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Self-Rescue Mechanism for Screw Drive In-pipe Robots

Peng Li, Shugen Ma, *Senior Member, IEEE*, Bin Li, Yuechao Wang and Yunhui Liu, *Fellow, IEEE*

Abstract—**This paper presents a self-rescue mechanism for a screw drive in-pipe robot, which only uses one DC motor. The robot has two working modes, Normal Working Mode and Self-rescue Mode. Under normal working mode, the robot propels itself in the pipe just as other classical screw drive robots. When the robot encounters the obstacle and gets jammed, the lock up mechanism and motion control mechanism of the robot are activated. Then, the robot changes from working mode to self-rescue mode and moves away in the reverse direction to avoid jamming in the pipe. The change of the working mode is determined by the characteristics of the mechanism. The proposed mechanism can be used as a safety protection method for the pipe robot. Experiments have been conducted to testify the proposed mechanism. Compared with those with screw drive mechanisms, robots with self-rescue mechanism are able to avoid jamming in the pipe.**

I. Introduction

PIPE inspection robots are highly useful for monitoring the pipelines used in the industry and our daily life. Because of aging, some pipelines are prone to internal corrosions and leakages. In-pipe robots can monitor the conditions of the pipes, find the potential defects, and prevent serious accidents and environmental pollutions.

Many in-pipe robots are developed for the above reasons, and most of them are for medium or small size pipes, to which humans cannot access. Wheel type pipe robots are the most common type, due to their mobility. The wheel type pipe robots are mainly classified into two groups, direct drive pipe robots [1]-[5], and screw drive pipe robots [6]-[12].

The direct drive pipe robot is usually equipped more than one motor that drives itself in pipe; multiple motors enable the robot better mobility [2]-[4]. The screw drive robots are usually designed as a single driving unit with one motor, which can deduce not only the energy consumption but also the cost of the servo system. Some screw drive robots use a single unit and a single motor as a platform for inspection tasks [7,9-11]; others employ the link configuration type that can be formed by connecting two identical driving units together[6,8,12]. Screw type is very effective in the smooth pipe, and the robot works effectively in this situation, see Fig 1(a). However, when the robot encounters an obstacle and gets stuck with the obstacle, the robot will lose traction, and will not move. This stuck problem can be solved by reversing the driving motor, but *sometimes*, simply reversing the motor does not work, because the jamming-force is big enough that the motor can not conquer this force. The following experiment shows this problem.

The robot in Fig. 1 is a classical screw drive robot developed by the authors, and the robot has very similar properties with other ones [7,9-11], Fig. 1(a). This robot can climb the initial step of the concentric reducer. But the minimum size of the robot is lager than that of the reducer whose minimum size is 150mm, thus, the deeper the robot goes, the more possible it will get jammed in the reducer. Fig. 1(b) shows the robot is jammed in the reducer. When we reverse the driving motor, the robot still can not drive backward, see Fig. 1(c).

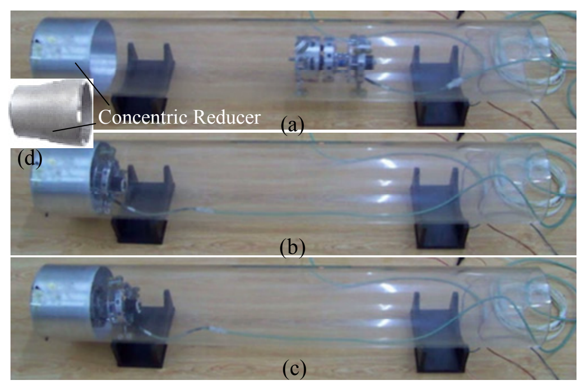

Fig. 1. A classical screw drive robot got jammed in the reducer.

The solution to avoid this stuck problem is to employ link configuration or send another robot to rescue the jammed one. But employing link configuration or sending rescue robot means that we need prepare another one identical driving unit at least, which doubles the cost of the robotic system.

In this paper, we attempt to avoid using the above method to help the robot to get un-jammed, and to find other solutions to this stuck problem. Our strategies are presented as follows:

1) Enable the robot with self-rescue ability; that means, when a robot gets jammed, the other rescue robot is not needed, because the robot can rescue itself.

2) Only one motor is used for the robot for the reduction of the cost and energy consumption.

Thus, we propose a self-rescue mechanism for screw drive

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P. Li was with Shenyang Institute of Automation, Chinese Academy of Sciences(CAS), Shenyang, China. He is now with the Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong, China.(e-mail: pli@mae.cuhk.edu.hk).

S. G. Ma is with the Department of Robotics, Ritsumeikan University, Shiga-ken, Japan. He is also holding the professor position at Shenyang Institute of Automation, CAS, China. (e-mail: shugen@se.ritsumei.ac.jp).

B. Li and Y. C. Wang are with the State Key Laboratory of Robotics, Shenyang Institute of Automation, CAS, Shenyang, China.

Y. H. Liu is with the Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong, China.

pipe robots. This mechanism employs only one motor, and can provide the robot with self-rescue ability. Robots with the self-rescue mechanism have two working modes, normal working mode and self-rescue mode. Under normal working mode, the robot acts like any other classical screw drive robot, see Fig. 1(a). When the robot is jammed in the pipe and can not drive away by reversing its motor, the robot changes from normal working mode to the self-rescue mode. Then, the robot moves toward the opposite direction to avoid jamming. The change of working mode is autonomous, and does not need human intervention.

This paper only deals with the jamming problem in the straight pipe, because the straight pipe is the basic element of pipelines and it is our first time to equip the robot with self-rescue ability. We do not consider the curved pipe yet.

The following section presents the proposed self-rescue mechanism. From section III to section V, we introduce the design of the robot's transmission mechanism, locking up mechanism and motion control mechanism respectively. Then, the results are presented and the conclusions are followed.

II. Concept of the Self-Rescue Mechanism

A typical screw drive robot is usually composed of a rotator, elastic support arms, rollers and a motor for driving. The rollers have an incline angle with respect to the cross section of the pipe, as shown in Fig. 2. When the motor turns, the whole body moves forward. If the motor turns reversely, the body moves backward. To propel a screw drive robot, one motor is enough for straight pipe and elbow. However, for the T-shape pipe, extra navigation mechanism is needed.

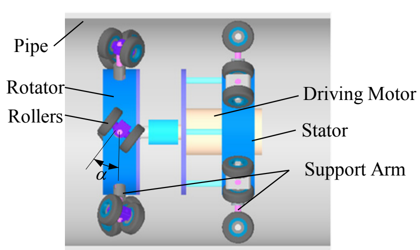

Fig. 2. Typical configuration of a screw drive robot.

Based on the screw drive principle, a robot with self-rescue property is proposed, as seen in Fig. 3.

The robot is composed of stator, rotator 1, rotator 2, rotator 3, lock up mechanism, motion control mechanism and only one driving motor. Two sets of the supporting arms are fixed to the stator in which the single motor is installed. Another set of the driving arms (driving arm 2) are *hinged* on the rotator 2. The rotator 1 is located at the head of the robot, on which three driving arms 1 are fixed. Each set of the support arms and the driving arms has three identical entities that are mounted around the robot at 120 degrees intervals.

The robot has two working modes, normal working mode and self-rescue mode.

1) Normal Working Mode: The rotator 1 and the driving arm 1 rotate to pull the robot forward or backward, while the rotator 2, the rotator 3 and the stator keep still because of the constraint that is exerted by the motion control mechanism. Thus, the stator and the rotator 2 and 3 act as an equivalent stator, and the robot acts as a classical screw drive robot under this mode, see Fig. 4. If a CCD camera device is installed, the robot can inspect the pipe, when moving in the pipe.

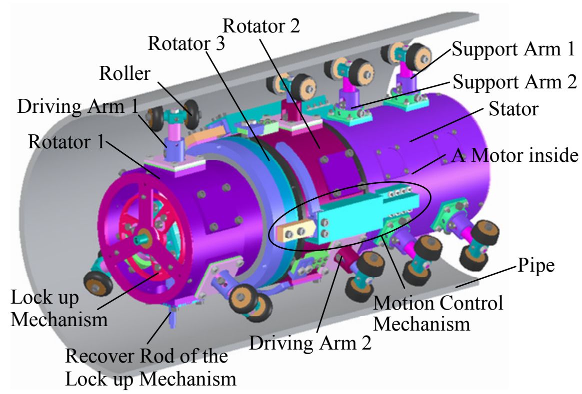

Fig. 3. Concept of the self-rescue mechanism.

2) Self-rescue Mode: The robot can overcome small obstacles in the pipe in the normal working mode, and the obstacles can be surmounted with several attempts as long as the robot is not jammed by the obstacle. In case the robot encounters an obstacle and jams itself, the lock up mechanism works and the constraint of the motion control mechanism is conquered. As a result, the rotator 1 and its driving arms 1 stop rotating; while the driving arms 2 on the rotator 2 slant themselves to an angle of 12° with respect to the cross section of the pipe. Then, the rotator 3 and the rotator 2 rotate together. The traction forces generated by the rotation of the rotator 2 and rotator 3 are just opposite to that of rotator 1 at this time. Therefore, the robot moves far away from the obstacle and avoid jamming itself in pipe. It is necessary to point out: the *robot can still move forward or backward under self-rescue mode*, when the driving motor turns clockwise or anticlockwise.

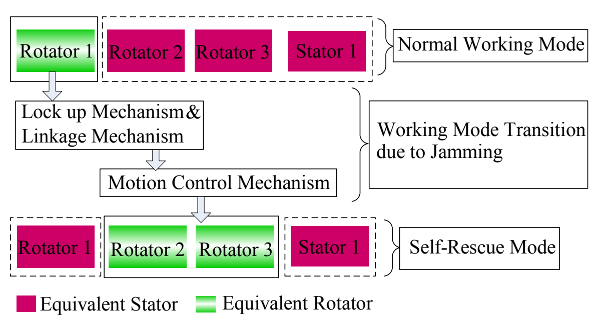

Fig. 4. Illustration of the robot's working mode.

We can see that the working modes of the robot are determined by the motion of the rotator 1, the rotator 2 and the rotator 3. The relations between this two working modes and these triple rotators are listed in Table I.

TABLE I
RELATIONS BETWEEN WORKING MODES AND ROTATORS

	Rotator1	Rotator3	Rotator2
Normal Working Mode	●	⊗	⊗
Mode Changing Process	⊗	●	⊗
Self-rescue Mode	⊗	●	●

● ROTATOR IS ACTIVE; ⊗ ROTATOR IS INACTIVE.

III. DESIGN OF THE TRANSMISSION MECHANISM

The robot's transmission mechanism is the critical element to fulfill the function of self-rescue ability. Detailed design of the transmission mechanism is shown in Fig. 5.

The transmission part of the robot is mainly composed of a DC motor with an encoder, a spur gear 1 and a spur gear 2, a transmission shaft, a sun gear, three planetary gears, a ring gear and a pair of bevel gear (bevel gear 1 and 2). The spur gear 1 is fixed on the output shaft of the motor, while the spur gear 2 is fastened on one end of the transmission shaft. The sun gear is fixed on the other end of the transmission shaft. The sun gear is the input of the planetary gear train, which is formed by the sun gear, planet gears and ring gear. The carrier is the rotator 1 in Fig. 3, which is hinged with three planet gears. The ring gear is the rotator 3. The bevel gear 1 and bevel gear 2 are meshing together. The bevel gear 2 is fixed on the driving arm 2, and they are hinged on the rotator 2.

There are two possible power transmitting routes in this transmission.

1) Power Transmitting Route1: The DC motor turns the spur gear 1 and the spur gear 2, then, the motion of the motor will be transmitted to the sun gear through the transmission shaft. Finally, the power of the motor is transferred to the rotator 1 on which three driving arms 1 are fixed.

2) Power Transmitting Route2: The power of the motor is transferred to the sun gear through the spur gear1 and the spur gear 2. The sun gear turns the planet gears and the ring gear. When the ring gear turns, it drives the bevel gear 2 through the bevel gear 1. Then, the driving arm 2 can be slanted to an angle 12°. A slant angle of the driving arm 2 is necessary to generate traction force, when rotator 2 and 3 rotate in the self-rescue mode.

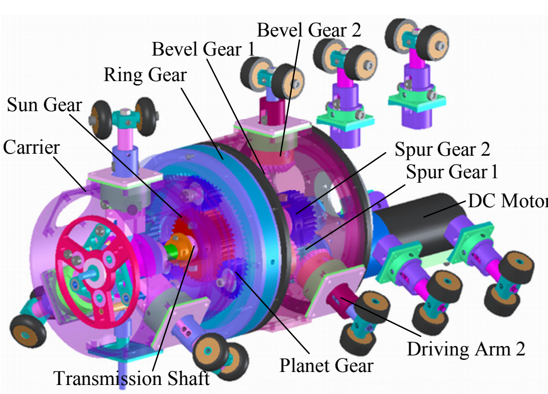

Fig. 5. The design of the transmission.

The power transmitting route1 and the power transmitting route 2 correspond to the normal working mode and the self-rescue mode respectively. It is necessary to pointed out that only the transmission itself will not perform the self-rescue function, if the lock up mechanism and the motion control mechanism are not designed.

IV. LOCKING UP MECHANISM AND MOTION CONTROL MECHANISM

The function of the lock up mechanism is used to constrain the motion of the rotator 1, if the robot can not surmount the obstacle and get jammed. However, to achieve the lock up function, the driving arm 1, the linkage mechanism and the lock up mechanism need to cooperate with each other.

A. Design of the Driving Arm 1

The driving arms are used to generate traction forces, when they are rotating with the rotator. A basic driving arm 1 unit is composed of a base, a slider, a container, a spring, two pins and two free rollers, as seen in Fig. 6(a). The base and the container are fixed on the rotator 1. The container has two slots on its cylinder profile at 180 degrees intervals. Inside the container, a compressive spring is placed between the container and the slider. Due to the slots and the pins, the slider can only expands under the spring force or contract due to the external forces. Two free rollers are joined on the block, and the block is attached on the slider. Thus, the incline angle of the roller is determined by the installing angle of the container. In this study, the incline angle of the roller with respect to the cross section of the pipe is 15 degrees.

As shown in Fig. 6, a lock up slider that has a cylindrical jut lays beneath the container, and the cylindrical jut fits the hole in the bottom of the container well. At the bottom of the slider, there is a cylindrical jut too, and the inner diameter of the spring is larger than the outer diameter of the jut. When the roller and the slider contract a short distance due to climbing an obstacle, the lock up slider will not glide. But if the distance is long enough, these two juts will contact and the lock up slider will trigger the lock up mechanism.

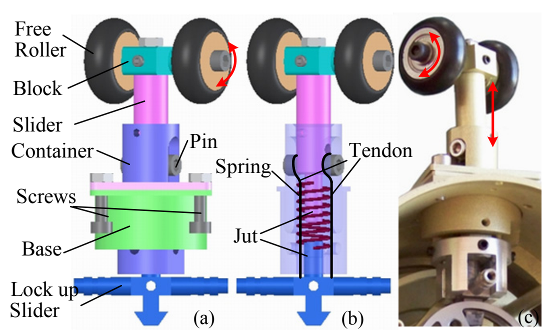

Fig. 6. The structure of the driving arm 1. (a) Basic structure. (b) Inside the container. (c) Real picture.

Each of the driving arms 1 is connected with the corresponding lock up slider by using the tendon, seen in Fig. 6(b). The length of the tendon is set to give no influence on the contraction of the slider, but once one of the three lock up sliders(active slider) goes down a certain distance, due to the functions of the *linkage mechanism*, the tendons on the other two sliders will be straightened. And if the active slider continues to contract, the other two sliders will follow this motion through tendons and the linkage mechanism.

B. *Linkage Mechanism*

The linkage mechanism is used to fulfill the following task: *any* of the three driving arms 1 in Fig. 6 contracts in the direction of the radius of the pipe by the external forces, the rest two driving arms1 can follow the motion.

Fig. 7 shows the designed linkage mechanism. The linkage mechanism has a bilateral symmetry configuration, and two turnplates are placed on both sides of the lock up slider, where each turnplate is hinged with one end of the three links, whose other ends are hinged with the lock up slider. The overall structure of this part can be seen in Fig. 8.

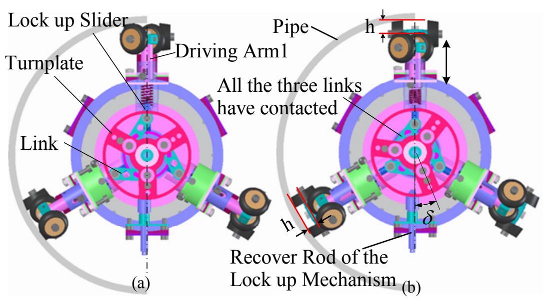

Fig. 7. The Linkage mechanism. (a) Posture without the contraction of the driving arm1. (b) Posture with the contraction of the driving arm1.

As long as one of the three driving arms pushes the lock up slider and goes down a certain distance(the distance that the tendon will be straightened in Fig. 6), the other two arms will contract simultaneously. The explanation is as follows:

One of the driving arms 1 contracts and its cylindrical jut collides with the jut of the lock up slider due to surmount an obstacle, see also Fig. 9(a). If the slider of the driving arm contracts further, it will push down the lock up slider, see also Fig 9(b). When the lock up slider moves, it forces the turnplate to rotate an angle of δ through the link that is hinged with the turnplate. Because all the links are hinged with the turnplate, the other two links and the corresponding lock up sliders contract, too. As mentioned above, when the lock up slider contracts a certain distance, the tendon between the slider and lock up slider itself will be straightened and will pull the slider of the driving arm 1 down (depicted in Fig 6(b)). Thus, the total three sliders of the driving arms will contract *simultaneously*, which is the main feature of this linkage mechanism, as shown in Fig. 7(b) and Fig 9(c).

C. *Lock up Mechanism*

The lock up mechanism is used to confine the motion of the rotator 1. If the height of the obstacle does not exceed the ability of the robot, the lock up mechanism does not work, and the robot can overcome the obstacle with several attempts. But when the height of the driving arm 1 contract too much, sometimes the robot is prone to wedge itself in the pipe. Thus, the lock up mechanism will constrain the motion of the rotator 1, when the driving arm 1 contracts too much.

Fig. 8(a) shows the overview of the linkage mechanism and the lock up mechanism, and Fig. 8(b) is the actual picture.

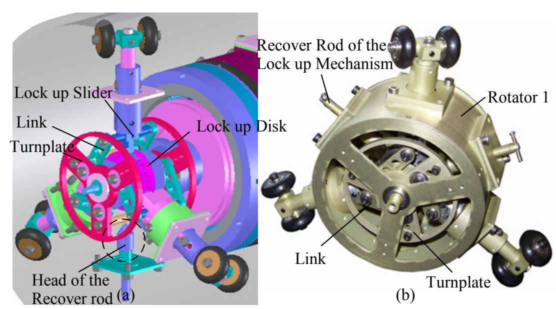

Fig. 8. The Lock up mechanism. (a) Basic structure. (b) Real picture.

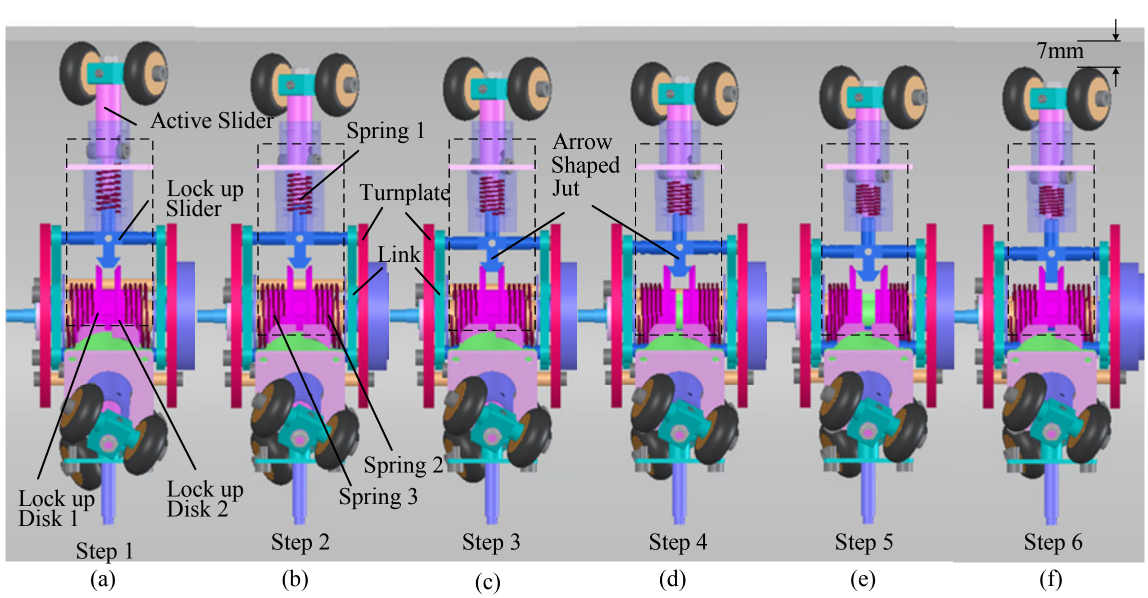

Fig. 9. The working principle of the lock up mechanism.

Fig. 9 shows the working principle of the lock up mechanism. When any of the three sliders on the rotator 1 (active slider) contracts due to the robot surmounts an obstacle, the linkage mechanism and the lock up mechanism are not active until the contraction distance reaches about 4mm, because the distance between the cylindrical jut of the driving arm 1 and the jut of the lock up slider is set 4mm, as seen in Fig. 9(a). Thus, when the linkage and lock up mechanism is not active, the robot acts the same as a classical screw drive pipe robot.

If the contraction distance of the active slider is larger than 4mm, the jut of the active slider collides with the jut of the lock up slider. Then, the linkage mechanism is activated and all the three lock up sliders contract together, as seen in Fig. 9(b) and Fig. 7(b). When the active slider continues to contract, the tendons of the rest two sliders are straightened and pull the rest of the driving arms' sliders down (depicted in Fig. 6(b)), and the three arrow-shaped juts of the lock up sliders contract with the lock up disks, as seen in Fig. 9(c). Fig. 9(d) shows that the three sliders and lock up sliders go down and push the two lock up disks aside until the arrow shaped jut and the lock up disk lose contact with each other. Fig. 9(e) shows the critical position where the arrow shaped juts and the lock up sliders lose contact. As long as the active sliders continue to go down a little, the two lock up disks will close up again under the forces of the spring 2 and spring 3 in Fig. 9(f).

When the lock up slider fall into the space that the two closed lock up disk formed, the motion of rotator 1 will be constrained, which means the rotator 1 has been locked up, see Fig. 8 and Fig. 10. Screwing down the recover rod manually in Fig. 8(b) is the way that releases the lock up mechanism. The head of the recover rod is big enough to force the enclosed lock up disks to open, then, the arrow shaped jut is recovered under the spring force of the driving arm 1 by the action of the tendon (depicted in Fig. 6(b)).

Because the diameter of the free roller is 20mm, theoretically, the maximum height of the obstacle that the roller can overcome is 10mm, thus, one stoke of the active slider's contraction (from Fig. 9(a) to Fig. 9(f)) is about 7mm in the direction of the pipe radius.

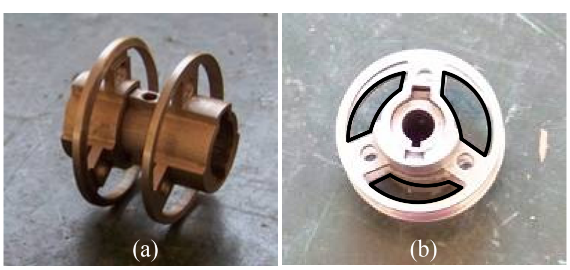

Fig. 10. Real picture of the lock up disk. (a) Basic structure. (b) Top view, when the arrow shaped jut falls into the sector space (three sections enclosed by black line in this figure), this structure will confine the rotation of the arrow shaped jut. Because the lock up slider is on the rotator 1, the rotation of the rotator 1 is confined.

D. Motion Control Mechanism

The motion control mechanism is used to adjust the motion of the rotator 1 and the rotator 2. The motion control mechanism is composed of an indicator, a constraint rod, the sleeve1, the sleeve 2, a recover spring and a stopper.

One end of the indicator has an obtuse angle shape, and the constraint rod has a concave at one end and a jut at the other end. The indicator is fixed on the rotator 3 and contacts with the concave of the constraint rod. Because the force of the recover spring, the indicator and the constraint rod contact tightly, and the other end of constraint rod lays in the sleeve 2 that is fixed on the stator, as seen Fig. 11(a).

Under this condition (Fig. 11(a)), the motion and the power of DC motor is transmitted to the rotator 1 through the power transmitting route 1, because both the position of rotator 3 and rotator 2 are limited to that of the stator due to the indicator-constraint rod contact.

As soon as the rotator 1 has been locked up, the motion of the motor is confined and the driving torque of the motor increases rapidly. When the motor's torque increases large enough, the torque acting on the rotator 3 and the indicator will conquer the constraint force exerted by the constraint rod and the recover spring. Then, the rotator 3 will rotate an angle until the indicator contact with the stopper on the rotator 2. The three driving arms 2 will turn the same angle simultaneously because of the meshing of the bevel gear 1 and bevel gear 2 in Fig. 5. When the rotator 3 and its indicators contact with the stopper, the indicator and the constraint rod lose contact and the recover spring will push the constraint rod get out of the sleeve 2, shown in Fig. 11. The constraint between the stator and the rotator 2 and 3 disappears. Finally, the rotator 2 and the rotator 3 can turn together; the robot is under self-rescue mode. The traction force generated by the rotation of the rotator 2 and 3 is just opposite to that of the rotator 1, therefore, the robot moves far away from the obstacle and prevent jamming itself.

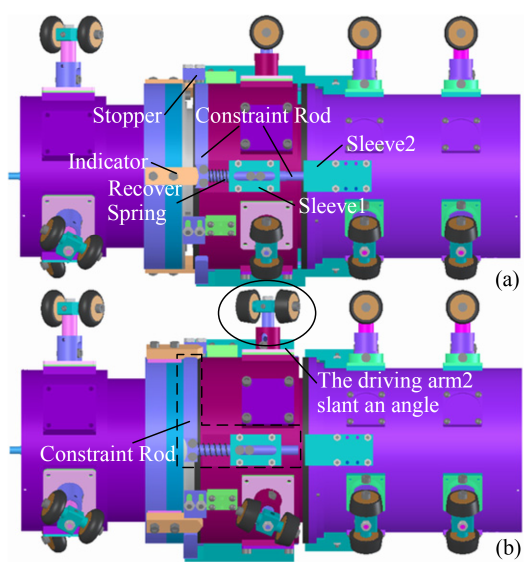

Fig. 11. Motion control mechanism. (a) Posture under normal working mode. (b) Posture under self-rescue mode.

During this changing process of working mode, we do not need reverse the output of the motor. The motor drives the robot through the power transmitting route 1 under the normal working mode; when the robot encounters a small obstacle, the robot will overcome it or climbing it with several attempts. Once the robot jams itself, the lock up mechanism works and confines the motion of the rotator 1. Then, the motion control mechanism is activated to permit the rotator 2 and rotator 3 to turn and drive the robot reversely. Thus, extra rescue robot is not needed, and this mechanism can not only prevent the robot from jamming but also the driving motor from stalling at high ampere armature current.

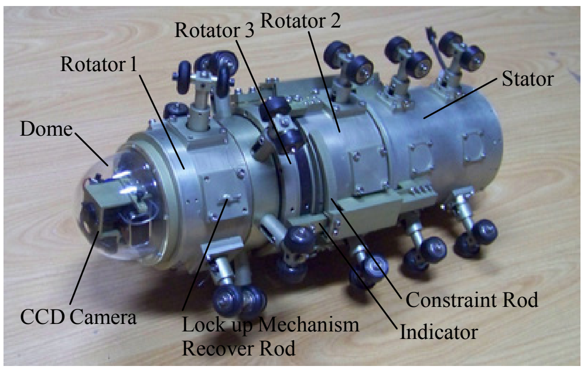

Fig. 12. The prototype of the in-pipe robot.

Fig. 12 shows the prototype of the in-pipe robot with CCD camera assembly, thus, the robot can be used for inspection task by using the CCD camera. Table II shows the robot's parameters.

TABLE II
SPECIFICATIONS OF THE ROBOT

Max Diameter	200mm	Axial Length (with camera)	349mm
Min Diameter	173mm	Total Mass	4.35Kg

V. EXPERIMENTS

To test the effectiveness of the proposed mechanism, experiments have been performed. Fig. 13 shows that the in-pipe robot moves in a straight pipe with the inner diameter of 190mm under the normal working mode.

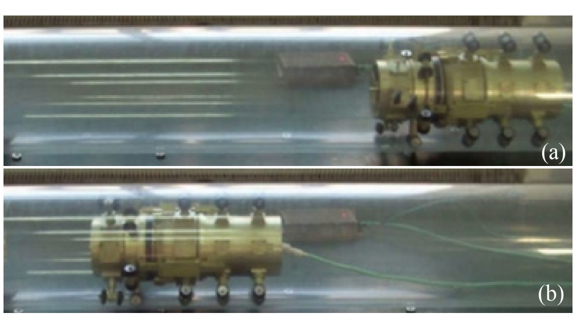

Fig. 13. The driving test in a smooth pipe.

Further, the performances of the lock up mechanism and linkage mechanism are tested, as seen in Fig. 14.

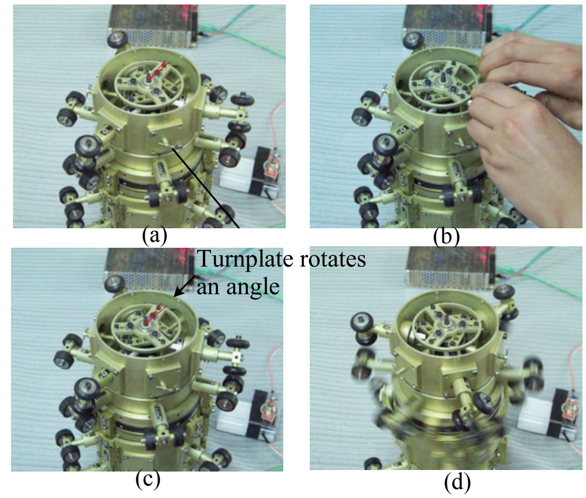

Fig. 14. Test of the lock up mechanism. (a) Initial status that the lock up mechanism is inactive. (b) Lock up mechanism is activated by compressing an driving arm 1. (c) Status that the lock up mechanism is active, which means the arrow shaped juts of the lock up sliders have fall into the sector spaces of the lock up disk. (d) Motion control mechanism is activated and the rotator2 and 3 turn together.

Fig. 14(a) shows that the lock up mechanism has not been activated, and the rotator 1 can turn freely. Next, we compress one of the driving arms 1, then, the other two driving arms 1 are contracting because of the linkage mechanism, see Fig. 14(b). Fig. 14(c) shows that the lock up mechanism has been activated, and the rotator1 is confined. When the motor is powered on, the motion control mechanism works and the rotator 2 and the rotator 3 begin to rotate, see Fig. 14(d). Thus, the linkage mechanism, the lock up mechanism and the motion control mechanism indeed work as expected.

The environment of Fig. 15 is composed of a segment of straight pipes and a conical pipe that tends to imitate the concentric reducer, which is the same with that of Fig. 1. The two elements are connected concentrically, and the diameter of this conical pipe is 186mm at one end and 150mm at the other end. It means that if the robot penetrates into the reducer, the robot must surmount a step of 4mm.

The self-rescue experiment is shown in Fig. 15. In Fig. 15(a) and (b), the robot is moving under normal working mode, and it has surmounted the initial step of the concentric reducer in Fig. 15(c). When the robot moves into the pipe deeply, the contraction of the driving arms 1 become higher and the lock up mechanism works and confines the motion of the rotator 1. Then, the motion control mechanism is activated. The rotator 2 and rotator 3 rotate and slant the driving arm 2 an angle simultaneously, as seen in Fig. 15(d). The robot changes its working mode into the self-rescue mode, and drives itself reversely, as seen in Fig. 15(e)~(g). The result shows that the mechanism can prevent the robot from jamming in the reducer.

The result of classical screw drive robot that runs in the same environment is shown in Fig. 1. The robot is jammed in the reducer, and we can not help the robot get out of the stuck status by reversing its driving motor.

VI. Discussion

Although we have proposed a self-rescue mechanism to prevent the screw-drive robot from getting jammed in the pipe, other rescue options are also needed. For example, once the only one driving motor gets out of order, the robot will be uncontrollable, thus, a retrieval function trough a tether cable is still needed to pull the robot out.

VII. Conclusion

In this paper, we have proposed an in-pipe robot based on the self-rescue mechanism. The self-rescue mechanism aims to prevent the robot from jamming in the pipe. By using the self-rescue mechanism and a single motor, the robot moves in pipe under the normal working mode, and the robot can climb a small obstacle. The robot acts as a typical screw drive robot under normal working mode. When the robot surmounts an obstacle and robot's radius is contracted too much, it runs the risk of being jammed itself in the pipe, so it changes its working mode into the self-rescue mode and moves reversely. This feature provides the robot self-rescue ability.

The results show that classical screw drive robot sometimes jammed itself in the concentric reducer, while a robot with proposed mechanism can escape from the obstacle. Further, even in the self-rescue mode, the robot is able to move forward and backward by reversing its driving motor.

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References

[1] T. Okada, and T. Sanemori, "MOGRER: A vehicle study and realization for in-pipe inspection tasks," *IEEE J. Robotics, Automation*, vol. 3, no. 6, pp. 573-582, 1987.

[2] H.R. Choi, and S.M. Ryew, "Robotic system with active steering capability for internal inspection of urban gas pipelines," *Mechatronics*, vol. 12, pp. 713-736, 2002.

[3] S.G. Roh, and H.R. Choi, "Differential-drive in-pipe robot for moving inside urban gas pipelines," *IEEE Trans. Robotics*, vol. 21, no. 1, pp. 1-17, 2005.

[4] T. Oya, and T. Okada, "Development of a steerable, wheel-type, in-pipe robot and its path planning," *Advanced Robotics*, vol. 19, no. 6, pp. 635-650, 2005.

[5] A. A. F. Nassiraei, Y. Kawamura, A. Ahrary, Y. Mikuriya, et al, "Concept and design of a fully autonomous sewer pipe inspection mobile robot "KANTARO"," in *Proc. IEEE Int. Conf. Robotics, Automation*, 2007, pp. 136-143.

[6] S. Hirose, H. Ohno, T. Mitsui, and K. Suyama, "Design of in-pipe inspection vehicles for $\phi 25$, $\phi 50$, $\phi 150$ pipes," in *Proc. IEEE Int. Conf. Robotics, Automation*, 1999, pp. 2309-2314.

[7] S. Iwashina, I. Hayashi, N. Iwatsuki, and K. Nakamura, "Development of In-Pipe Operation Micro Robots," in *Proc. Int. Symp. Micro Machine, Human Science*, 1994, pp. 41-45.

[8] I. Hayashi, N. Iwatsuki, and S. Iwashina, "The running characteristics of a screw-principle microrobot in a small bent pipe," in *Proc. Int. Symp. Micro Machine, Human Science*, 1995, pp. 225-228.

[9] M. Horodinca, I. Doroftei, E. Mignon and A. Preumont, "A simple architecture for in-pipe inspection robots," in *Proc. Int. Colloq. Autonomous, Mobile Systems*, 2002, pp. 61-64.

[10] A. Brunete, M. Hernando, and E. Gambao, "Modular Multiconfigurable Architecture for Low Diameter Pipe Inspection Microrobots," in *Proc. IEEE Int. Conf. Robotics, Automation*, 2005, pp. 490-495.

[11] Jinwu Qian, Linyong Shen, Weiming Cheng, and Yanan Zhang, "A micro robotic system for pipeline inspection using eddy-current technique". *Robot*, vol 23, no. 2, pp.127-131, 2001.(in Chinese)

[12] C. Ratanasawanya, P. Binsirawanich, M. Yazdanjo, M. Mehrandezh, et al, "Design and Development of a Hardware-in-the Loop Simulation System for a Submersible Pipe Inspecting Robot," in *Proc. Canadian Conf. Electrical and Computer Engineering*, 2006, pp. 1526-1529.

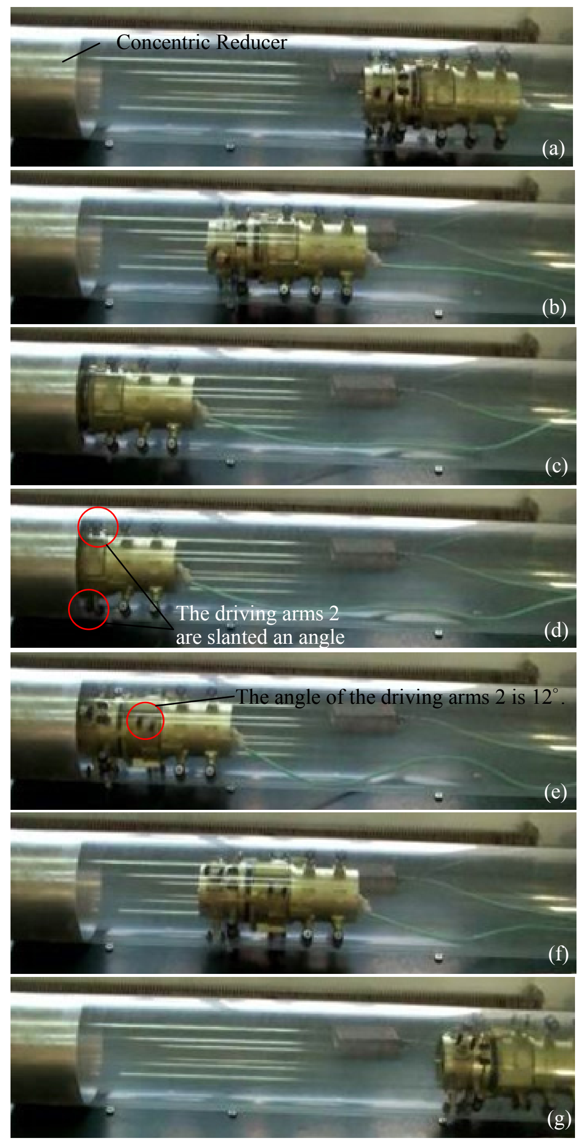

Fig. 15. The self-rescue experiment of the proposed mechanism.