify the relationship between the mobile velocity and the screw angles, the experiments are conducted with a valid movement distance of 1200 mm long, and the mobile time of each test is recorded. In Table 2, tests are repeated ten times for each screw angle, and the mobile velocity is obtained by calculating the mean value of measured results. The results indicate that the mobile velocity can be increased observably by amplifying the screw angles, and the test results are almost identical with the theoretical values computed by Eq. (1).

The changing screw angles detected by the potentiometer sensors are shown in Fig. 15. The result indicates that the screw angles can be changed by the servo motor and their values are almost the same in the straight pipe due to the uniform acting forces from the pipe.

The smooth and controllable movement of the robot proves that the proposed conservative design approach is valid when the robot is in the horizontal straight pipes.

4.3 Climbing in Vertical Straight Pipes. In the design of elastic arms in Sec. 3, the climbing ability is considered in vertical straight pipes when screw angles $\alpha_i$ are all 15 deg. Therefore, it is necessary to test the movement in vertical straight pipes.

As shown in Fig. 16, verified experiments are completed in a vertical straight pipe of polyvinyl chloride materials. The result shown that the robot can move up smoothly and stably with about 39 s from the pipe’s bottom to the top of 1.5 m long. When the robot climbs up, it almost succeeds every time. However, when the robot moves down, the screw angles must be adjusted slowly and carefully in case that the robot drops down suddenly. This is because that the length of the elastic arms decreases with the decreasing screw angles due to the special arm structure of cantilever bar. Then, the pressing force onto the inner wall of the pipe is lost in a moment. The three screw angles almost maintain the same as those in the horizontal pipes.

Furthermore, when $\alpha_i$ increases up to 20 deg, the robot cannot climb up any more. This result reveals that the load ability of the robot decreases with the screw angle increasing. On the contrary, the load ability increases with the screw angle decreasing. The alternative adjusting mode independent of the output torque of the driving motor can make the robot work more efficiently through some optimal control method.

The experiment results in the vertical straight pipes verify the validity of the proposed parameter design approach. The selected parameters of the spring and arm length can make the robot climb stably.

4.4 Movement in Curved Pipes. The steering tests are made in several standard types of curved pipes ($D = 209$ mm), including different bending angles $\Phi = 45$ deg, 90 deg) and curvature radius $R = D/2$ as shown in Fig. 17. These basic types of pipes are assembled into different configurations for steering tests.

First, the tests are conducted in a curved pipe whose curvature radius $R = 1.5D$. As shown in Fig. 17(a), both ends of the curved pipe are connected with a straight pipe of 500 mm long, and the pipes are positioned horizontally. The results show that the robot can always succeed in striding the pipe and reach the other end. As shown in Fig. 17(b), the robot climbs up and steers simultaneously in the pipe that is positioned with an inclined angle. The experiment results show that the robot can still pass through the pipe adaptively by the mechanical adjusting screw angles.

In order to test the mobile ability, two pipes with more complex configuration are established as shown in Figs. 17(c) and 17(d). The robot can pass through these pipes smoothly and convert naturally among the pipes with different curvature radius. With multiple tests, the results prove that the proposed robot and the parameter design method are always valid in the curved pipes of $R = 1.5D$ and $R = 2D$, which is just anastomotic to the theoretical
design \((R = 1.5 \, D)\). However, the robot sometimes could sink into the curved pipes when \(R\) is equal to \(1 \, D\).

The success movements in pipes with different geometry structures are largely due to the novel adaptive mechanism and the reasonable design parameters. In Fig. 18, the curves describe the adjusting rules in different pipe’s sections of Fig. 17(c). When the robot steps from the straight section into the curved section at 10 s, the screw angles changes all along for harmonious mobile velocities. When the robot is in the straight pipe, the force on each roller by the pipe is almost the same. Therefore, the screw angles are all equal. After stepping into the curved section, the forces on the rollers become different. The force balance is broken up. The adaptive linkage mechanism begins to adjust the speeds of the rollers for a new motion balance. When the time is 32–45 s, the robot is moving through the pipe Sec. 4. And then the robot steps into Sec. 5. The amplitudes of screw angles become smaller because the curvature radius \((R = 2 \, D)\) is larger. When the time is 75 s, the robot steps into Sec. 6, and the screw angles change sharply due to the smaller curvature radius \((R = 1 \, D)\). These screw

![Diagram](image)

**Fig. 13** Structure diagram of the control system

![Experiment environment of the straight pipe](image)

**Fig. 14** Experiment environment of the straight pipe

<table>
<thead>
<tr>
<th>No.</th>
<th>Rotational velocity of driving motor (rpm)</th>
<th>Screw angles (deg)</th>
<th>Mobile velocity mean values (mm/s)</th>
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<tr>
<td>1</td>
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<td>300</td>
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<td>300</td>
<td>37.5</td>
<td>120.6</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>45</td>
<td>150.2</td>
</tr>
</tbody>
</table>

**Table 2** Motion velocity adjustment experiment

![Graph](image)

**Fig. 15** The screw rollers of the robot in the straight pipe
angles change a bit disorderly because the elastic arms are not long enough and the rollers lose contact with the pipe wall. The results reveal that the length of elastic arms is well designed by the proposed approach for the pipes with 1.5 $D$ or more curvature radius. The extension and compression of the elastic arms can adapt to the change of pipe structure. The rollers of the robot always keep contact with the inner wall.

5 Conclusion

In this paper, a novel in-pipe robot with differential screw angles is proposed for curved pipes and vertical straight pipes. The detailed mechanism designs of the proposed robot are illustrated. In order to realize the fast and reliable design in different applications, a conservative design approach is proposed for the springs and the length of elastic arms. This simple and effective approach is already applied to the prototype design. The experiment results prove that the selected parameters are valid, and that the proposed robot can move smoothly in the curved pipes and vertical straight pipes. The proposed conservative design approach is a valid tool for the fast design of the in-pipe robot. In the future, some mechanism improvements of the elastic arms will be made in order to solve the problem that the robot is easy to slide down in the vertical pipes.
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References


