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Development of spiral driven type mobile robot for NDT inspection in small pipes of thermal power plants.

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Abstract: A high traction force mobile robot has been developed as a platform for a long distance inspection under 10cm scale diameter pipes for plants facilities. The dimensions of robot body and optimal mechanism were studied to maximize the robot volume capacity and traction force. The mechanism was adopted with a spiral driven type to drag a cable and pass through a u-bent pipe area. Performance tests and robot system modifications were carried out in a real scale mock-up to verify and review the applicability in utilities.

1. INTRODUCTION

Pipes are one of the main mechanical components in industry infrastructure such as thermal power plants, chemical plants, gas delivery plants, etc. Issued problems in pipes are caused by aging, fatigue and corrosion cracking. Hence, the piping system has to be enforced to inspect periodically to guarantee the integrity of each component by an NDT (Non-Destructive Test) and in a visual way.

Because of the space limitation of a pipe and narrow passage, an inspection was carried out at the outer side for finding defects using an X-ray or ultrasonic waves. However, these are not the direct inspection of pipes, and the reliability cannot be assured by comparing with the pipe inspections. Moreover, the procedure to dismantle and reattach the insulations of pipes took much time and higher labor charge.

To solve these problems, a lot of researches are being performed for the development of an inspection mobile robot to find defects by moving inside [1-5].

In-pipe mobile robot should carry the NDT instruments such as a laser scanner, visual inspection cameras and power/signal cables for inspecting the pipes. Thus, in-pipe robots need sufficient torque and stable contact with the pipe.

This paper describes the development of an in-pipe mobile robot able to travel a long distance of 100m with inspection devices for thermal power plants. A spiral drive mechanism was adopted to increase the thrust force. Four types of wire were reviewed and modified to minimize the friction with the pipe. In addition, a feasibility test was carried out in 100m mock-up pipes to review the facility applications.

2. SYSTEM DESIGN

2.1 Size calculation of the mobile robot

The radius of curvature and diameter of the pipes are the major parameters to be considered for the design of a robot. The robot width is determined by the size within the pipe diameter. The robot length is related to the robot width in a small sized pipe.

Therefore, the motor dimension is strictly limited by the size of the robot system, and the propulsion is related to the motor size. The length and width of the mobile robot have to be designed to maximize the robot volume.

Eq.1 shows the limits of width corresponding to the size of the pipes. Eq.2 shows the relationship between the width and length for a maximum volume.

$$0 < W < \left(\mathrm{R} + \frac{D}{2}\right)\sin\left(\frac{\pi}{4}\right) - \left(\mathrm{R} - \frac{D}{2}\right), \tag{1}$$

$$\mathrm{H} = 2\sqrt{\left(2 + \frac{D}{R}\right)^2 - \left(2 + \frac{R-D}{w}\right)^2}. \tag{2}$$

where D is the pipe diameter, R is the curvature of the pipes, H indicates the length, and W is the width of the mobile robot. Fig.1 shows a simulation of the robot dimension in the pipe.

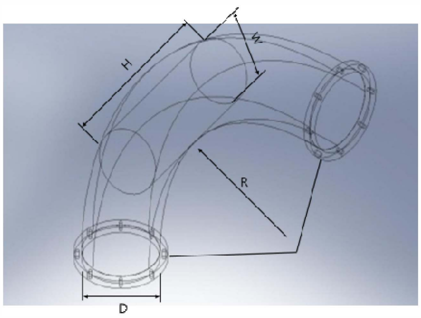

Fig. 1 Graphical parametric simulation of pipe mobile robot

2.2 Spiral driven mechanism in mobile robot design

The diameter of the drive motor for the mobile robot was determined based on the diameter of the pipes. Because a wheel type of in-pipe mobile robot generally used a small sized motor compared to the body, the generated torque is small.

A spiral driving structure has been proposed for increasing the thrust. The thrust force of screw drive method is generated using a drive motor, relatively large force emitted, and bidirectional movement is possible using the forward and reverse rotation of the drive

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motor. This manner will reduce the weight as well as reduce the numbers of other equipment and motor drivers.

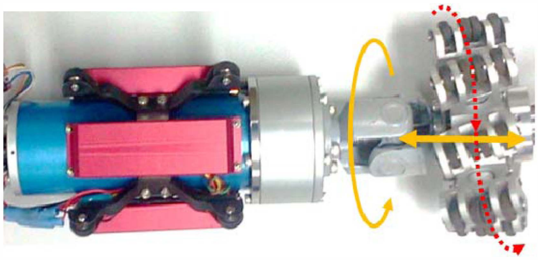

Fig. 2 Spiral driving mechanism of the mobile robot

Fig. 3 shows the mechanism for the motion of a helical structure. The rotational force generated at the motor body is transmitted to the inclined roller wheel in contact with the inner surface of the pipes.

When the inclination angle of the roller wheel is increased, the speed of the mobile robot is faster. However, the required force increases for the movement of the robot. On the contrary, when the inclination angle of the roller wheel is decreased, the robot can move with relatively little power. However, the movement speed is reduced.

Eq. 3 shows the relation between the distance to move the wheels, the travel distance and the actual robot.

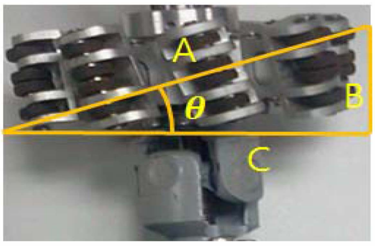

Fig. 3 Moving distance calculation of the robot

$$B = A\sin\theta = C\tan\theta, \tag{3}$$

where, A is the length of the hypotenuse, C is the length of the pipe diameters, θ is the angle of the wheel and pipe circumferential direction, and B is the moving distance of the robot.

3. MANUFACTURING OF MOBILE ROBOT

Fig. 4 shows a detailed design of the prototype of the in-pipe mobile robot. This prototype is the basic structure for the final prototype. The roller assembly and output parts are connected directly. The In-pipe robot can move smoothly in a curved pipe using a universal joint in the middle of the roller assembly and motor output part. Each roller assembly has four rollers in contact with the pipe at the inner surface.

To keep good contact conditions, the direction of rotation of the roller assembly should be in contact perpendicular to the moving direction of the robot, where each roller wheel consists of two rollers. Connection with the roller assembly is supported with a spring having a 1cm margin displacement to overcome obstacles or irregular boundaries in the pipe.

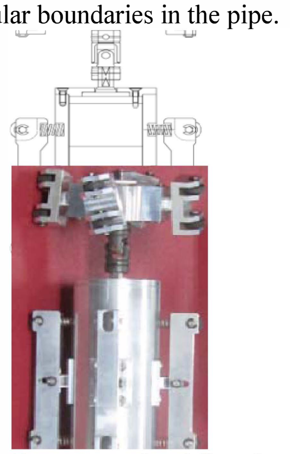

Fig. 4 Prototype of mobile robot

Fig. 5 shows a detailed design and out look of robot of the first version of the robot to complement the primary prototype. By applying the two reduction gear structures to connect the wires and camera smoothly, structures were changed to a hollow design, and a universal joint was applied to a hollow structure.

The interval of the roller assembly for supporting the pipe inner surface of the body becomes a change of 1 to 5.5cm from 6.5cm, size of robot was increased about 8.3cm to 30.6 from a length of 22.3cm. Traction force increased by adding two more wheels on two rollers of the driving wheels.

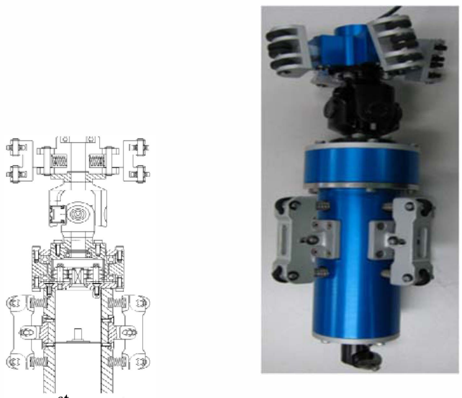

Fig. 5 The 1st version view of the mobile robot

Fig. 6 The 2nd version view of the mobile robot

Fig. 6 shows a detailed design of the second version of the in-pipe mobile robot. Roller wheels of this version were increased to eight from four to improve traction. Because there are 4 rollers supporting one point, roller assembly were designed that 32 rollers hold in the pipe.

The second version of the robot with a flat spring support structure maintained a firm posture in the pipe by giving a flexible displacement of 20mm.

Fig.7 shows a camera module mounted on a mobile robot. The basic configuration as a cylindrical shape, skeleton structure is adopted to reduce the weight. A spring structure is applied to minimize the shaking caused by a deflection when the robot moves in the pipe.

The lens of the camera module has been a forward protruding structure overall. Thus, the structure of the skirt is applied to the front of the camera to protect the lens, and mounting 4 line lasers around.

The camera modules go through a curved portion of the pipe first because it is located at the front of the mobile robot. The connection structure of the camera module and a mobile robot was applied to the ball joint so that the camera module can pass smoothly through a curved pipe point. The outer diameter of the camera module was designed be 11cm, and the length is 22.3cm. The overall shape is designed as a bent type cylindrical structure with four support portions on the inner surface of the pipe. Each support portion has a structure that utilizes a flat spring. Fig.8 shows the mobile robot with a camera module.

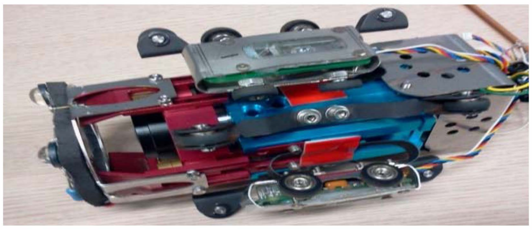

Fig. 7 mobile robot mounted camera module

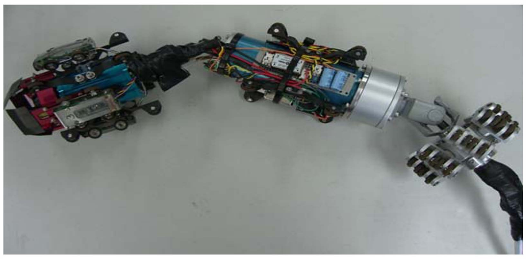

Fig. 8 Manufactured full system

The overall configuration of the mobile robot inspection system is set to mobile robot '1' and the camera module system for acquiring image data. 40m of cable made of Teflon is connected to the end of robot '1'. To compensate the traction force decreased by friction force between the cable and pipe, mobile robot 2 is connected to the back of the cable.

The camera module configuration is as follows: A high-resolution camera system for the transfer and acquisition of the video, lighting for visual inspection, quantity expression distance measuring sensor for measuring the distance traveled, communication units for power line communication, power units, processor board for sensor data processing, and communication / control.

Mobile robots '1' and '2' are composed of a power line communication unit, power supply unit, a motor driver and sensor processing unit to measure the cable tension.

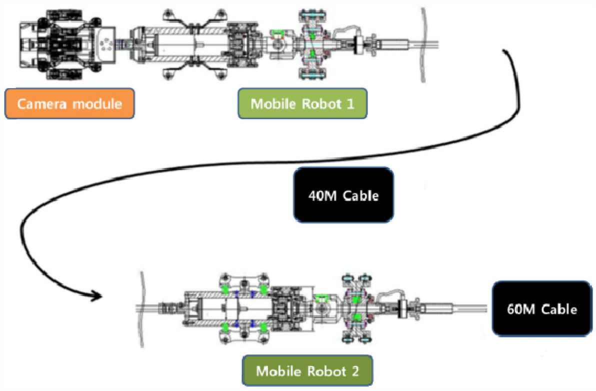

Fig. 9 Long-distance moving using two mobile robot

4. MOCK-UP DRIVING TESTS

4.1 Experiment to measure traction force

A traction experiment of a mobile robot has been performed. The traction force was measured by a spring scale/digital scale using clear acrylic pipe with a diameter of 10cm. About 9.5kg$_f$, 20kg$_f$ and 25kg$_f$ of force are generated for 8, 16, and 32 rollers respectively. The results show that traction force is increased in proportion to the number of wheels.

Fig. 10 Traction force test

4.2 Mobility experiment depends on wire and coating material

The dragging force was measured experimentally by friction force between the inner surfaces of the pipe and mobile robot according to the type of the wire.

The coating materials of Urethane, Teflon, and large and small rollers were used in the experiment. A small roller is a cylindrical roller without bearings and with a 3mm diameter. A large roller is a low-profile roller with a diameter of 5mm.

The dragging forces were measured by the change in the current of the drive motor by a 50m traveling of the mobile robot in the pipe.

(a) Polyurethane

(b) Teflon

(c) Small size roller

(d) Middle size roller

Fig. 11 Wires used for reducing the friction force

The motor current under no load condition is 200mA. However, it rises to 700mA when moving the curved pipe section. The current variations are induced by increasing contact friction force of the spring drive unit with the curved section surface of the pipe.

The experiment was carried out to check the changes of the current by the friction force occurring when the robots pass completely through a bent portion of the pipe using different types of wire under the same pipe conditions. Table 1 shows results of the experiments.

Table 1 Mobility test depending on the type of wire

Wire type	Mobility	Current
Polyurethane	Bad	Max
Teflon	Good	700mA
Small size Roller	Best	500mA
Middle size Roller	Better	500mA

4.3 Long-distance driving test

The mock-up of a 100m pipe was manufactured for investigating the mobility of the robot. The developed in-pipe robot feasibility test was successfully carried out in a full length mock-up to verify the applicability to real plants.

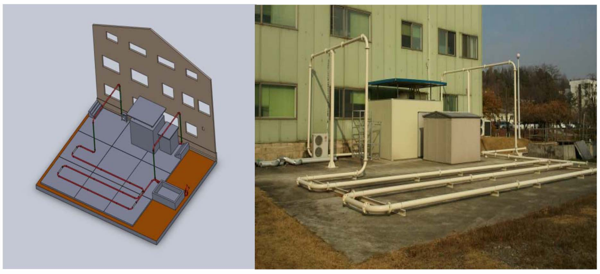

Fig. 12 Pipe mock-up for driving test

5. CONCLUSIONS

This paper described the development of a mobile robot necessary for an internal inspection in the small size pipes of thermal power plants. A simulation was performed to maximize the size of the mobile robot according to the size of the pipes. A spiral driven structure is adopted to solve the constraints of the numbers of motors occurring to limit the in-pipe robot size. The friction force of the four different types of wires was measured to find the proper wire. The mobile robot of a small size pipe mounting inspection system was developed. We set up mock-up pipes to test the developed in-pipe robot. The test verified the mobility of the developed robot in small pipes.

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REFERENCES

[1] H. Schemp, "In-pipe-assessment robot platform - phase 1 -state -of-the-art review" , Canergie Mellon University, Pittsburgh, USA, National Energy Technology Laboratory, REP- GOV-DOE 20041102, Nov. 2004.

[2] H. T. Roman and B. A. Pellegrino, "Pipe crawling inspection robot : An overview", *IEEE Trans. on Energy Conversion*, Vol. 8, No. 3, pp.576-583, 1993.

[3] H. B. Kuntze and H. Haffner, "Experiences with the development of a robot for smart

multisensoric pipe inspection," *Proc. of IEEE Int. Conference on Robotics and Automation*, pp. 1773-1778, 1998.

[4] W. Fischer, F. Tache, and R. Siegwart, "Magnetic wall climbing robot for thin surfaces with specific obstacles," *Proc. of the International Conference on Field and Service Robotics (FSR'07)*, Chamonix, France, July 2007.

[5] S. Roh and H. R. Choi, "Differential-drive in-pipe robot for moving inside urban gas pepelines," *IEEE Transactions on Robotics*, Vol. 21, No. 1, pp. 1-17, Feb. 2005.