Research on a novel inner and outer spiral micro in-pipe robot

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Abstract
This study proposes a novel inner and outer spiral micro in-pipe robot. The inner and outer spiral robot structure is designed. The fluid flow field in the turbulent pipe is solved through computational fluid dynamics method, and the accuracy of the adopted numerical method is verified. The influences of environmental (liquid density, liquid viscosity, pipe diameter, and eccentricity) and operating (inner spiral rotational speed, outer spiral rotational speed, and robotic running speed) parameters on the robot performance are numerically analyzed. Inner and outer spiral driving devices are designed and fabricated according to the working principle of the inner and outer spiral robot. In addition, the feasibility of the proposed robot is verified by performing an experiment in a pipe filled with 201 methyl silicone oil.

Key words: Computational fluid dynamics, Inner and outer spiral in-pipe robot, Straight pipe, Performance analysis, Running experiment

1. Introduction

The medical field comprises numerous small liquid-filled pipes, such as the gastrointestinal tract and blood vessels. Traditional means such as the direct insertion of endoscopic catheters are mainly employed to inspect and sample human pipes. Given that inserting catheters is dependent on human capability, a catheter can easily damage soft tissues and cause pain to a patient. Particularly, an endoscope cannot easily penetrate the internal corners of the human body when the effective inserting length of the catheter is long and the curved shape of the catheter is complex. Thus, achieving effective diagnoses and treatments is usually difficult. To solve these problems, scientists have begun to research on improving the disadvantages of catheters. Medical micro systems inside the human body have been developed in recent years to satisfy the requirements of changing times. Developing autonomous medical micro-robots for human pipes to improve invasive or noninvasive diagnoses and treatments has become a major research topic in international medicine and electronics.

Several medical capsule endoscopy systems have been developed since 1999 (Meron, 2006; RF Co., Ltd, 2014; Park, et al., 2002; Maqbool, et al., 2009). These systems address patient discomfort and other problems that result from using traditional medical endoscopic catheters. The movement of the wireless capsule endoscopy system is mainly dependent on gastrointestinal peristalsis. The speed and position of this system cannot be controlled and determined, and this system cannot completely and carefully check certain positions. Therefore, this system can potentially result in omissions. In addition, the movement direction of this system cannot be changed. Therefore, a diseased region is ineffectively checked. Hence, active capsule in-pipe robots have been developed to address these problems. The leg types of these capsule endoscopy robots have been developed using micro batteries or external magnetic fields for actuation (Yim and Sitti, 2012; Simi, et al., 2010), using peristalsis as the movement mode of the robots. Peristalsis refers to crawling, such as the creeping of insects, and is a typical movement of soft animals, such as inchworms,
earthworms, and snakes. Various crawling bionic in-pipe robots have been developed (Nakazato, et al., 2010; Phee, et al., 2003; Kim, et al., 2005; Yan, et al., 2002). However, researchers have not intensively studied inchworm-, earthworm-, or snake-like movements. Researchers have searched instead for different actuating materials because various robot design schemes correspond to different actuators. Actuating materials include shape-memory alloys, ion-exchange polymer–metal composites, piezoelectric materials, and ionic conducting polymer films. When crawling in-pipe robots operate in a pipe, the robots are in direct contact with the pipe walls. Such contact can easily damage inner pipe walls, especially human pipes. These robots can damage the internal organic tissues of human pipes, which causes suffering and discomfort to a patient.

Numerous animal species are aquatic and move by swimming. Water, which is heavier than air, is the means for aquatic animals to move. Aquatic animals are subject to the buoyancy of water, and resistance to movement in water is greater than in air. Several in-pipe robots that can swim like fishes, jellyfish, sperms, and tadpoles have been developed (Triantafyllou and Triantafyllou, 1995; Shi, et al., 2010; Chen, et al., 2008; Byun, et al., 2011). Swimming robots are flexible and can efficiently accelerate. When swimming robots operate in a pipe, the backward movements of these robots require a large-angle steering. However, large-scale steering is difficult for these robots in small-diameter pipes, such as blood vessels. Therefore, backward movement and position adjustment are the main problems of swimming robots.

Ikeuchi determined that when a cylinder with a spiral shell rotates at a high speed in a pipe filled with fluid, the liquid will produce an axial thrust on the cylinder (Ikeuchi, et al., 1997). When the liquid has a certain viscosity, it will produce a supporting force against the opposite direction of the gravity because of its dynamic pressure effect. Then, a layer of liquid membrane, which separates the cylinder from the pipe wall, is formed. Therefore, a spiral-type robot is a new kind of in-pipe robot that causes relatively less damage in a pipe compared with other types of in-pipe robots. A single sectional, spiral-type, micro, in-pipe robot is driven by an external magnetic field in a pipe filled with fluid, as shown in figure 1 (Zhang, et al., 2011). Controlling the strength and direction of the external magnetic field can change the clockwise or counterclockwise rotation of the permanent magnet inside the robot. Consequently, the generated liquid force drives the robot forward or backward. Zhou proposed a double sectional, spiral-type, medical, micro, in-pipe robot, as shown in figure 2 (Zhou et al., 2001). The robot consists of a cylinder with a left spiral groove, a micro motor with a right spiral shell, and a flexible coupling. When the power of the micro motor is turned on, the rotational direction of the micro motor shell with the right spiral shell is opposite to that of the cylinder with the left spiral shell, thus driving the robot forward. Changing the rotational direction of the micro motor can change the direction of movement of the robot. The flexible coupling enables the robot to move in the bending pipe.

Ikeuchi has determined that when a cylinder with a spiral shell rotates rapidly in a fluid-filled pipe, the liquid produces an axial thrust on the cylinder (Ikeuchi, et al., 1997). When the liquid has a certain viscosity, the liquid produces a supporting force opposed to gravity because of the dynamic pressure effect of the liquid. Subsequently, a layer of liquid membrane, which separates the cylinder from the pipe wall, is formed. Therefore, a spiral-type robot is a new kind of in-pipe robot that causes relatively less damage in a pipe compared with other types of in-pipe robots. A single sectional spiral-type micro in-pipe robot is driven by an external magnetic field in a fluid-filled pipe, as shown in Figure 1 (Zhang, et al., 2011). Controlling the strength and direction of the external magnetic field can change the clockwise or counterclockwise rotation of the permanent magnet inside the robot. Consequently, the generated liquid force drives the robot forward or backward. Zhou has proposed the double sectional spiral-type medical micro in-pipe robot shown in Figure 2 (Zhou et al., 2001). The robot consists of a cylinder with a left spiral groove, a micro motor with a right spiral shell, and a flexible coupling. When the micro motor power is on, the rotational direction of the micro motor shell with the right spiral shell is opposite to that of the cylinder with the left spiral shell, thus, the robot is driven forward. Changing the rotational direction of the micro motor can change the movement direction of the robot. The flexible coupling enables the robot to move through curved pipes.
The aforementioned spiral robots possess spiral grooves or strips on the outer surface. When the robots rotate rapidly, the thrust of liquid on the robotic surface drives the robot to move. Simultaneously, based on the dynamic pressure effect of the liquid in a pipe, the supporting force of the robot is generated and a liquid film is formed, which can further prevent damage to the inner pipe wall. However, when the liquid film is thin (because of low viscosity of the liquid) and the rotating speed of the robot is high, the robotic spiral shell may damage the inner pipe wall. Simultaneously, when the rotating speed of the robot shell is reduced, the supporting force produced by the dynamic pressure effect of the liquid insufficiently supports the robot. Thus, the robot becomes in contact with the inner pipe wall and damages the pipe.

To overcome the previously mentioned problems of outer spiral in-pipe robots, a novel inner and outer spiral in-pipe robot is proposed based on a liquid environment. Computational fluid dynamic method is used to solve the fluid flow field in the turbulent pipe, the accuracy of the adopted numerical method is verified, the influences of environmental and operating parameters on the robot performance are numerically analyzed, and an experiment is conducted to verify the operation principle of the robot. The proposed robot is expected to be used in small liquid-filled pipes such as the gastrointestinal tract and blood vessels to perform functions such as inspection, sampling, and dredging.

2. Structural design of the inner and outer spiral robot

Based on the outer spiral micro in-pipe robots shown in Figures 1 and 2, the authors of this study propose an inner and outer spiral micro in-pipe robot in a liquid environment. The robot is small, but the supporting force of the liquid on the robot and the axial thrust force per unit volume are large. Furthermore, the rotating speeds of the inner and outer spiral surfaces are changeable.

The structure of the inner and outer spiral robot is shown in Fig. 3a. As shown in this figure, the micro motor is comprised of the permanent magnet (2) and the coil (3), between which the rotating (or sliding) bearing (8) provides support. A permanent magnet (2) is fixed on the body shell (7) with the right threads, whereas a coil (3) is fixed on the hollow shaft (6) with the left threads. The imaging, wireless communication, and control module (1) are arranged along the circumference of the robotic body, which allow wireless control of the robot. The micro battery (4) and the other modules are fixed on the hollow shaft (6) or on the body shell (7).

The robotic system mainly includes the inner spiral part (including coils) and the outer spiral part (including a permanent magnet), between which the bearing provides support. The external environment includes the pipe wall (5) and the liquid. During operation of the robot, the outer spiral part rotates, and \( n_1 \) is the rotating speed of this part, \( F_{r1} \) is the liquid circumferential resistance, \( F_{t1} \) is the liquid axial thrust force, \( T_{l1} \) is the liquid drag torque, and \( W \) is the wedge-shaped supporting force. Moreover, the inner spiral part also rotates, and \( n_2 \) is the rotating speed of this part, \( F_{r2} \) is the liquid circumferential resistance, \( F_{t2} \) is the liquid axial thrust force, and \( T_{l2} \) is the liquid drag torque.

Given that the robotic outer spiral shell is in contact with the pipe wall, friction occurs between the robot and the pipe wall. When the power is on, the inner spiral part of the robot starts rotating, and liquid forces \( F_{c2} \) and \( F_{c2} \) and drag torque \( T_{l2} \) are generated. When the rotating speed of the inner spiral part is increased to a certain value, the liquid force is greater than the friction between the outer spiral part and the pipe wall, and the outer spiral part begins to rotate. Given the dynamic pressure effect of the wedge liquid between the robotic spiral shell and the pipe wall, the liquid generates the supporting force on the robot, and a layer of liquid film is formed between the robot and the pipe. Meanwhile, when the robotic outer spiral part rotates, liquid forces \( F_{c1} \) and \( F_{c1} \) and drag torque \( T_{l1} \) are also generated. When the rotating speed of the outer spiral part increases to a certain value, the drag torque \( T_{l1} \) of the outer spiral part is equal to that \( T_{l2} \) of the inner spiral part. During this period, the rotating speeds \( n_1 \) and \( n_2 \) of the outer and inner spiral parts are relatively balanced, and the robot system runs steadily. Given that the spiral and rotational directions of the outer and inner spirals are all opposite, the two axial thrust forces \( F_{t1} \) and \( F_{t2} \) generated have similar directions, which drive the robot forward.

When the robot runs, \( F_{r1} \) is the liquid axial resistance on the outer spiral part, and \( F_{r2} \) is the liquid axial resistance on the inner spiral part. At the beginning state (see Fig. 3b), the axial resultant force of the robot (i.e., \( F_{r1} + F_{r2} - F_{r1} - F_{r2} \)) in the z-axial direction is greater than 0, thus, the robot acceleration \( (a) \) is greater than 0, and the robot is in an accelerating state. As the robotic running speed \( (U) \) hastens, the liquid axial resistances on the outer and inner spiral parts \( (F_{r1} \) and \( F_{r2} \)) both increase, whereas the acceleration \( (a) \) decrease. The speed \( (U) \) is constant until the acceleration...
(a) is 0. Here, the robot runs in a steady state, as shown in Fig. 3c.

The inner and outer spiral robot comprises outer and inner spiral surfaces. The sum of the inner and outer spiral rotating speeds is constant and is called the micro motor rated speed. Adjusting the area ratio between the outer and inner spiral parts can change the rotating speeds of the outer and inner surfaces of the robot, which can subsequently decrease the rotating speed of the outer surface and reduce damage to the internal pipe wall. If the micro-battery power is insufficient, an external magnetic drive can also be considered, and at this time, the coil (3) of the robotic system shown in Figure 3a is removed. The proposed inner and outer spiral micro-robot can be used in human intestinal tract, blood vessels, and other small liquid-filled pipes.
3. Numerical calculation models and methods

When the proposed spiral robot runs in a liquid-filled pipe, the liquid in the pipe also flows. The robotic force and speed can be obtained by analyzing the liquid flow field near the robot. Turbulent flow is very common in nature. In the turbulent motion process, the fluid particles mix and move randomly. The local velocity, pressure, and other physical quantities are likely to pulsate irregularly in space and time.

When the spiral in-pipe robot rotates rapidly in a liquid-filled pipe, a turbulent liquid flow is generated. The pressure and velocity of the liquid vary with time, and the pulsation is strong. Suppose the liquid is a Newtonian fluid, the liquid is unaffected by temperature and pressure, and the inner and outer surfaces of the robot are rigid. The fluid in the pipe satisfies the continuity and momentum equations (Wang, 2004).

Obtaining the analytic solution of these equations is difficult. The approximate solution to meet the practical requirements is obtained through a numerical method, that is, the computational fluid dynamics (CFD) software FLUENT 14. The solution steps are roughly as follows: first, a 3D model of the robotic system is established through the PRO/E software. Subsequently, the grids are divided and the boundary conditions are set through the GAMBIT software. Finally, these equations are solved using the FLUENT software. After the solution, the liquid flow field near the robot, and the forces and moments on the robot are obtained.

3.1. Numerical Calculation Models

Suppose that the inner and outer spiral robot shown in Figure 3a is applied to a liquid-filled pipe, and the centerlines of the robot and the simulating pipe coincide. According to human arterial size, we assume that the initial pipe diameter is 12 mm, and the pipe length is 75 mm. The robotic outer spiral parameters are as follows: outer diameter is 8 mm, axial length is 15 mm, thread number is 6, lead is 15 mm, and spiral groove is rectangular; the groove face width is 1 mm, groove bottom width is 1.5 mm, and groove depth is 0.8 mm. The robotic inner spiral parameters are as follows: inner diameter is 2.8 mm, axial length is 15 mm, thread number is 6, lead is 15 mm, and spiral groove is rectangular; the groove face width is 1.5 mm, groove bottom width is 1 mm, and groove depth is 0.6 mm. The 3D robotic system in a straight pipe is modeled using the PRO/E software, as shown in Figure 4.

3.2. Grid Division of the Robotic System

The fluid zones between the robot and the pipe wall are divided into three fluid zones: inner hollow zone, adjacent zone of the robotic shell, and the remaining region, which correspond to the blue zones in Figures 5a–5c, respectively.

According to the geometric shapes of the three fluid zones, all three zones use unstructured tetrahedral grids, whereas zones a and b use refined grids. The grid numbers of zones a–c are 28,271; 132,275; and 186,586, respectively. The grids of the robotic system are shown in Figure 6.
3.3. Selecting and Setting the parameters of the model

As previously mentioned, the fluid flow in the pipe is turbulent, thus, the standard $k$-$\varepsilon$ turbulent model is chosen, and the standard wall function is used for the fluid flow near the wall.

We assume that generally the liquid density is 1,000 kg/m$^3$, the liquid dynamic viscosity is 1 Pa·s, the robotic running speed is 0, the rotational speed of the robotic shell is 600 r/min (forward), and the rotational speed of the robotic inner shaft is $-600$ r/min (reverse). The gravity of the liquid, whose direction is the negative direction of the $y$-axis, is considered. The standard SIMPLE algorithm is adopted to solve the pressure and velocity coupling equations of the fluid flow field. The difference schemes of pressure, momentum, turbulent kinetic energy, and dissipation rate are second-order upwind schemes. Multiple reference frames are used to simulate the movement of the fluid in Figures 5a and 5b. The rotational speed of the fluid in Figure 5a is equal to the rotational speed of the robotic inner shaft, while the rotational speed of the fluid in Figure 5b is equal to the rotational speed of the robotic shell. The calculated state is steady, and the convergence precisions are as follows: continuity; $x$, $y$, and $z$ axial velocity; $k$; and $\varepsilon$ are all 0.0001.

The pipe inlet is near the robot, and the pipe outlet is away from the robot. The boundary conditions are the pressure inlet and outlet, and the liquid flow is not considered. The initial values of the entire area are all zero.

3.4. Verifying the accuracy of the adopted numerical method

To verify the accuracy of the numerical calculation method employed, the authors compute the thrust forces indicated in the reference (Ikeuchi, et al., 1996). Figure 7 illustrates the contrast curve of the calculated values using the numerical method, while Figure 6 shows the experimental values of the reference (Ikeuchi, et al., 1996). In the experiment, the silicone oil viscosity is 100 Pa·s, the width is 40 mm, and the ribbed plate length is 50 mm. The rib span is 7 mm, the rib width is 0.7 mm, the rib height is 1 mm, the helical angle of the rib is 45°, and the minimum gap between the rib and the mating face is 1 mm.

According to the figure, the calculated values are basically close to the experimental values. The calculated results
well agree with the experimental results, which verifies the accuracy of the numerical calculation method employed in this study.

Fig. 7 Relation curve of the thrust force with the sliding speed

4. Numerical calculation results

4.1. Flow Field Analysis in the pipe

Figure 8 shows the contour diagram of the pressure on the pipe wall when the robot is rotating in a straight pipe. The different colors represent various pressure values. Evidently, the high pressure area is mainly concentrated near the area around the robot, the maximum positive pressure value is 33.3 Pa, and the maximum negative pressure value is 37.5 Pa. When the robot runs along the central axis of the pipe, the pipe wall is not substantially damaged.

Fig. 8 Contour diagram of the pressure on the pipe wall in the straight pipe

4.2. Force analysis of the robot

Table 1 displays the z-axial thrust forces of liquid on the outer and inner surfaces, and on the whole robot when the robot is rotating in the straight pipe. Moreover, the thrust force includes the pressure and viscous force of liquid. The negative sign in Table 1 denotes the opposite direction of the z-axis.

According to this table, the direction of the axial thrust force on the robotic outer surface is similar to that on the robotic inner surface. However, with the same rotational speed, the axial thrust force on the robotic outer surface is greater than that on the robotic inner surface.

Table 1. Robot performance parameters in the straight pipe

| Robot performance parameter | Robotic outer surface | Robotic inner surface | Whole robot |
|-----------------------------|-----------------------|-----------------------|-------------|
| Axial thrust force (mN)     | -3.697                | -0.202                | -3.899      |

5. Performance analysis of the robot

5.1. Effect of Environmental Parameters on the Robot Performance
When the inner and outer spiral robot runs in a liquid-filled pipe, the environmental parameters that influence the robot performance indices (including the axial thrust force and the maximum pressure of the pipe wall) involve liquid density, liquid viscosity, pipe diameter, and eccentricity (distance between the centerlines of the robot and the pipe).

We analyzed the performance of the robot with the following assumptions: the robotic running speed is 0; the rotational speed of the robotic shell is 600 r/min; and the rotational speed of the robotic inner shaft is -600 r/min. In addition, the values of the parameters were initially set as follows: liquid density is 1,000 kg/m$^3$; liquid viscosity is 1 Pa·s; pipe diameter is 12 mm; and eccentricity is 0.

5.1.1 Liquid Density

Liquid density changes from 500 kg/m$^3$ to 1,500 kg/m$^3$. Figures 9 and 10 show the curves of the robotic axial thrust force and the maximum pressure of the pipe wall with liquid density, respectively.

Based on these figures, the robotic axial thrust force and the maximum pressure on the pipe wall all intensify as the liquid density is increased. When the liquid density is increased thrice, the robotic axial thrust force increases by 0.9% and the maximum pressure of the pipe wall increases by 13.5%, which indicate less influence by the liquid density on the robot performance.

5.1.2 Liquid Viscosity

Liquid viscosity changes from 0.5 Pa·s to 2.5 Pa·s. Figures 11 and 12 are the curves of the robotic axial thrust force and the maximum pressure of the pipe wall with liquid viscosity, respectively.

According to these figures, the robotic axial thrust force and the maximum pressure of the pipe wall both intensify as the liquid viscosity increases. The influence of liquid viscosity is greater than the influence of liquid density on the robot performance. Furthermore, the calculated Reynolds number is 1.56, thus, the effect of liquid viscosity dominates the robot performance. The axial thrust force of the single or double sectional outer spiral robot is proportional to the viscosity of the pipe liquid (Chen, et al., 2006; Liang and Zhou, 2002), which is consistent with the inner and outer spiral robot. When the axial thrust force of the robot needs to increase, i.e., the robot needs to move faster, some highly viscous biological solution can be added to the working pipe without considering the solution density.

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5.1.3 Pipe Diameter

Pipe diameter changes from 10 mm to 14 mm. Figures 13 and 14 are the curves of the robotic axial thrust force and the maximum pressure of the pipe wall with pipe diameter, respectively.

According to these figures, the robotic axial thrust force and the maximum pressure of the pipe wall both reduce as the pipe diameter increases. This finding shows that increasing the robotic axial thrust force can make the robotic diameter similar to the pipe diameter. Meanwhile, the axial thrust force of the outer spiral robot is inversely proportional to the pipe diameter (Chen, et al., 2006), which is consistent with the inner and outer spiral robot. A larger robotic diameter that is close to the working pipe diameter should be designed to improve the robot performance.

5.1.4 Eccentricity

Eccentricity changes from 0 to 1.2 mm. Figures 15 and 16 are the curves of the robotic axial thrust force and the maximum pressure of the pipe wall with eccentricity, respectively.

According to these figures, the robotic axial thrust force and the maximum pressure of the pipe wall both intensify as eccentricity increases, and the influence of eccentricity on the robot performance is also much greater. When the outer shell of the inner and outer spiral robot is very close to the inner pipe wall, the robotic axial thrust force increases significantly, but the maximum pressure of the pipe wall becomes greater. The axial thrust force of the outer spiral robot is proportional to eccentricity (He, et al., 2005), which is consistent with the inner and outer spiral robot. Therefore, when the robot is heavier, the thickness of the liquid film between the robot and the pipe wall reduces, but the robotic axial thrust force increases.

5.2 Effect of Operating Parameters on the Robot Performance

When the inner and outer spiral robot runs in a liquid-filled pipe, the robot performance indices are influenced by operating parameters such as inner spiral rotational speed, outer spiral rotational speed, and robotic running speed. Thus, the effect of these operating parameters on the robot performance is numerically analyzed when liquid flows at a certain pulsation cycle (Liang, et al., 2011).

For this analysis, we set the following initial values: robotic running speed is 0; rotational speed of the robotic shell...
is 600 r/min; and initial rotational speed of the robotic inner shaft is −600 r/min. In addition, the values of the parameters were set as follows: liquid density is 1,000 kg/m³; liquid viscosity is 1 Pa·s; pipe diameter is 12 mm; and eccentricity is 0.

5.2.1 Inner Spiral Rotational Speed and Outer Surface Rotational Speed

The rotational speed of the robotic shell changes from 200 r/min to 1,000 r/min, and the rotational speed of the robotic inner shaft changes from −200 r/min to −1,000 r/min. Figures 17 and 18 are the curves of the robotic axial thrust force and the maximum pressure of the pipe wall with the inner and outer spiral rotational speeds, respectively. According to these figures, the influence of the outer spiral rotational speed on the robot performance is greater than that of the inner spiral rotational speed. The robotic axial thrust force and the maximum pressure of the pipe wall both intensify as the outer spiral rotational speed increases, but both basically remain unchanged when the inner spiral rotational speed increases.

Therefore, the outer spiral rotational speed should be changed first to improve the performance of the inner and outer spiral robot. Similarly, the rotational speed of the outer spiral robot is proportional to the robotic running speed, and the running speed is also proportional to the robotic axial thrust force (Ikeuchi, et al., 1996), thus, the case of the outer spiral robot is the same with the inner and outer spiral robot.

5.2.2 Robotic Running Speed

The robotic running speeds are 5, 10, and 15 mm/s, and the running time ranges from 0.2 s to 0.8 s for this period. Figure 19 is the curve of the robotic axial thrust force with the robotic running speed. Given that dynamic mesh technology is adopted in the transient calculation, the calculation results are related to factors such as solution accuracy, calculation errors, and time, and the results have some fluctuations. In addition, the variation in the axial thrust force with time is largest at 15 mm/s, which is caused by the strong coupling effect of the pressure and velocity in the flow field at certain environmental parameters.

Based on this figure, when the robot runs at a certain speed in different running times, the robotic axial thrust force slightly changes. The robotic axial thrust force reduces until the axial thrust force reaches zero (the liquid resistance to
the robot is equal to the liquid thrust of the robot) when the robotic running speed increases, and the robotic running velocity reaches a maximum value and runs at a constant speed. The axial thrust force of the single sectional outer spiral robot decreases as the robotic running speed increases (Zhang, et al., 2001), which is consistent with the inner and outer spiral robot.

6. Experimental verification of the inner and outer spiral robot

The robotic axial thrust force and the supporting force of the liquid on the proposed inner and outer spiral robot in a fluid-filled pipe are analyzed through a numerical method. Experimental verification needs to determine the actual operating situation when the robot works in a pipe and the possibility of the robot moving forward and be suspended in a liquid environment. Considering problems such as manufacturing micro-batteries and other micro-components, and assembling the micro-robot, an inner and outer spiral driving device (the robotic prototype) is designed and fabricated. The rationality and feasibility of the proposed robot are verified through an experiment in a pipe filled with a certain viscous liquid.

When the inner and outer spiral robot operates in a small liquid-filled pipe, the robot is suspended in the pipe via the force produced by the wedged liquid between the robotic shell and the pipe wall. The liquid reacting thrust force produced by the high-speed rotation of the inner and outer spiral surfaces enables the robot to move, with no relatively fixed part involved in the rotation. Therefore, based on the aforementioned operating principle of the inner and outer spiral robot, the designed inner and outer spiral driving device uses an epicyclic gear train. The structural principle is shown in Figure 20. The battery is fixed considering the external power supply that affects the robotic operation and force.

![Structural principle of the designed inner and outer spiral driving device](image)

Fig. 20 Structural principle of the designed inner and outer spiral driving device

As shown in Figure 20, the micro-motor (4) is fixed on the spiral inner body (1), whereas a bearing connects the inner and outer spiral bodies (1, 2) to the entire device. The planetary wheel (6) (i.e., the gear on the micro-motor output shaft) is driven by the micro-motor and is meshed with the internal wheel (5) (i.e., the spiral outer body). The planetary and internal wheels have the same modulus.

Figure 21 shows the deconstructed view of the robot prototype. The robotic parts include the left spiral inner body with lining, the right spiral outer body, covers, micro motors, no. 9 batteries, wireless transceiver module, and remote control. Figure 22 shows the prototype system of the inner and outer spiral robot. The spiral outer and inner bodies, the lining, and covers are made of aluminum alloy.

The outer spiral parameters are as follows: outer diameter is 50 mm, thread number is 6, spiral groove is rectangular, groove face width is 1.5 mm, groove bottom width is 4.5 mm, groove depth is 2 mm, and spiral angle is 12.9°. The inner spiral parameters are as follows: inner diameter is 21 mm, thread number is 6, spiral groove is rectangular, groove face width is 1.5 mm, groove bottom width is 4.5 mm, groove depth is 2.5 mm, and spiral angle is 28.6°.

The experimental pipe is made of transparent organic glass with a diameter of 59 mm and a length of 1,200 mm, as shown in Figure 23. The experimental liquid is 201 methyl silicone oil with a viscosity of 1 Pa·s. Figures 24 and 25 are the forward displacements of the robot in the pipe at 0 and 20 s, respectively, when the rotational speed of the motor is...
600 r/min. The measured forward average speed is 5 mm/s. Figure 26 shows the robotic forward locomotion speed against the rotational speed of the motor. The eccentricity in the numerical calculation is determined by the robotic mass, and the robotic running speed (i.e., the vertical coordinates in Fig. 26) is obtained when the axial resultant force of the robot is zero. The sum of the inner and outer spiral rotational speeds is the micro motor speed (i.e., the horizontal coordinates in Fig. 26). The values of the inner and outer spiral rotational speeds are obtained when the circumferential drag torque of the inner spiral part is equal to that of the outer spiral part. The calculated results evidently well agree with the experimental data. This inner and outer spiral in-pipe robot can viably work in a liquid environment.

1–Left spiral inner body with the lining  2–End cover  3–Micro motors  4–No. 9 batteries  5–Right spiral outer body  6–End cover with gears  7–Wireless transceiver module  8–Remote controller

Fig. 21 Parts of the robotic prototype system

Fig. 22 Robotic prototype system

Fig. 23 Experimental pipe

Fig. 24 Forward displacement of the robot at 0s

Fig. 25 Forward displacement of the robot at 20s

Fig. 26 Comparison of the calculated results and the experimental data
7. Conclusions

A novel inner and outer spiral micro in-pipe robot is proposed. The robot is small, but the supporting force of the liquid on the robot and the axial thrust force per unit volume are large. Moreover, the rotating speeds of the inner and outer spiral surfaces are changeable, and damage to the internal pipe wall is minimal. The robot is expected to be used in intestinal tracts, blood vessels, and other small liquid-filled pipes in the medical field.

The CFD method is used to solve the fluid flow problem in the pipe. The accuracy of the adopted numerical method is verified. The influences of environmental (liquid density, liquid viscosity, pipe diameter, and eccentricity) and operating (inner spiral rotational speed, outer spiral rotational speed, and robotic running speed) parameters on the robot performance (axial thrust force and maximum pressure of the pipe wall) are obtained. The axial thrust force of the inner and outer spiral robot is proportional to the liquid density, liquid viscosity, eccentricity, and outer surface rotational speed, but this force is inversely proportional to the pipe diameter and robotic running speed, and has little relation to the inner spiral rotational speed. The maximum pressure of the pipe wall is proportional to the liquid density, liquid viscosity, eccentricity, and outer surface rotational speed, is inversely proportional to the pipe diameter, and has little relation to the inner spiral rotational speed.

An inner and outer spiral driving device is designed and fabricated based on the operation principle of the inner and outer spiral robot. The feasibility of the proposed robot is verified through an experiment in a pipe filled with a certain viscous liquid.

Micro-batteries supply energy to the proposed inner and outer spiral robot, thus, developing these batteries with large capacity and small size is an important foundation for this robot to function for long hours. Another energy source is an external magnetic drive. The size of the robot prototype is bigger than that required in practical applications, such as in human blood vessels, thus, the robot requires further reduction through some processing methods such as micro-injection molding and micro-casting forming. Actual clinical applications and in vivo experiments of the inner and outer spiral robot in organismal lumen have not been conducted. Therefore, numerous experimental studies are still required.

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