A Novel Crawling In-pipe Robot Design

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Abstract: A novel crawling in-pipe robot was designed to improve the adaptive ability with self-locking principle applied. In the moving, the robot was adaptable to horizontal, vertical and bending pipes with different diameters and sections without exerting additional pressure to the shell. The robot used a telescopic umbrella stand as a basic structure. The force of telescopic mechanism, self-locking principle of supporting mechani sm and shell were deduced from design requirements. The design of supporting and coupling mechanism was completed. The relationship between screw rod thrust and parallelogram driving force was established. A prototype was made and tested according to the suggested design methods. The results show that the robot with powerful traction, good self-locking performance and smooth passage through curve can move forward in the pipe with 90~150 mm inner diameter.

Keywords: robot; pipe; crawling; self-locking; screw-driven

1 Introduction

In recent years, with the development of pipeline transportation of petroleum, natural gas and other fluids, it was urgent and important to conduct regular inspection and maintenance[1]. Especially on August 1st, 2014, the explosion of gas pipeline in Kaohsiung, Taiwan reminds people to give sufficient weight to installation and maintenance of pipelines. The limitations of pipe restrict man's active operability. As an effective testing tool carrier, a micro in-pipe robot can go deep into confined space while many common testing tools can't do so. Nowadays, various in-pipe robots as the main testing carriers have emerged in response to the solution to the industrial problem of pipe inspection[2-5]. Due to complicated environment yet limited space, in-pipe robot should adopt simple unit structure and self-adaptability[6].

For successful march, a robot should have: 1.the ability to adaptable changes in the pipeline; 2. sufficient traction;3. miniaturized dynamical system and transmission mechanism. In terms of ways of moving in the pipeline, there are different types of in-pipe robots such as wheeled robot, crawler-type robot, hydraulic robot, vibrating robot and bionic crawling robot, etc. The vibrating robot was used for pipe with rigid shell; the wheeled drive was a frequently-used mobile carrier by in-pipe robot. the wheeled robot has advantages of simple structure, fast speed, and powerful traction; while the crawling robot with compact structure can be miniaturized, it was widely applied in minor-caliber pipe testing[7]. Based on force condition, the maximum tractive effort from crawling robot was equal to the maximum static friction force of moving mechanism and shell. To increase system traction, it was necessary to raise pressure between system and shell of pipe; On the other hand, with increasing pressure, there was a growing demand for dynamical system and moving speed will be restricted. So the crucial part of design was to deal with the contradiction between system traction and positive pressure[8-9]. The study attaches importance to take advantage of friction against pipe to drive robot.

In the passage, a telescopic in-pipe robot based on self-locking mechanism was adaptable to horizontal, vertical and bending pipes with different diameters and sections. According to mechanics principles, the force of telescopic mechanism, self-locking principle of supporting mechanism and shell are deduced to develop telescopic in-pipe robot prototype. Furthermore, related tests are completed successfully.

2 In-pipe robot structures

Figure 1 shows the basic structure for in-pipe robot.

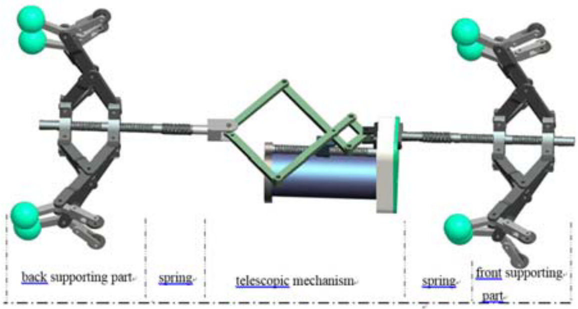


Fig.1 the in-pipe robot overall structure

It can be seen from Fig.1 that the robot was composed with three parts, including front, back supporting structures and central telescopic structure. The front and back supporting structures use umbrella stand to support pipe shell and movement for robot; central telescopic structure adopts parallelogram structure to stretch out and draw back driven by motor and screw rod to move ahead. The soft connection by spring among three parts makes robot to meet the need of turning and restoring to its original state after turning for better movement.

Cycle of robot moving ahead was shown in Figure 2.

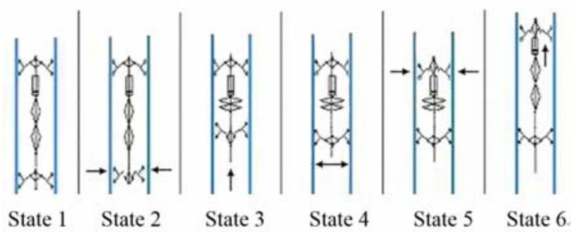


Fig.2 schematic drawing principle of in-pipe robot movement

It can be seen from Fig.2 that after central parallelogram starting to stretch out, the robot need finish the following 6 actions in one cycle: contracting back supporting, parallelogram, stretching out back supporting, front supporting, stretching out parallelogram and front supporting. It should be noted that the needed movement range of front, back stretching out and drawing back was different from that in Fig.2. The purpose of contraction was to reduce friction between support and pipe shell.

3 Parameter design of in-pipe robot

3.1 Supporting structure design.

The main requirements of supporting structure design were: ① with enough friction between supporting structure and pipe shell to offer driving force to move forward when parallel mechanism draws back;②with manual and automatic adjustment for pipes with different sizes and sections; ③with guide mechanism to pass corner led by pipe shell[10]. To meet the above requirements, the supporting structure was designed as shown in Figure 3.

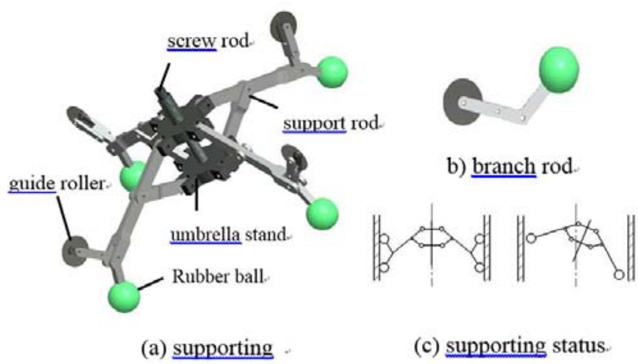
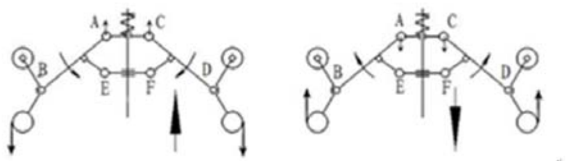


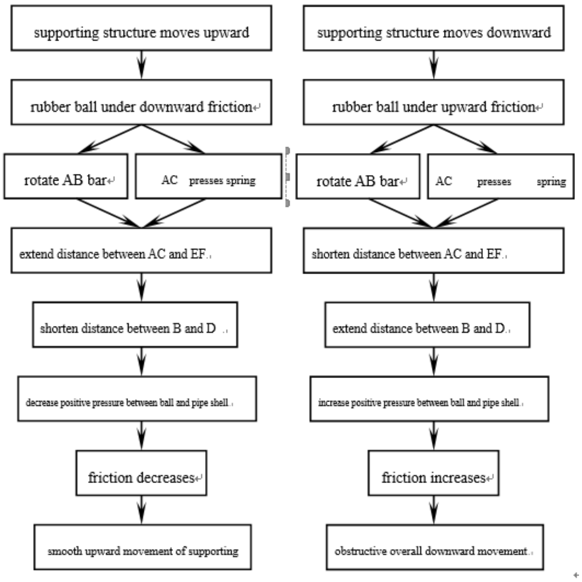
Fig.3 the in-pipe robot supporting structure

The fundamental supporting form in Fig.3(a): it adopts umbrella stand as overall structure and two umbrella stand bearings up and down are connected with screw rod. At the top of umbrella rod there was a branch rod that can be turned as shown in Fig.3(b); each supporting rod has two supporting points to keep the supported surface perpendicular to pipe axes in case of falling down as shown in Fig.3(c). The aluminium truckle at the front serves as guide wheel to keep pure rolling with pipe shell; there was a rubber ball at the back to increase frication with pipe shell.

Supporting mechanism was provided with self-locking function from structural design. Its self-locking principle was shown in figure 4. The direction shown in Fig.4(a) indicates that mechanism can move upward easily while downward movement was not allowed. AC and intermediate shaft connected with slider can be moved up and down; EF and intermediate shaft are connected with helical pair. The relative location of EF and intermediate shaft can be changed manually. Because of spring, when diameter was changed, EF rod was fixed and B,D points bear pressure outward or inward. And AB,CD separately revolve about central points with relevance in order to shorten or extend the distance between AC and EF. The force from spring may support umbrella stand to stretch out or draw back until supporting ball and supporting roller come into contact with inwall of pipe. The self-adaptable diameter of section ranges from 90 mm to 150 mm as shown in Fig.5. The principle of downward movement can be seen from Fig.4(b).

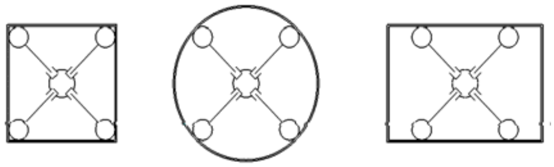


（a）supporting structure moves up （b）supporting structure moves down



(c) motion principle of supporting structure moves up (d) motion principle of supporting structure moves down

Fig.4 Self-locking principle of supporting mechanism



（a）square （b）round （c）rectangle

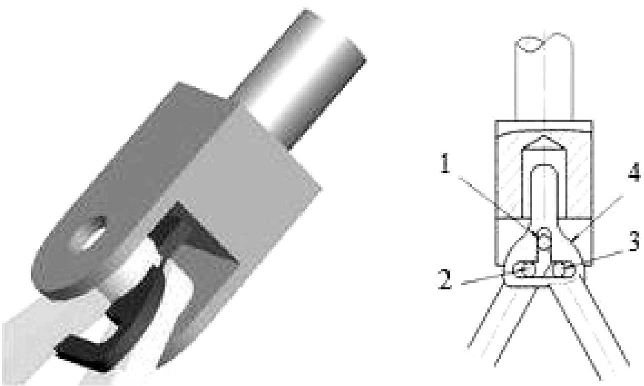
Fig.5 Self-adaptability of supporting mechanism to section

3.2 Coupling mechanism design.

The basic mode of robot was set up in the above-mentioned structural design. The crucial part were composed with connection between back, front supporting and telescopic structures. There are two couplings between supporting structure and telescopic structure as supporting bands. Taken easy turnning at corner into consideration, turnning center should be placed near the supporting structure, so large degree of freedom was set at front, back supporting structures, while telescopic structure adopts common hinge to couple.

Due to turning towards uncertain direction in the movement, coupling methods should be provided with large degree of freedom. Thus, front, back supporting structures and telescopic structure are connected with spring. When the robot goes through the bend, it can return to intermediate state to make better movement.

Figure 6 show the coupling between telescopic structure and back supporting.



(a)coupling between back supporting and telescopic mechanism (b)T-shaped sliding block mechanism

Fig. 6 coupling methods of back supporting and telescopic mechanism

Figure 6 shows the coupling requires free rotation of relative parallelogram pin. On the other hand, the connected cylinder in Fig.6(a), the better use of restoration function, cylinder axes and diagonal of parallelogram based on the back supporting structure by spring should be coincided. So the degree of freedom should be limited to ensure free movement of parallelogram and that axes of spring and diagonal of parallelogram always coincide.

To implement the control of degrees of freedom, T-shaped sliding block structure was chosen as shown in Fig.6(b). Axis 1 works as rotary shaft for bar 2 and pin 2, 3 are separately installed in 2 bars of telescopic structure. If the bar turns around, hinge pin 1,2,3 can only move in the "T-shaped" slot of sliding block 4. The slot shape makes axis of sliding block 4 and diagonal of parallelogram always coincided.

4 Design calculation

4.1 Relationship between screw rod thrust and parallelogram impetus.

Figure 7 show the inequilateral parallelogram mechanism to shorten mechanism length effectively. The structure not only ensures magnifying power of movement but also improves transmission efficiency.

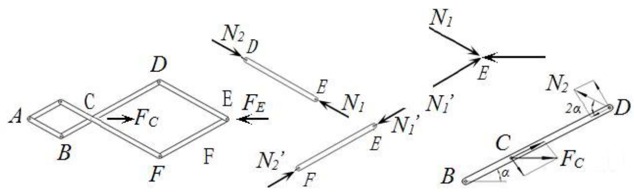


Fig.7 force analysis of telescopic mechanism

1) DE,EF both are two force bars. The force status was shown in Fig. 7, $N_1 = N_2$, $N_1' = N_2'$.

2) For E point, due to all symmetrical bars so here $N_1 = N_1'$. For any angle α, here

$$F_E = 2N_1 \cos\alpha , \tag{1}$$

2) For BD bar, based on the banlance of moment of force, there

$$F_C L_{BC} \sin\alpha = N_2 L_{BD} \sin 2\alpha , \tag{2}$$

$$F_C L_{BC} = 2N_2 L_{BD} \cos\alpha , \tag{3}$$

$$N_2 = F_C \frac{L_{BC}}{2L_{BD}\cos\alpha} \tag{4}$$

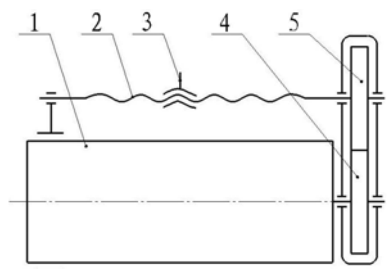
substitute formula (2) into formula (1) to get:

$$F_E = F_C \frac{L_{BC}}{L_{BD}} \tag{5}$$

From formula (5), it could be found that the application of force from quadrangle agsint supporting mechanism, proportional to scew rod thrust, not depend on BD bar or the parallelogram angle.

4.2 Relationship between motor power and robot impetus FE.

Figure 8 show the transmission from motor to screw rod according to the transmission mechanism that has been worked out.



1-motor 2-screw rod 3-nut 4,5 gear bank

Fig.8 motor transmission diagram

In Figure 8, motor 1 transmits driving force to gear 4 by built-inspeed reducer. And force was transmitted to screw rod 2 by gear set 4-5. Screw rod 2 drives nut 3 to return rotary motion to rectilinear motion. By pin, nut 3 puts parallelogram structure into motion to drive robot.

If output power of motor was P, while rotative speed was n.

1)Output power of screw rod P_0 was

$$P_0 = P \cdot \eta = 0.9P \tag{6}$$

2) M6 screw rod and triangle screw thread are adopted and equivalent frictional coefficient fv was

$$f_v = f / \sin(90° - \beta) = f / \cos\beta \tag{7}$$

In the formula, β represents half of thread angle of common triangle screw thread.

Equivalent friction angle was

$$\varphi_v = \arctan f_v \tag{8}$$

3) Pressured by external load FC, the required maximum torque of screw rod rotation was

$$T = F_C \cdot d_2 \cdot \tan(\alpha + \varphi_v) / 2 \tag{9}$$

and in the formula, α represents helix angle of screw thread.

4)The relationshop between torque and input power of screw rod was

$$T = 9.55 \times 10^6 P_0 / n \tag{10}$$

According to formulas (5)-(6), (9), the relatonship between motor power and suffered thrust by robot can be deduced as

$$F_E = \frac{L_{BC}}{L_{BD}} \cdot \frac{2 \times 9550 \times 10^3 . \eta . P}{d_2 \tan(\alpha + \varphi_v) . n} \tag{11}$$

The effeiency of spur cylindrical gear 4, 5 was 0.9;

pitch diameter of screw rod d2=5.355 mm; helix angle $\alpha = 3°24'17''$; half of thread angle $\beta = 30°$; assign f=0.1; in parallelogram mechanism, LBD=15 mm,LBC=63 mm; output power of motor was P=2.4 W, rotative speed n=420 r·min-1, substitute them into above formula to get

$$F_E = \frac{L_{BC}}{L_{BD}} \cdot \frac{2 \times 9550 \times 10^3 \cdot \eta \cdot P}{d_2 \tan(\alpha + \varphi_v) \cdot n} = 51.97(N)$$

5 Experimental verification

The relative in-pipe robot prototype was made according to the above parameters from theory and caculation. It weighs only about 0.4 kg with the maximum load of 17. 4 N and it was adaptable to 90~150 mm inner diameter. Figure 9 shows test of in-pipe robot.

a)load self-locking test b)turning test

Fig.9 in-pipe robot test

The load test of Figure 9(a) with an iron block of 1.5 kg to show good self-locking performance of prototype. Figure 9(b) shows ability test to pass throught pipe. Taking control of screw rod, trial prototype moves back and forth four times between two ends of 2-meter straight pipe. The mesured average speed in the straight pipe reaches 2.7 $m \cdot min^{-1}$.

To test motion characteristics of in-pipe robot, it requires to test electric current (I) and voltage(U) under different load and operating conditions. The results are shown in Table 1.

Table 1 power test of in-pipe robot under different load conditions

Load G[kg]	Voltage U[V]	Horizontal linear motion		Curve-way motion		Vertical upward	
		I[A]	P[w]	I[A]	P[w]	I[A]	P[w]
0	12	0.07	0.84	0.12	1.44	0.11	1.32
1.0	12	0.09	1.08	0.13	1.56	0.16	1.76
1.5	12	0.09	1.08	0.132	1.58	0.21	2.52

From the above analysis result, output power P in idle load was mainly to overcome the friction between robot and pipe shell. The resistance of friction was about 18 N, increasing with raising load. The robot need maximum power in upward vertical motion. The maximum external load was 17.4 N which was 4 times larger than its own weight.

6 Conclusion

1) The crawling in-pipe robot was adaptable to horizontal, vertical and bending pipe with good self-locking performance without exerting additional pressure to the shell.

2) The robot was adaptable to pipes with 90~150 mm in square, round and rectangle sections with the automatic adjustment.

3) Proper coupling methods and restraint function of pipe shell made robot to pass through a nearly 90°right-angled bending pipe successfully.

4) The telescopic mechanism uses inequilateral parallelogram to shorten transmission screw rod effectively which ensures magnifying power in the movement.

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