An In-pipe Inspection Robot based on Adaptive Mobile Mechanism: Mechanical Design and Basic Experiments

Peng Li, Shugen Ma, Member, IEEE, Bin Li, Yuechao Wang and Changlong Ye

Abstract—A robot, which is composed of adaptive mobile mechanism, is developed for the purpose of performing the internal inspection tasks of pipelines. Adaptability and efficiency are the basic considerations for this robot. Based on these concepts, a prototype is designed and fabricated. The proposed adaptive mobile mechanism equipped with one actuator can perform two working modes, a normal working mode and an assistant enhanced mode. Robot under the normal working mode is used for moving in pipe or monitoring the inner surface of the pipe. On the other hand, robot under the assistant enhanced mode will produce a larger torque to help itself surmount an obstacle in the pipe without any other driving actuator. This special feature is achieved by applying a power transmission mechanism. The rotation problem of the stator is solved according to the calculation results of the robot kinematics. Basic experiments have been conducted to testify the adaptability and efficiency of the robot.

I. INTRODUCTION

PIPELINES are the major tools for the transportation of oil and gas. With time went on, a lot of problems emerged, such as corrosion caused by the chemical elements in pipeline, cracks and damages by outer circumstances. These problems should be detected to avoid the leakage of oil and gas, which may cause environment pollution and great losses.

Robots can enter the narrow spaces of the pipelines to execute the inspection tasks with electronic devices, such as sensors and cameras. The most importance is that the pipe robots have access to the areas which are difficult and dangerous for human beings.

Up to now, a lot of pipe robots have been reported. Okada developed a three-wheeled pipe robot that uses scissors-like structure [1]. Hirose et al. developed a series of in-pipe inspection robots called “THES” that have some unique characteristics [2]. Hayashi et al. developed a micro pipe robot driven by an external motor by using the screw drive principle [3, 4]. Choi and Ryew developed MRINSPECT3 which is 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 is propelling and performing 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 we faced in design of the pipe robot propelling mechanism. This problem can also be summarized as: enable the robot extra working function, but use less actuators. Thus, the robot may acquire various propelling functions, while the number of the driving actuators does not increase. This paper is aimed to develop such a robot.

II. MOVEMENT PATTERN OF THE NEW PIPE ROBOT

It is hard to specify all the requirements for in-pipe robots designed and used in some certain circumstances. But some factors are still to be considered:

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

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

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

Pipe robots usually are classified into pig type, wheel type, walking type, inchworm type and other hybrid types [6]. Pig type is usually used in the trunk pipelines [8]. Because of the low translate velocity, inchworm type is not suitable for our robot, either [9, 10]. Walking type carries too many actuators whose locomotion is hard to control [11]. In addition, it is so difficult to integrate so many actuators in the pipe of diameter 200 mm. Active wheel types robot may be a good choice, but it also carries many actuators of which energy consumption is high. Thus, our proposed pipe robot aimed to move in the pipe of diameter 200mm is a wheel type robot based on the screw drive principle. Robot of this type travels in pipe at a relatively high speed compared with inchworm and walking type and traction force will be enhanced by increasing the normal force and the adhesion coefficient between the wheels and the inner surface of the pipe.

The principle of screw drive wheel type robot is illustrated...
in Fig. 1. Screw drive wheel type robot is usually composed of rotator, elastic support arm and free rollers. The free rollers that are pressed on the inner surface of the pipe have an incline angle with respect to the axis of the pipe. When the driving torque applied on the periphery of the pipe, the rollers not only rotate with respect to its own axis but also around the axis of the pipe. The trajectory of the center of roller displays a helical line. Thus, the whole mechanism moves forward. If the driving torque reversed, the mechanism will move backward.

Robot that employs the screw drive principle has several advantages. Because less driving actuators are needed, robot will consume less power but have more continuous time to perform the inspection tasks. Moreover, robot of this type simplifies the control complexity and downsizes the mechanism. Screw drive has its own locomotion characters, which will be exhibited in section V.

III. CONCEPT OF THE ADAPTIVE MOBILE MECHANISM

The new robot is based on the screw drive principle and modularly designed for the further development, as shown in Fig. 2. The driving arms of the robot are mounted with paddles that rotate together with the driving arms. The rotary paddles will generate extra driving force when the robot 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 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 arm stuck by the obstacle. The stator that is connected with the driving actuator should not to rotate in order to keep the posture of the robot all the time. When the robot carries out inspection tasks in the pipe 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.

IV. MECHANISM DESIGN OF THE ROBOT

Actually, designing such an adaptive mobile mechanism proposed above is not an easy job. The job is different from designing a mobile robot moving on the ground. When the robot travels in pipes, the axial length of the robot should meet some geometric conditions.

A. Adaptive Mechanism of The Robot

Before designing the adaptive mechanism, the following requirements are firstly considered.
1) Output torque from actuator can not 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 geometric constraints of the pipe.
3) Less actuators should be used to achieve more functions of the robot.

These requirements are not independent but intertwined. Finally, we 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.

As shown in Fig. 3, the power of the actuator is transmitted via coupling to spur gear1 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. Another 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 are 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 arms have a constant incline angle with respect to the axis of the pipe. Torsion springs are predetermined and set between latter driving arms and rollers (shown in Figure 4). The predetermined forces keep the rollers parallel to the axis of the pipe, when the former arms are rotating. The forces should be conquered, if the latter driving arms begin to rotate.

\[ \omega_i^6 + H \omega_3 = K \omega_3 \]

From (1), if \( \omega_i = 0 \), we obtain the ratio from spur gear 1 to ring gear \( i_{6i} \) is equal to \( i_{63} K \); while the angular velocity of the ring gear is zero, the ratio from spur gear 1 to the planet gear carrier \( i_{61} \) is \( i_{63}(K+1) \). Consequently, the mechanism can work under two modes whose ratios of transmission are different from each other.

**B. Locomotion Mode of The Mechanism**

The adaptive mechanism mentioned above has two typical working modes. Under neither mode of the mechanism does the stator rotate.

1) **Normal Working Mode**: The resistance between the robot and the pipe usually is not so high in most of the time when the robot is propelling in the pipe. 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 of the reaction force between the latter driving arms and pipe is not easy to overcome. The ratio from the actuator to former driving arms \( i_{63} \) is less than \( i_{61} \), so the robot can travel at a high speed in the pipe.

2) **Assistant Enhanced Mode**: When the robot encounters an obstacle (such as a step), the angular velocity of the former driving arms fall 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 arms. 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 \( i_{61} \). Because \( i_{61} > i_{63} \), the latter arms produce larger torque to help the former arms overcome the obstacle.

The mobile mechanism of the robot can switch its working mode according to the environment of the pipe. Robot will move at a high speed when the normal working mode is active. On the other hand, the mobile mechanism produces high torque, when the robot encounters an obstacle. This feature is achieved only by one actuator that is equipped on the robot. From the above, we can see that the new pipe robot has unique adaptability to the change of the pipe environment and efficiency in power consumption because of one driving actuator equipped. The switching of the working mode is the characteristics of the mechanism, and we do not need to control the robot to switch the working mode. This unique character of the new pipe 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 that is shown in Fig. 4. Main parameters of the robot are listed in table I.

**V. Kinematic Analysis of The Robot**

The proposed robot is in the pipe of inner diameter of D, as shown in Fig. 5. Point C denotes the centroid of the robot. \( O_r \), \( O_{hi} \) and \( O_i \) denote the centers of the rollers on the driving and support arms, respectively. Point \( C_1 \), \( C_h \) and \( C_2 \) denote the rolling centre of \( O_r \), \( O_{hi} \) and \( O_i \) with respect to the axis of pipe.
Orthogonal unit vector \( i, j \) and \( k \) are defined at the centroid of the robot. \( Q \) denotes the contact point between the rollers and pipe. Triple orthogonal unit vectors \( h_i, g_i \) and \( k_i \); \( h_j, g_j \) and \( k_j \) are defined and fixed to the centre of the roller \( O_i, O_{ij} \) and \( O_j \), respectively. \( \alpha \) denotes the incline angle of \( h_i \) with respect to the cross section of pipe.

\[ \dot{r}_c = \dot{r}_w + \nu_{ci} \]  
\[ \dot{r}_{ci} = \dot{\phi}_i + \nu_{i} \]  
\[ \dot{\phi}_i = (\omega_{i2} + \dot{\phi}_i g_i) \times r_w \]  
\[ \omega_{i2} = -\dot{\theta}_i \]  
\[ \nu_{i} = \omega_{i2} \times O_i C_i \]  

Because the relative velocity \( \nu_{ci} \) is zero, we can obtain the following expression from (2) to (6)

\[ \dot{r}_c = r_w \dot{\phi}_i h_i - r_w \dot{\phi}_i j - L \dot{\phi}_i j \]

The relationship between \( h_i, g_i \) and \( i, j \) is expressed as

\[ \begin{align*}
\dot{h}_i &= \sin \alpha i + \cos \alpha j \\
\dot{g}_i &= \cos \alpha i - \sin \alpha j
\end{align*} \]

The velocity of the centroid can be written

\[ \dot{r}_c = r_w \dot{\phi}_i \sin \alpha i + \left( r_w \dot{\theta}_3 + L \dot{\theta}_3 - r_w \dot{\phi}_i \cos \alpha \right) j \]

The pipe constrains the robot in the direction of \( j \), the angular velocity of the roller can be written

\[ \dot{\phi}_i = \frac{\dot{\theta}_3 (r_w + L)}{r_w \cos \alpha} \]

The velocity of the centroid of the robot is

\[ \dot{r}_c = \dot{\theta}_3 (r_w + L) \tan \alpha i \]  

Where \( \dot{\theta}_3 \) denotes the velocity of the DC motor, \( \theta_3 \) denotes the total ratio of power transmission.

From (10) we can see that the velocity of the robot is not only determined by the actuator speed but also has relationships with \( r_w, L \) and incline angle \( \alpha \).

The velocity of the direct drive wheel robot, when the robot moving in the straight pipe, can be expressed

\[ \dot{r}'_c = r_w \dot{\theta}_3^m / \dot{\theta}_3^m \]  

Compare (10) with (11), the result of \( \dot{\theta}_3^m \) multiply \( \tan \alpha \) is equivalent to \( \dot{\theta}_3^m \). This hints that \( \tan \alpha \) is equivalent to the ratio of reduction and should be considered in mechanical design.

B. Kinematic Analysis with Rotation of the Stator and Latter Driving Arms

In the early stage of experiments, we observed that the stator was not stay still, but had an angular velocity when the robot was traveling in pipe. Fig. 6 shows the phenomenon of the rotary stator.

\[ \begin{align*}
\dot{r}_{ci} &= \dot{\phi}_i + \nu_{ci} \\
\dot{\phi}_i &= \dot{\psi} r_j - \dot{\phi}_i r_i \\
\nu_{ji} &= \dot{\psi} i \times O_j C_j
\end{align*} \]

The relationship between \( h_i, g_i \) and \( i, j \) is expressed

\[ \begin{align*}
\dot{h}_j &= \sin \beta i - \cos \beta j \\
\dot{g}_j &= -\cos \beta i - \sin \beta j
\end{align*} \]

We get the velocity of \( C_2 \)

\[ \dot{r}_c = \dot{\psi} (r_w + L) \tan \beta i \]

Where \( \beta \) is the incline angle of the roller mounted on the stator (shown in Figure 5).

The calculation of velocity \( C_1 \) is also similar to \( C_2 \), we replace \( \dot{\psi} \) with \( \dot{\psi} - \dot{\theta}_3 \) that is the relative velocity of former driving arm with respect to the stator in (12). Then

\[ \dot{r}_{ci} = (\dot{\theta}_3 - \dot{\psi}) (r_w + L) \tan \alpha i \]

And the velocity of \( C_3 \)

\[ \dot{r}_{ch} = (\dot{\theta}_3 + \dot{\psi}) (r_w + L) \tan \alpha s i \]
Where $\dot{\theta}_h$ and $\alpha_h$ denote the angular velocity of latter driving arm and the incline angle of its roller.

The velocity of the centroid can be describe as

$$\begin{align*}
\dot{r}_c &= \dot{r}_{c_1} + v_{c_{x_1}} \\
\dot{r}_c &= \dot{r}_{c_2} + v_{c_{x_2}} \\
\dot{r}_c &= \dot{r}_{c_3} + v_{c_{x_3}}
\end{align*}$$

(16)

Because the relative velocity $v_{c_{x_1}}$, $v_{c_{x_2}}$, and $v_{c_{x_3}}$ is zero, we have the equation

$$\dot{r}_{c_1} = \dot{r}_{c_2} = \dot{r}_{c_3}$$

(17)

Equation (1) can be written in the below form

$$\dot{\theta}_h / i_6 + K(-\dot{\theta}_h) i = (K + 1) \dot{\theta}_h i$$

(18)

From (13) to (18), we obtain

$$\psi = \begin{cases}
\frac{\dot{\theta}_h}{i_6} \left( \frac{(K+1)\tan\beta}{\tan\alpha_h} + K \frac{\tan\beta}{\tan\alpha} - 1 \right)^{-1} & \alpha_h \neq \frac{\pi}{2} \\
\frac{\dot{\theta}_h}{i_6} \left( K + \frac{\tan\beta}{\tan\alpha} \right)^{-1} & \alpha_h = \frac{\pi}{2}
\end{cases}$$

(19)

The velocity of centroid of the robot is presented

$$\begin{align*}
\dot{r}_c &= \begin{cases}
\frac{\dot{\theta}_h (r_w + L)}{i_6} \left( (K+1) \frac{1}{\tan\alpha_h} + K \frac{1}{\tan\alpha} - 1 \right)^{-1} & \alpha_h \neq \frac{\pi}{2} \\
\frac{\dot{\theta}_h (r_w + L) K}{i_6} \frac{1}{\tan\alpha} \left( K \frac{1}{\tan\alpha} \right)^{-1} & \alpha_h = \frac{\pi}{2}
\end{cases}
\end{align*}$$

(20)

While the domains of the incline angles are as follows: $0 \leq \alpha < \pi/2$, $0 \leq \beta < \pi/2$, and $0 \leq \alpha_h < \pi/2$.

In order to understand the effect of the phenomenon of the rotary stator, variable settings are as follows, $L=90$mm, $r_w=10$mm, $K=2$, $i_{61}=1$, $\alpha=12^\circ$, $\dot{\theta}_h=144$\degree/min. Analysis in Fig. 7 shows that with the rotation of the stator, the translate velocity of the robot is always below the ideal condition, but the distinct will be decreased with the increase of $\beta$. Finally, if the $\beta$ reaches the angle of $90^\circ$, the stator will stop rotate. Fig. 8 shows the similar effect caused by $\alpha_h$. The effect is similar to that of $\beta$.

Now we can get some conclusions based on the above discussion. If the robot is under the normal working mode, the incline angle of the roller on the stator should be kept at $90^\circ$ to prevent the rotation of the stator. Furthermore, if $\alpha_h=90^\circ$, the velocity of the robot will be maximum. On the other hand, if the robot is working under assistant enhanced mode, we need the change of $\alpha_h$ to generate traction force.

VI. EXPERIMENTS

We adopted the results of the kinematic analysis, and improved some parts of the robot. Experiments show that the rotation of the stator has been suppressed, as shown in Fig. 9.

Obstacle surmounting experiment has been conducted. In Fig. 10, the pipe is composed of two segments of pipes with different diameter. 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(a) and (b), the robot is moving in the pipe of
inner diameter 190mm under normal working mode, since the traction force that the robot needed is not high. In Fig. 11 (c), the former arms contact the step formed by the conjunction of the two pipes. Thus, the angular velocity of the former driving arms falls rapidly. The power transmission changes the working mode and the latter driving arms begin to rotate. Since 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 generate traction force. The robot is working in the assistant enhanced mode. The reduction ratio of the assistant mode is bigger than that of the normal mode, so the latter driving arms output a larger torque to help the former driving arms overcome the obstacle, as seen in Fig. 11(d). Figs. 11(e) and (f) show that the latter diving arms contact the step that the former arms have just overcome. At this time, just on the contrary, the former driving arms will help the latter diving arms surmount the obstacle. Fig. 11(g) is the 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 goes on propelling forward.

Because the robot does not equip other mechanism for navigation, it can not pass the T-shaped pipe. But the surmounting experiment also testifies the efficiency of the mechanism that can change its transmission ratio autonomously and the adaptability of the robot, while the diameter of the pipe changes.

VII. CONCLUSION

An adaptive mobile mechanism based on the screw drive principle has been proposed and fabricated for in-pipe robots. The proposed mechanism has two working modes, a normal working mode and an assistant enhanced mode. The robot in the normal working mode moves at a relatively high speed compared with that in the assistant enhanced mode. Robot under the assistant enhanced mode generates larger torque to help the former driving arms surmount the obstacle without any other driving actuators’ installation.

Kinematics of the robot has also been analyzed. According to the analysis results, we have improved some of the robot’s parts. Basic experiments show that the rotation of the stator is eliminated almost and the rotation of the latter driving arm is suppressed. Furthermore, the obstacle surmounting experiments have been conducted to testify the efficiency and the mobility of the developed robot.

REFERENCES

Fig. 11. Obstacle surmounting experiment