Development of an Adaptive Mobile Robot for In-Pipe Inspection Task*

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Abstract—For the purpose of performing internal inspection task of pipe, a robot based on adaptive mobile mechanism is developed. The robot equipped with one actuator has two working modes, a normal working mode and an assistant working mode. Robot under normal working mode performs monitoring tasks and travels in the pipe, while under assistant enhanced mode robot will surmount obstacle without any other driving actuator during executing tasks. The special feature is achieved by applying the adaptive mobile mechanism we proposed in this paper. A prototype has been set up and experiments have been conducted to testify the adaptability and efficiency of the robot. The results show that the robot can successfully climb up a step that is formed by concentric junction with a height of 5mm.

Index Terms – In-pipe Robot, Adaptive Mobile Mechanism, Mechanical Design, Screw Drive.

I. INTRODUCTION

Pipelines are the main facilities for the transportation of oil and gas that are used in many countries. Leakage and damage of the pipeline should be detected because these problems may cause environmental pollution and affect the production of the industry. The pipelines should be monitored and inspected regularly to prevent such problems. Robot technology provides a good solution so that robots can access into the narrow space and the dangerous and difficult environments that are forbidden to approach or out of reach, such as poisonous chemical plants or pipes in the bottom of the sea, and perform inspection tasks.

Various pipe robots are developed for the inspection of pipes. Okada developed a three-wheeled pipe robot that uses scissors-like structure [1]. Hirose et al. developed a series of in-pipe robots called “Thes” that have some unique characteristics [2]. Hayashi et al. developed a micro pipe robot driven by an external motor [3, 4]. Choi and Ryew developed a multijoint pipe robot that uses the active universal joints as the steering mechanism [5]. Roh presented a wheel type pipe robot based on the differential drive principle [6]. Recently, Oya reported their wheel type robot that has steering ability [7]. The pipe has a compulsive constraint to the robot [5] when the robot propels and performs tasks. To realize some functions of the robot mentioned above, we have to use many actuators which cause too much energy consumption and highly cost to build a robot. How to make full use of the power and energy provided by the driving actuator is the problem that we faced in design of the pipe robot propelling mechanism. In this paper we aim to develop a pipe robot that has adaptability to the change of the pipe, while we try to reduce the number of the driving actuators.

II. CONCEPT OF THE ADAPTIVE MOBILE MECHANISM

Mobility, multifunction and efficiency are the main factors that we take into consideration, because:

1) Adaptability: Pipe robots designed for inspection task should have adaptability to the change of the environment.

2) Multifunction: Pipe robots should have more moving modes or forms. This will enlarge the application range of the pipe robots.

3) Efficiency: Due to the narrow space, robots should make full use of the capacity of the driving actuator and consume less power.

A. Moving Pattern of The New Pipe Robot

Pipe robots usually are classified in to pig type, wheel type, walking type and inchworm type [6]. Performing inspection tasks in pipeline of inner diameter 50mm-300mm, the robot should have high speed, powerful traction force that not only pull the robot itself but also some payloads such as electronic devices and cables. The inchworm type that used widely in micro pipe robots is thus not suitable because of low velocity and traction force [8, 9]. Walking type is hard to control due to the number of the actuators. Moreover it is hard to integrate so many actuators below the diameter 300mm [10]. As mentioned above wheel type can reach a relatively high speed. The traction force will be increased through enhancing the normal force and the adhesion coefficient between the wheel and the inner surface of the pipe. Thus the wheel type satisfies our requirements to the new robot.

Wheel type robots can also be divided into Direct Drive Wheel type robots (DDW) and Screw Drive Wheel type robots (SDW). As shown in Fig.1 (a), the wheel orientation of the DDW is parallel to the axis of the pipe. The driving motors rotate the wheels directly or via some transmission when the DDW is moving. The function of the power transmission is...
only to reduce the speed of the driving motor or change the orientation of the velocity produced by the motors.

Different from the Direct Drive Wheel type, Screw Drive Wheel type is usually composed of rotator, elastic support arm and rollers, as shown in Fig.1 (b). The rollers have an incline angle with respect to the axis of the pipe. When the driving torque is applied, the rollers rotate not only with its own axis but also around the axis of the pipe. Then the whole mechanism moves forward.

Table I enumerates the characteristics of the robot systems that employed the direct drive type and screw drive type, respectively.

<table>
<thead>
<tr>
<th>CHARACTERISTICS OF DIRECT DRIVE AND SCREW DRIVE ROBOT SYSTEM</th>
<th>Direct Drive type</th>
<th>Screw Drive type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheels</td>
<td>Active</td>
<td>Passive</td>
</tr>
<tr>
<td>Number of actuators</td>
<td>More</td>
<td>Less</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>Fair or High</td>
<td>Low</td>
</tr>
<tr>
<td>Complexity in control</td>
<td>Fair</td>
<td>Simple</td>
</tr>
<tr>
<td>Axial length</td>
<td>Fair</td>
<td>Short</td>
</tr>
</tbody>
</table>

As shown in Table I robot employing the screw drive principle has several advantages. Because of less driving actuators needed, robot will consume less power but have more continuous time to perform the inspection tasks. This robot also simplifies control complexity and downsizes the mechanism.

B. The Robot based on Adaptive Mobile Mechanism

As shown in Fig. 2, the robot is a wheeled type based on screw drive principle. We adopt modular design for the further development. The driving arms of the robot are mounted with paddles that rotate together with the driving arms. The rotary paddles will generate extra force to pull the robot when the robot is propelling in the pipe full of liquid and gas or entirely full of liquid. CCD camera is attached to the front body of the robot for monitoring the inner surface of the pipe.

The adaptive mobile mechanism of the robot is composed of rotator output 1, former elastic driving arms, rotator output 2, latter elastic driving arms, stator, rollers, paddles and one driving actuator. The former elastic driving arms are fixed every 60 degrees on the periphery of the rotator output 1. The latter driving arms and rotator output 2 have the similar structure to that of the former driving arms and rotator output 1. All the rollers are pressed on the inner surface of the pipe, and rollers on the former arms have an incline angle with respect to the axis of the pipe. When the rotator output 1 begins to rotate, this part of mechanism will generate traction force to pull the robot forward or backward. In most of time, the rotator output 2 will keep still. But in some condition the former driving arms are stuck by the obstacle in the pipe and can not generate traction force, rotator output 2 and the latter driving arms begin to rotate to help the former arms to overcome the obstacle. There is a similar process when the latter arms are stuck by obstacle. The stator which connected with the driving actuator should not rotate in order to keep the posture of the robot all the time. When the robot carries out inspection tasks in the pipe filled with liquid, the paddles mounted on the former, latter and stator arms will flap the liquid to acquire extra traction force.

Thus, the robot based on the adaptive mobile mechanism has the ability to travel not only in common gaseous pipes but also in pipes with liquid.

III. MECHANICAL DESIGN OF THE ROBOT

When the robot travels in pipes, the axial length of the robot should meet some geometric conditions.

A. Adaptive Mechanism of The Robot

The following requirements are considered, before the power transmission of the adaptive mechanism is designed.

1) Output torque from actuator can be used directly, so a power transmission mechanism is needed.
2) The axial length of the robot should be as short as possible, because of the pipe geometric constraints.
3) Less actuators should be used to achieve multifunction of the robot.

These requirements are not independent but intertwined. After comparing several designs, we finally adopt the mechanism shown in Fig. 3. The axial length of this mechanism is shorter than other designs that have the same ratio of power transmission.

The principle of this adaptive mechanism is that the power of the actuator is transmitted via coupling to spur gear 1 and gear 2. The coupling eliminates the offset between the
actuator and spur gear, when these parts are working. The spur gear 2 and sun gear are fixed on the central axis. When the central axis rotates, the power of the actuator is transmitted to the ring gear. The former driving arms are fixed to the ring gear that can rotate the former driving arms. This is one route of the power output. The other route is that when the actuator rotates, the power is transmitted to the central axis and turns the sun gear. The sun gear turns the planet gear; finally the power of the actuator is transferred to the planet gear carrier to which the latter driving arms attached. The rollers mounted on the driving arms and supporting arms are pressed by the force of the compressed springs, except that the rollers on the former driving arm have a constant incline angle with respect the axis of the pipe. Between the roller and the latter driving arm there is a tension spring to pull the roller parallel to the axis of the pipe.

Let \(\omega_1\), \(\omega_3\), and \(\omega_H\) denote the angular velocity of spur gear 1, ring gear and planet gear carrier of the mechanism in Fig. 3 respectively. \(i_{63}\) denotes the reduction ratio from sun gear to spur gear 1, while \(K\) is the ratio of teeth of ring gear to that of sun gear. We obtain the following relation

\[
i_{63}\omega_3 + K\omega_1 = (K + 1)\omega_H
\]  

(1)

From (1), if \(\omega_H = 0\), we obtain the ratio from spur gear 1 to ring gear \(i_{63}\) is \(i_{63} = K\); while the angular velocity of the ring gear is zero, the ratio from spur gear 1 to the planet gear carrier \(i_{63H}\) is \(i_{63H} = i_{63}+(K + 1)\). Consequently, the mobile mechanism can work at two modes whose ratios of transmission are different from each other.

**B. Locomotion Mode of The Mechanism**

The adaptive mechanism has two typical working modes.

1) **Normal Working Mode:** When the robot is propelling in the pipe, the resistance between the robot and the pipe usually is not high in most of the time. In such a condition, the former driving arms rotate and generate traction force that the robot need to move in pipe, while the latter driving arms do not rotate because reaction force between the latter driving arms and pipe is not easy to overcome. The ratio from the motor to the former driving arms \(i_{63}\) is less than \(i_{63H}\), so the robot can travel at a higher speed than that of in the condition of \(i_{63H}\) in pipe.

2) **Assistant Enhanced Mode:** When the robot encounters an obstacle (such as a step), the angular velocity of the former driving arm falls rapidly because of the reaction force imposed by the obstacle. In such cases, the actuator outputs torque without stalling, the torque acting on the latter driving arms is big enough to rotate the latter arm. Once the latter driving arms begin to rotate, they will generate extra traction force. The ratio of the power transmission changes from \(i_{63}\) to \(i_{63H}\). Because \(i_{63H} > i_{63}\), the latter arms will produce larger torque to help the former arms to overcome the obstacle.

**Fig. 4 The process of surmounting step**

Fig. 4 illustrated the typical process of the robot surmounting a concentric step in a pipe. In Fig.4 (a), the robot propels in a pipe of larger diameter under normal working mode. Ahead of the robot, there is a step with a height of \(h\). Because of the contact force between the former driving arms and the step, the angular velocity of the diving arms fall rapidly so that the power output route is bound, as seen in Fig.4 (b). The mechanism changes the mode from normal working mode to assistant enhanced mode, and the latter driving arms began to rotate and generate traction force to push the former arms over the step in Fig.4 (c) and (d). After the former arms overcome the step, the latter driving arms encounter the step, this time the former driving arms will pull the latter arms to surmount the step. At last, the former driving arms will pull the stator to overcome the step when the rollers contact the step. Finally, the robot will entirely climb over the step.

**C. Design of The Latter Driving Arm**

To ensure the mechanism runs smoothly, there is one problem to be solved. The requirements listed below should be satisfied for the rollers on the latter driving arms.

1) Rollers should be parallel to the axis of the pipe under the normal working mode.
2) Rollers should have an incline angle with respect to the axis of the pipe under the assistant enhanced mode.

Under the assistant enhanced mode the rollers on the latter driving arms should have a slant angle with respect to
the axis of the pipe in order to produce traction force. While under the normal working mode, the rollers should not have such a slant angle to avoid extra resistance. For these reason, we employed the mechanism in Fig. 5. This mechanism is composed of rolling block, slider, compressed spring, free roller and torsion spring.

![Fig. 5 Mechanism of latter driving arm](image)

The rolling block can rotate around the slider that is pressed by the compressed spring. The free rollers are mounted on the rolling block. Between the centre of the roller and the axis of the slider there exist an offset. A pin mounted on the slider confines the rolling range between the rolling block and the slider. A torsion spring that is predetermined pulls the rolling block and the roller at the position that is parallel to the axis of the pipe.

Under the normal working mode, the rollers on the latter driving arms are parallel to the axis of the pipe, because of the predetermined torsion force. Thus, the rollers do not produce extra restriction, just follow the movement of the robot; when the robot is under assistant enhanced mode, the torque acting on the later driving arms will conquer the predetermined force and slant the rollers an angle with respect to the axis of the pipe. Then the rollers and the latter driving arm can generate torque when they are rotating.

From the above, we can see that the new pipe robot have unique adaptability to the change of the pipe environment and efficiency in power consumption because of only one driving actuator equipped. The adaptive mobile mechanism of the robot will switch its working mode according to the environment of pipe. Robot will move at a high speed under the normal working mode. On the other hand, the mechanism will produce high torque, when the robot encounters an obstacle. The switching of the working mode is the characteristics of the mechanism. This unique character of the robot provides another solution to the low capacity of surmounting obstacle of the classical screw drive robot. Other solution may employ linked type configuration, but we only use one module of the robot.

A prototype based on the adaptive mobile mechanism has been set up as is shown in Fig. 6. Main parameters of the robot are listed in table II.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>SPECIFICATIONS OF THE PIPE ROBOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max-Min Diameter</td>
<td>205-175mm</td>
</tr>
<tr>
<td>Axial Length</td>
<td>207mm</td>
</tr>
<tr>
<td>Total Weight</td>
<td>1.8Kg</td>
</tr>
<tr>
<td>Ratio of Transmission</td>
<td>2(normal mode), 3(assistant mode)</td>
</tr>
<tr>
<td>Velocity in horizontal pipe</td>
<td>163mm/s</td>
</tr>
</tbody>
</table>

IV. ANALYSIS OF THE LATTER DRIVING ARM MECHANISM

We have introduced the mechanism of the latter driving arm in the above section. The offset between the roller and the axis of the slider must satisfy some conditions, if the mechanism really works as we imagine.

![Fig. 7 Force analysis of the latter driving arm](image)

When the robot is working under the normal working mode, the forces acting on the latter driving arm is shown in Fig. 7(a). Fig. 7(b) shows the situation when the robot is climbing an obstacle with a height of $h$.

$F_n$ and $F_r$ denote the normal force and rolling resistance acting on the roller respectively; $F_v$ and $F_f$ represent the normal force and friction force acting on the slider; $F_{r_x}$, $F_{r_y}$ and $M_o$ denote the force and torque acting on the roller axis; $e$ represents the offset between the roller axis and symmetry line of the slider; $f_s$ is the rolling friction coefficient, and $f_i$ is the static friction coefficient.

Now, we suppose the mechanism in Fig. 7 is under equilibrium condition. There will be an equation about the offset. If the value of offset we designed is less than the value calculated from the equation, the mechanism will be unbalance unless other external force appears, and move as we expected.
The following equations describe the static condition in both Fig. 7(a) and (b)

\[ F_x = f_1F_a \]
\[ F_y = f_2F_a \]
\[ M_o = F_xr \]

From Fig. 7(a), we have the following relation

\[ F_{1x} - F_{2x} = F_{rx} = F_x \]
\[ F_{1y} + F_{2y} = F_{ry} = F_y \]
\[ F_{1x}b + F_{1y}c - F_{rx}(e_{cal1} + c/2) - F_{ry}(a + b) - M_o = 0 \]  

\( e_{cal1} \) denotes the calculated value from (1) to (6), while \( e \) denotes the actual value. The following inequality should be satisfied.

\[ 0 < e < e_{cal1} \]  

From Fig. 7(b) we retrieve the following static equations.

\[ F_{1x} - F_{2x} = F_{rx} = F_x \cos\theta + F_y \sin\theta \]
\[ F_{1y} + F_{2y} = F_{ry} = F_x \sin\theta - F_y \cos\theta \]
\[ F_{1x}b + F_{1y}c - F_{rx}(e_{cal2} + c/2) - F_{ry}(a + b) - M_o = 0 \]  

\( \theta \) is defined as

\[ \theta = \arcsin(r - h)/r \]

\( e_{cal2} \) can also derive from (1) to (3) and (8) to (11)

\[ 0 < e < e_{cal2} \]

The offset of the mechanism should satisfy inequalities (7) and (12), considering the factors of \( a, r, b, c, f_1, \) and \( f_2 \). The offset can be determined according to inequality (7). Fig. 8 shows the offset range under the influence of other variables, the values of which are as follows: \( r = 11, \ a = 25, \ b = 5, \ c = 7 \).

From Fig. 8 4mm is determined as the offset value.

\[ \text{Fig. 8 The range of } e \text{ under the influence of other variables} \]

Fig. 9 shows the result of the offset under the influence of the \( f_1 \) and \( f_2 \), while \( r = 11, \ a = 25, \ b = 5, \ c = 7, \ h = 5 \). From the figure, the determined offset value 4mm satisfies the inequality (12). From Figs. 8 and 9 we know that the friction coefficient \( f_1 \) has an obvious influence to the value of the offset. In our design, the value of \( f_2 \) has been reduced by the lubricant.

V. EXPERIMENTS

Basic experiments have been conducted to testify the mobility of the robot, as shown in Fig. 10. The results show that the robot can move in the pipe smoothly. The velocity in the horizontal pipe is about 163mm/s.

\[ \text{Fig. 9 Influence of the friction coefficient climbing steps} \]

Obstacle surmounting experiment also has been conducted. Fig. 11(a) shows the experiment environment, the pipe is composed of two segments of pipes with different diameters. The inner diameters of the pipes are 190mm and 180mm, respectively. The two pipes are connected concentrically and formed a step in peripheral of the pipe with a height of 5mm. In Fig. 11(b), the robot is moving in the pipe of inner diameter 190mm under normal working mode. In Fig. 11(c), the former arms contact the step formed by the conjunction of the two pipes, so the angular velocity of the former driving arms falls. The working mode of the mechanism changed. The rollers of the latter driving arms change the position from parallel with respect to the axis of the pipe to a slant angle with respect to the cross section of the pipe. The latter driving arms begin to rotate and generate traction force. Since the robot is working under the assistant enhanced mode, the ratio of the assistant mode is bigger than that of the normal mode, so the latter driving arms will output a larger torque to help the former driving arms overcome the obstacle, as is shown in Fig. 11(d). Figs. 11(e) and (f) show that the latter diving arms contact the step which the former arms have just overcome. This time, the former driving arms help the latter diving arms surmount the obstacle. Fig. 11(g) is a similar process that the stator of the robot is climbing the step with the help of the former arms. Then the robot entirely enters the pipe of inner diameter 180mm, and keeps propelling forward.

The climbing step experiment testifies the adaptability of the robot while the pipe environment changed.
VI. CONCLUSION

A pipe robot based on the adaptive mobile mechanism has been developed to perform inspection tasks. The proposed mobile mechanism has two working modes, a normal working mode and an assistant enhanced mode. Robot under the normal working mode moves and monitors the condition of the pipe. On the other hand, robot under the assistant enhanced mode generates larger torque to help the former driving arm surmount the obstacle without any other driving actuators. This special feature is achieved by employing the proposed transmission mechanism and only one actuator.

The latter driving arm mechanism has been analyzed. According to the analysis results, the value of the offset has been determined. Moreover, the obstacle surmounting experiment has been conducted. The result testifies the efficiency and the adaptability of the developed robot.

REFERENCES