Research Article

Design and Motion Simulation of a Soft Robot for Crawling in Pipes

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In recent years, soft pipeline robot, as a new concept, is proposed to adapt to tunnel. The soft pipeline robots are made of soft materials such as rubber or silicone. These materials have good elasticity, which enhance the adaptability of the soft pipeline robot. Therefore, the soft pipeline robot has better performance on deformability than rigid robot. However, the structure of tunnel is complex and varied that brought challenges on design structure of soft pipeline robot. In this paper, we propose soft pipeline robot with simple structure and easy fabrication, which can be realized straight, turning motion in a variety of tunnels with different diameters. The soft pipeline robot composed of two types of structure, which are expansion part and deformation part. Front and rear deformation part for bending and position fixation, and middle expansion part for elongation, so the pipeline soft robot can be moved in various structures of tunnels. Moreover, the locomotion ability and adaptability in tunnel are verified by simulating on software. The structure of chamber proposed in this paper can guide the design method of soft pipeline robot.

1. Introduction

In recent years, both traditional industrial fields such as oil, gas, chemical, and nuclear facilities, as well as urban water pipelines, oil and gas pipelines and biomedical fields have developed rapidly. With the increase of usage time, the pipelines used in various fields will gradually age or corrode to produce cracks, perforations, and reduction of cross-sectional area [1]. Since most of the pipelines are installed underwater or underground and other places that are not easily accessible by human power, it is very difficult to overhaul them. If a problem occurs inside the pipeline, it can usually only be scrapped in advance, causing huge economic losses [2, 3]. Therefore, it is necessary to design a robot that can adapt to the internal environment of the pipeline to enter the complex and changing pipeline environment and complete the inspection and maintenance of the pipeline [4, 5]. Most of the traditional pipeline robots are rigid structures [6, 7]; the pipeline inspection robot developed by Ritsumeikan University [8] used a parallelogram drive mechanism to effectively improve the dragging capability of the robot when it encounters obstacles in the pipe. The V-type [9] and TH-type [10] pipeline cleaning robots successfully developed by Tsinghua University have reached the category of intelligent pipeline robots. Zhang et al. [11] and Wang [12] of Shanghai Jiao Tong University have conducted research on wheeled and crawler pipeline inspection robots. Usually, these rigid robots are designed for specific pipelines, which limit their ability to apply to multiple branches in different pipe diameters, complex-shaped cross sections, nonuniform pipe networks [13], slow action speed, and inability to make turns or bends. In order to overcome the limitations of rigid pipe robots and increase the flexibility of the robot, soft robots composed of soft materials offer a better alternative for such applications [14–16].

Kulkarni [17] and Martinez et al. [18] designed several soft actuators that can perform active bending and twisting. Heung et al. [19] developed an earthworm-like robot that can perform active bending and forward movements. Su [20] designed a single-actuator soft-body pipeline robot using elastic bands and biomimetic artificial muscles, which was able to
achieve robust crawling in horizontal, vertical, bent pipes, and even wet pipes partially or filled with water. With the rapid development of society and the increase of pipeline branching in pipelines, soft robots face greater challenges in steering control in pipelines [21]. Lin et al. [22] developed an earthworm-like soft pipeline robot for complex small-sized pipelines, and Calderón et al. [24] developed a soft crawling robot made of silicone that can work in horizontal and vertical pipelines. The robot is able to adapt to various pipeline environmental changes [23, 24]. Sui et al. [25] from Harbin Engineering University and Liu et al. [26] from Beihua University designed and fabricated a soft crawling robot that can run in pipes, and used silicone rubber to design and fabricate a pneumatic soft actuator capable of bending, elongation, and expansion movements. Wang et al. [27] introduced a soft pipe crawling robot consisting of a negative pressure driven flexural pneumatic actuator. Zhang et al. [28] designed a bionic soft robot for large-diameter pipe inspection, which can operate in pipes with sharp turns and large diameter changes. Zhang et al. [29] developed a worm-like soft robot consisting of three multi-degree-of-freedom extension modules and two flexible feet for movement and steering. However, the above soft robot in the pipeline cannot adapt to the pipeline with changing diameter and has difficulty in controlling the direction during right-angle turns and slow motion.

In this paper, we design a simple structure of soft robot that has crawling ability inside of pipeline. The parameters of the soft pipeline robot are optimized by comparing simulation results. In addition, two locomotion simulations are performed to verify the crawling ability. The structure design and parameter optimization of soft pipeline robot are introduced in Section 2. Section 3 shows the locomotion simulations by utilizing software. Finally, Section 4 discusses the results.

2. Design Structure of Pipeline Soft Robot

2.1. Design Functional Structure. Pipe robots have main functions as it can move inside the pipe and adapt to complex structure of the pipe. However, the pipe robot cannot be used to all types of pipes. Pipe soft robots have better adaptivity than grid pipe robots. Although soft pipe robots are made of soft materials, which have good deformability, but pipe soft robots cannot be used by any diameter of pipe. Therefore, we design a pipe pneumatic soft robot by using simple structure to adapt to inner diameter range from 20 to 42.4 mm of pipes.

The pipe soft robot is composed of three parts, which are two deformation parts and one expansion part, as shown in Figure 1. The expansion part is used to realize the robot movement inside the pipe, and the deformation part is used to realize the robot turning inside the pipe. Chamber structures of the pipe soft robot are shown in Figure 2. Expansion part is a cylinder and has one chamber in the center of the cylinder (Figure 2(a)). The expansion part is inflated and stretched by high air pressure. Deformation part is a cylinder and has four chambers (Figure 2(b)). The deformation part can be bent at different angles by actuating different chambers. Therefore, the pipe soft robot can be crawled inside of pipe.

2.2. Structural Parameters Design. The expansion part is a cylinder and has one chamber in the center of the cylinder. The parameters of expansion are shown in Figure 3, and the values of parameters are shown in Table 1. The expansion part’s diameter, length, and wall thickness are denoted as $D_1$, $L_1$, and $T_1$, respectively, and the chamber’s diameter and length are denoted as $d_1$ and $l_1$, respectively. Moreover, simulation conditions are shown in Table 2. The material density of the soft robot is denoted as $\rho_1$. The hyperelasticity feature is selected as the second-order Yeoh model and coefficients are $C_{10}$ and $C_{20}$ [30], and the material type is isotropic. The material density of the pipe is denoted as $\rho_2$. Young’s modulus is denoted as $E$, and Poisson’s ratio is denoted as $\gamma$.

The deformation part is cylinder and has four chambers. The parameters of deformation part are shown in Figure 4 and the values of parameters are shown in Table 3. The
Values $1.165 	imes 10^{-9}$ × $\rho_d$  

The four air chambers are identical and independent of each other, and the angle between the chambers is 90°. The eccentricity of the air cavity is denoted as $a$.

Numerical simulations of axial elongation and radial expansion of the expansion member were performed using finite element analysis software to derive the state of the expansion member under the action of atmospheric pressure, and the simulation results are shown in Figure 5. The simulation condition of the expansion member is the air pressure from 0 to 300 kPa, and the function of the extension part is extended. Figure 6 shows the tensile and expansion curves of the expansion member for different pressure values.

As shown in Figures 5(a) and 5(b), the simulation data of the expansion member without constraint and the simulation data inside the pipe are illustrated, respectively. As shown in Figure 6, when the pressure in the chamber is 150 kPa, the axial elongation is 16.8 mm and the radial expansion is 8.2 mm. When the pressure in the chamber is 300 kPa, the axial elongation is 68.6 mm and the radial expansion is 33.8 mm. The overall elongated length reaches 2.14 times of the original length. With the increase of air pressure, the axial length and radial diameter of the expanded parts increase, but with the accumulation of certain lengths, the axial elongation is larger and the elongation is well.

Considering that the soft robot can move within the pipe, the expansion range is limited to the inner diameter of the pipe. Therefore, the expansion member is simulated inside the pipe with an inner diameter of 25 mm. The simulation results show that when the air pressure value is 286 kPa, the expansion member can be squeezed in contact with the inner wall of the pipe while expanding longitudinally, contacts and squeezes the inner wall of the pipe, and the module elongation is 63.3 mm, which meets the requirement of the soft robot crawling inside the pipe.

By observing the simulation results (Figure 6), the curvatures of pressure-extending curve and pressure-expansion curve are all increasing with increment of pressure, and rate of curvature growth under air pressure greater than 100 kPa is faster than air pressure less than 100 kPa. It explains nonlinear characteristics of soft robot.

### Table 2: The parameters of simulation conditions.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$\rho_1$</th>
<th>$C_{10}$</th>
<th>$C_{20}$</th>
<th>$\rho_2$</th>
<th>$E$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>$1.165 \times 10^{-9}$</td>
<td>0.11</td>
<td>0.02</td>
<td>$7.2 \times 10^{-9}$</td>
<td>$6.1 \times 10^{5}$</td>
<td>0.27</td>
</tr>
</tbody>
</table>

### Table 3: The parameters of deformation part.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$D_2$</th>
<th>$d_3$</th>
<th>$L_3$</th>
<th>$l_2$</th>
<th>$T_2$</th>
<th>$a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values (mm)</td>
<td>20</td>
<td>5</td>
<td>45</td>
<td>40</td>
<td>2.5</td>
<td>5</td>
</tr>
</tbody>
</table>

The deformation part simulating results are shown in Figure 7. The simulation conditions of expansion are values of air pressure from 0 to 450 kPa. The deformation part has two functions that are bending ability and expanding ability. The soft robot can be move inside in straight pipe through coordinate the expanding function with extending function of the expansion part. Moreover, combining with the bending ability, the soft robot can be move inside in angled pipe.

The deformed part has four chambers, and it can be realized by various multiple angles bending. Figure 7(a) shows the simulation data of deformation part with one chamber. The bending angle of deformed part is increasing with increase of air pressure. The internal diameter and length of expansion part are thicker and longer with increment of air pressure. As shown in Figure 8, when the pressure in the air chamber is 200 kPa, the bending angle is 20.9° and when the pressure in the air chamber is 410 kPa, the bending angle is 90.5°. It can be seen that the deformation part has good bending ability. Moreover, when the cavity pressure value is less than 120 kPa, the expansion deformation of the cavity is small and the bending angle change rate of the structure is small. However, if the cavity pressure is set in the range of 120–350 kPa, the bending angle variation rate appears to rise significantly. Once the cavity pressure is greater than 350 kPa, the deformation is larger due to the inflatable cavity. In this way, the squeezing interference of the remaining three cavities becomes stronger and the bending angle variation rate becomes smaller. Therefore, the pressure load in this paper should be limited to below 350 kPa to ensure the accuracy of the experiment.

Figures 7(b) and 8 show the simulation data of deformation part with four chambers. The maximum diameter of deformation part is 22.4 mm under value of air pressure is 300 kPa. As shown in Figure 8, the pressure load of the single air cavity is small until it reaches about 120 kPa, and the bending angle of the structure changes at a small rate. Once the pressure load exceeds 120 kPa, the deformation of the loaded air cavity increases and the wall thickness of the structure becomes thinner. Therefore, if the pressure load is kept in the range of 120–350 kPa, there will be a significant increase in the rate of change of the bending angle after continued pressurization. However, when the pressure load reaches 350 kPa, the deformation of the inflatable cavity is larger. In this way, the extrusion interference of the remaining three cavities becomes stronger, resulting in severe extrusion deformation of the remaining cavities.

In summary, the pressure required to inflate all four cavities simultaneously will be less than that required to bend a single cavity for the same amount of expansion. Therefore, the inner cavities are set to a given pressure load range of 0–300 kPa, while each cavity is subjected to a linear pressurized load of 0–300 kPa.
3. Simulation of the Soft Robot Crawling inside of Pipeline

The pipe soft robot has main functions as it can move inside the pipe and adapt to complex structure of the pipe in this paper. Therefore, the pipe soft robot moving ability is verified by using simulation software. There are two types of simulation verifications, which are the pipe soft robot moving inside in different diameters of straight pipe and the pipe soft robot moving in curved pipe.

3.1. Simulation of Soft Robot Crawling in Straight Pipe

The pipe soft robot moving inside in pipe is simulated with two kinds of diameters of pipe. Diameters of pipe are 25 and 32 mm, respectively. The process of pipe soft robot moving inside of pipe has seven steps, as shown in Figures 10 and 11.
where step 0 is the initial state. Taking the motion of the soft robot crawling forward in the horizontal straight pipe as an example, the forward crawling motion steps can be divided into the following seven steps, and the forward motion of the soft robot crawling in the pipe can be realized by repeating the motion from steps 1 to 7 as follows, and the same can be done for backward motion of soft robots. Moreover, as shown in Figure 9, the deformation part and the expansion part are denoted as part A, part B, and part C, respectively.

Step 0: This step is the initial step. The soft robot is placed in the pipe statically without any air pressure load.

Step 1: Part A is inflated with air pressure with four chambers. Part A is expanded with four chambers that are inflated by the same air pressure values. Therefore, part A is expanded to contact and squeeze the inner wall of the pipe, and the back end of the soft robot is fixed.

Step 2: Part B is inflated with air pressure. Part B is elongated by inflating air pressure of chamber. Therefore, part C is pushed forward by part B in the pipe.

Step 3: Part C is inflated with air pressure. Part C is expanded with four chambers that are inflated by the same air pressure values. Therefore, part C is expanded to contact and squeeze the inner wall of the pipe, and the back end of the soft robot is fixed.

Step 4: Part A is deflated with air pressure. Part A is shrunk with four chambers that are deflated until the same air pressure values to zero. Therefore, part A recovers to initial state, and the front end of the soft robot is fixed.

Step 5: Part B is deflated with air pressure. Part A is shrunk with chamber that is deflated until the air pressure values to zero. At this time, the front end of the soft robot is fixed. Therefore, part A is dragged forward by part B that is shortens with decrease of air pressure.

Step 6: Part A is inflated with air pressure with four chambers. Part A is expanded to contact and squeeze the inner wall of the pipe, and the back end of the soft robot is fixed.

Step 7: Part C is deflated with air pressure. Part C is shrunk with chamber that is deflated until air pressure values to zero. Therefore, part C recovers to initial state, and the back end of the soft robot is fixed.

Figure 10 shows that a horizontal straight pipe with an inner diameter of 25 mm is used as the simulation environment for crawling inside the pipe of the soft robot. Moreover, the air pressure for simultaneous expansion of the four chambers of expansion parts is set to 180 kPa, and the value of air pressure of the deformation part is 300 kPa. The soft pipe robot moves 77 mm in one period.

Figure 11 shows that a horizontal straight pipe with an inner diameter of 32 mm is used as a simulated environment for the soft robot to crawl inside the pipe. In addition, the air pressure for the simultaneous expansion of the four chambers of the expansion section was set to 250 kPa, while the air pressure value for the deformation section was 300 kPa. The soft pipe robot moved 86 mm in one cycle.

3.2. Simulation of Soft Robot Crawling Curved Pipes. In order to test the passing ability of the previously designed soft robot in the bent pipe, we designed a bent pipe with an inner diameter of $D = 32$ mm as its motion simulation
environment, where the bent corner part of the bent pipe (Figure 12) was referred to the realistic pipe design. A short-radius elbow with a bend angle of 45° and a long-radius elbow with a bend angle of 90° were selected, where the bend of the short-radius elbow is one time the diameter of the pipe and the bend radius is \( R_1 = 32 \text{ mm} \). The bend of the long-radius elbow is 1.5 times the diameter of the pipe and the bend radius is \( R_2 = 48 \text{ mm} \).

In this paper, the motion of the pipeline soft robot inside the curved pipe is simulated under two pipe bending angles, which are 45° and 90°. Figures 13 and 14 show the turning motion process of the soft robot inside the pipe. In addition, as in the case of the straight pipe, the expansion part and the deformation part are denoted as part A, part B, and part C, respectively.

The biggest difficulty for a soft robot in a bend is to pass through the bend pipe smoothly, so the motion planning of a soft robot in a bend is different from the motion planning in a straight pipe. Therefore, the motion in one cycle is divided into seven steps, and by repeating the motion from steps 1 to 7, the forward motion of the soft robot crawling in the pipe can be achieved.

Step 0: This step is the first step. The soft robot is placed statically in the pipe without any air pressure load.

Step 1: Part A is inflated with four air chambers for air pressure. Part A is inflated with four air chambers with the same air pressure value. Therefore, part A is unfolded to touch and squeeze the inner wall of the pipe and to fix the back end of the soft robot.

Step 2: Part B is inflated with the air pressure. Part B is elongated by the air pressure of the inflation chambers. As a result, part C is pushed forward by part B in the pipe. When part C reaches the bend, a single cavity in part C corresponding to the direction of the turn expands, causing part C to bend. Meanwhile, part B continues to inflate and elongate, pushing the soft robot through the bend, and deflating the inflated cavity after part C passes through the bend.

Step 3: Part C is inflated with air pressure. Part C is inflated with four air chambers with the same air pressure value. Therefore, part C is unfolded to touch and squeeze the inner wall of the pipe and fix the front end of the soft robot.

Step 4: Part A is deflated with air pressure. Part A is contracted and deflated with four air chambers until the same air pressure value is zero. Thus, part A returns to its initial state and the front end of the soft robot is fixed.

Step 5: Part B is deflated with air pressure. Shrink part B together with part A until part A reaches the bend, where a single cavity in part A corresponding to the direction of the turn expands, causing part A to bend. Meanwhile, part B continues to deflate and contract, pulling the soft robot through the bend, and deflating the expanded cavity after part A passes through the bend.

Step 6: Part A is inflated with air pressure with four chambers. Part A unfolds to contact the inner wall of the squeeze tube and fixes the back end of the soft robot.

Step 7: Part C is deflated with air pressure. Part C is contracted and deflated at the same time until the air pressure value is zero. Thus, part C returns to its initial state and the back end of the soft robot is fixed.

As shown in Figure 13 of its crawling simulation, the second step is that the single cavity of the front expansion module inflates and expands to produce bending, resulting in an increase in the pipe passage rate, making it easier for the soft robot to overcome friction and improve the corner passage rate of crawling in the pipe and successfully pass the 45° corner pipe. In the simulation, if the front deformation module does not produce bending, the soft robot will extrude with the inner wall of the pipe when the front deformation module elongation reaches a certain level, making the simulation calculation more difficult to succeed.

As shown in Figure 14, the same method as described above for 45° bending can be used for a long-radius elbow.
with 90° bending. Therefore, when entering the bend in the second step of the soft robot motion planning, let the forward extension module inflate in a cavity first to pass through the bend smoothly. The motion simulation results show that the soft robot has a relatively limited mobility in the bent pipe with 90° elbow, mainly because the front elongated section is more difficult to pass through the bend, and it needs to subdivide the motion and gradually inflate the attempt. In the second step, the elongated section of the soft robot will be squeezed and bend in the pipe, which is also a point that needs to be continued to be studied to overcome.

4. Conclusion

In this paper, we design a simple structure of soft robot that consists of an elongated part and two expanded parts. The parameters of two kinds of parts were compared by simulation results. Using the design robot, we perform two types of simulations: motion inside of horizontal straight pipe and motion inside of curved pipe. The simulation results verify the crawling ability of our design soft pipe robot. The soft pipe robot was simulated in a pipe of 25 and 32 mm diameter. The soft body pipe robot was simulated crawling in a straight pipe with a pipe diameter of 25 mm and a pipe diameter of 32 mm, respectively, and moved different distances under different ranges of pressure, from which it can be seen that the soft body pipe robot can move in the range of pipe diameter less than 42.4 mm and greater than the original diameter of the robot (20 mm). In addition, we designed a 32 mm inner diameter pipe bend as its motion simulation environment, and selected a short-radius elbow with a bending angle of 45° and a long-radius elbow with a bending angle of 90°, and carried out the simulation of the soft pipe robot crawling in the bending pipe, which shows that the soft pipe robot can move within the bending angle of 0°–90°.

The structure design method proposed in this paper can realize the soft robot crawling ability inside of the specific pipe. Based on current results, we will continue to research the structural design and the experiments of soft pipe robot. We will discuss the control method of robot to move inside of pipe in the future work.

Data Availability

Data are available from the authors on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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