

# Inspection robot climbing vertical cross piping using magnetic adhesive mechanism

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A new robot is presented which is able to climb on a perpendicular piping with branches and moves on the ceiling in the piping. The robot is a crawler type whose crawler has made of magnetic tips. The magnetic tips of the robot adhere to the piping made of iron due to magnetic forces. When the adhesive force is larger than the gravity force of the robot, a connection between the robot and the ceiling can be maintained. That is, the inspection robot in piping can move freely in solid piping of all shape such as in the vertical T character piping and the vertical crossing piping. The robot has a camera so as to inspect inside of piping. To validate it, a compact crawler type robot is made, and its fundamental characteristics are investigated.

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## 1. Introduction

The robot for inspecting in piping is of importance to maintain pipes in gas-, water-, chemical- and nuclear-pipeline networks, and some inspection robots were developed [1-3]. In Ref. [1], the robot using the mechanical friction was developed, in which three tires pushed on the inner surface of a pipe, and the robot could move due to the friction forces between the tires and the inner surface of the pipe. In Ref.[2], the robot with magnetic wheels were used, which could move in a pipe due to magnetic adhesive force between the magnetic wheels and the iron made piping, but the magnetic force was small, because the adhesive area was small when the magnetic wheels were used, and it was difficult to climb vertical pipe line. Recently, a tractor type robot having a number of magnetic chips on its crawlers has been developed [3], which enables the adhesion between the crawlers and the inner surface of iron made piping. In the robot, however, the size of the piping has to be large. In the previously developed robots as just mentioned, there are serious problems on climbing piping with branches, because they cannot climb vertical T-shape branches and the vertical crossing piping. The problem should be solved in practical piping inspection robots.

In the present article, we consider a crawler type robot, in which crawlers have magnetic chips. Although the magnetic adhesive force between the magnetic chips and a piping wall made of magnetic material is large because the adhesive area is large for crawler type, it is difficult to move into the vertical T-shape branch or vertical crossing because the normal crawler type robot [3] will falls down in climbing such branches. The present article develops the new type robot, which will be able to climb the branches such as vertical T-shape and vertical cross piping. Therefore, the robot can move everywhere in piping networks. The robot has a compact camera, and so the driving is made by watching the monitor, and defects in

piping are also found by the monitor. Mechanisms and the design method for the robot have been developed, and to validate them, experimental tests have been performed.

## 2. Mechanism of the present robot

There are some problems to be solved when the crawler type is applied to the inspection robot in piping as written below:

(1) It is difficult to have face touching of the crawler due to the curvature of the pipe when normal type crawler is used. Therefore, the robot falls down in moving the ceiling of the pipe due to the lack of magnetic adhesive force.

(2) The robot has to turn in the piping when moving into the T-shape or cross piping; however, it is difficult to do it in normal type crawler.

(3) It is difficult to climb at the vertical T-shape or vertical cross piping because the normal type robot falls down due to the moment of gravity which is generated by curvature of the piping.

In the present article, we propose a new crawler type robot with special mechanisms for solving the above mentioned problems.

### 2.1 Mechanism having a face touching on piping walls

In order to have face touching, a new crawler type robot is presented as shown in Fig. 1 whose sizes are 103 mm in length, 69mm in width and 183gf in weight. The crawler has magnetic chips whose poles are arranged by turns (N,S,N,S,...), and each crawler is driven independently by a DC-servo motor. The robot carries a compact camera and LED light for inspecting the inner surface of the piping. This enables the remote driving and inspections of the inner surface of the piping by watching the monitor.

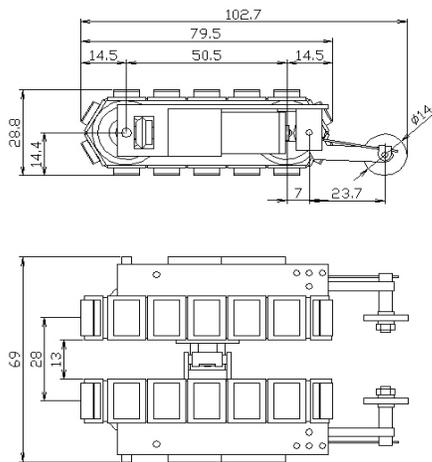


Fig. 1a. Geometry of the robot.

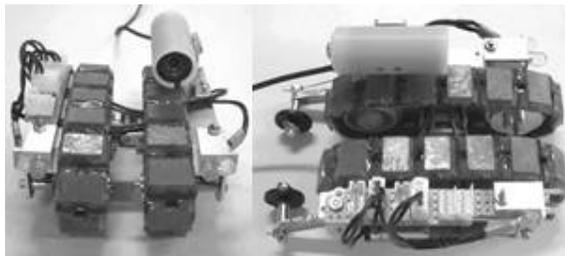


Fig. 1b. Photos of the robot.

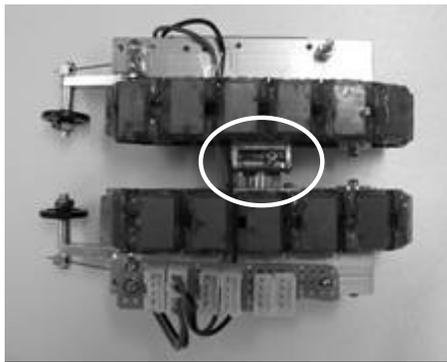


Fig. 2a. Portion of the hinge of the robot.

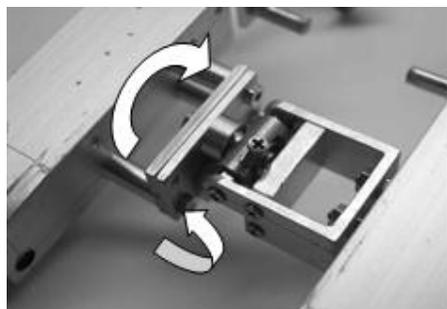


Fig. 2b. Hinge which enables both rolling and pitching motions.

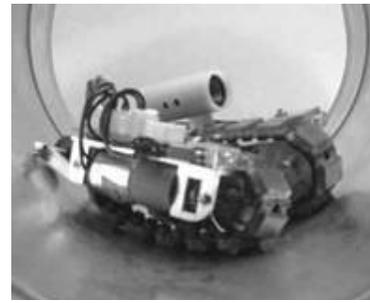


Fig. 3. Adhesion of the crawlers to the wall of piping.

In order to have the smooth face touching, two crawlers are connected by a middle hinge with a stopper which makes the rotations of each crawler in both rolling and pitching directions possible as shown in Fig. 2. Therefore, the crawler adheres smoothly to the piping wall as shown in Fig.3 even when the posture of robot varies from the axial direction of the pipe. This means that the adhesion force is significantly larger than that of the robot using magnetic wheels [2].

### 2.3 Driving system

Two crawlers in this system are driven independently by motors with gear reduction mechanisms. The specs of the motor is as follows: Ratings load rotational speed=130rpm, Ratings drive voltage=12 V, Ratings drive current=170 mA, Ratings torque=500 gcm, Gear ratio=1/97, Weight=25gf.

The traction force of the robot has to be larger than the tension of the power line and signal line coils. Then, the traction force of the robot was measured and shown in Fig. 4. Since the friction force is large when the crawler lies on the level ground due to the gravity force, the traction force is large, but it decreases in cases of ceiling wall due to the lack of friction force because the reaction force (=magnetic adhesive force–gravity force) decreases due to the gravity force. The traction force also decreases when the robot lies on the vertical wall because the gravity force acts directly in the down ward direction. The tension of the coils will not be large, and so the traction force for this robot is enough in practical use.

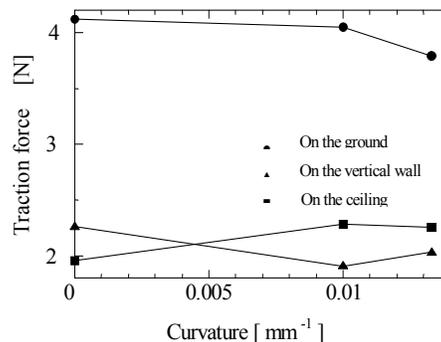


Fig. 4. Traction force of the robot.

### 3. Design of the robot

#### 3.1 Magnetic adhesive force

To protect the magnetic chips, a cover sheet with 0.5mm in thickness is pasted on the surfaces of the magnetic chips. The magnetic chips are alternatively arranged such as N,S,N,...to have magnetic circuit. The sizes of the magnetic chip used in the robot are as follows: length  $b=8\text{mm}$ , width  $a=12\text{ mm}$ , and thickness  $t=2\text{ mm}$ . The magnetic chip was pasted on an inner surface of a steel pipe, and the magnetic adhesive force was measured. The adhesive force for one magnetic chip is

$$F = 3.36 [N]$$

#### 3.2 Analysis of falling for the normal type crawler robot climbing the vertical T-shape wall of piping

Since the pipe wall at the T-shape connection point is not continuous, the posture of the robot becomes the figure as shown in Fig.5.

To prevent slips, the friction force should be larger than the gravity force:

$$2\mu \sum_{n=1}^N F_c \cos \beta_n > mg \quad (1)$$

where,  $\mu$  is the friction coefficient,  $F_c$  the magnetic adhesive force,  $\beta_n$  the angle between the vertical axis and the  $n$ -th magnetic chip,  $N$  is the number of attaching at the wall,  $m$  the mass of the robot and  $g$  the acceleration of gravity.

The moment due to the gravity force increases with the angle  $\phi_1$  in Fig.5, and so the robot falls down. In the case, let the tension of the crawler belt be  $T$ , the magnetic adhesive force be  $F_D$ , and the deflection of the belt be  $\delta$  at point D. There is the following relation:

$$2F_D \cos \theta_1 = T \sin \theta_1 + T \sin \theta_2 \quad (2a)$$

$$2F_D a = mgl_g \sin \phi \quad (2b)$$

From which we have the tension under the assumption that the angles  $\theta_1$  and  $\theta_2$  being small:

$$T = \frac{mgl_g (l-a) \sin \phi}{\delta l} \quad (3)$$

In order to have the adhesion of the magnetic chips on the curved surface of the piping wall as shown in Fig. 5, the length of the crawler belt should be greater than the ideal length  $[=l_c = 2(l + \pi r)]$ . The length of the belt in such case is

$$l_0 = l_c + \delta_0 = 2(l + \pi r) + \delta_0 \quad (4)$$

where  $\delta_0$  is the additional length. Then we have the following relations:

$$l_1 + l_2 = l + \delta_0 \quad (5a)$$

$$\left. \begin{aligned} l_1 \sin \theta_1 &= \delta, l_2 \sin \theta_2 = \delta \\ l_1 \cos \theta_1 &= a, l_2 \cos \theta_2 = l - a \end{aligned} \right\} \quad (5b)$$

From which we have

$$\delta \cong \sqrt{\frac{2a(l-a)\delta_0}{l}} \quad (6)$$

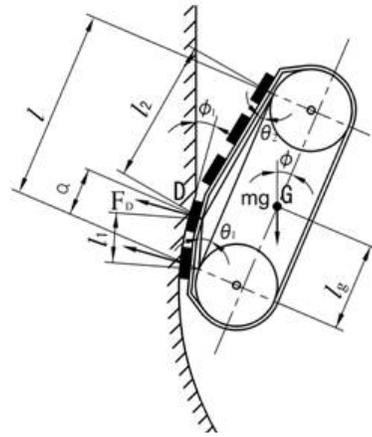


Fig. 5. Normal crawler robot climbing vertical T-shape branch.

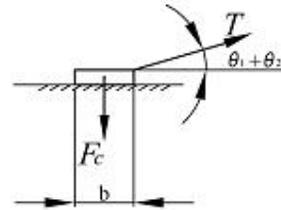


Fig. 6. Relation between the magnetic force and the tension.

The approximate values of angles are obtained as

$$\theta_1 = \frac{\delta}{a} = \sqrt{\frac{2(l-a)\delta_0}{al}} \quad (7)$$

$$\theta_2 = \sqrt{\frac{2a\delta_0}{(l-a)l}} \quad (8)$$

The inclination angle of the robot is

$$\phi = \phi_1 + \theta_1 \quad (9)$$

The equilibrium equation of the moment due to the magnetic adhesive force and the tension is (see Fig. 6).

$$T \sin(\theta_1 + \theta_2) b = \frac{b}{2} F_C \times 2 \quad (10)$$

Then the robot will fall down under the following condition:

$$F_c < F_f = T \sin(\theta_1 + \theta_2)$$

Since the tension  $T$  increases with the angle  $\phi$ , the robot will fall down for large curvature of piping (large value of  $\phi_1$ ). Therefore, it is difficult to climb the vertical T-shape or crossing branches by use of normal crawler type robots.

### 3.3 Mechanism for preventing falling from vertical T-shape wall or crossing in piping

In the present robot, a wheel is attached at each crawler by a spiral spring (see Fig. 7) to prevent the break of adhesion. Then the adhesion of crawler to the vertical cross piping is maintained due to the moment generated by the wheel and the spiral spring.



Fig. 7a. Attachment which gives the restoring moment to the robot.



Fig. 7b. Wheel with a spiral spring which gives restoring moment to the robot.

### 3.4 Analysis for the present robot climbing vertical walls of piping

In the present robot, the twisting moment of the spiral

spring is

$$M = k(\theta - \theta_0) = Rl \sin \theta \quad (11)$$

From which we have the reaction force of the wheel:

$$R = \frac{k(\theta - \theta_0)}{l \sin \theta} \quad (12)$$

There is the following relations:

$$\begin{aligned} Q_1 + Q_2 &= R \\ Q_2 l_1 &= R(l_1 + l_2) \end{aligned}$$

From which we have

$$\begin{aligned} Q_1 &= -\frac{kl_2(\theta - \theta_0)}{ll_1 \sin \theta}, \\ Q_2 &= \frac{k(\theta - \theta_0)(l_1 + l_2)}{ll_1 \sin \theta} \end{aligned} \quad (13)$$

where  $k$  is the spring constant of the spiral spring,  $\theta_0$  the initial angle of the lever, and  $\theta$  the angle of the lever when the wheel is on the inner surface of the pipe.

The forces are calculated as

$$Q_1 = -0.06 \text{ N}, Q_2 = 0.16 \text{ N}$$

for the system having the following values:  $k = 0.184 \text{ N} \cdot \text{mm}/\text{deg}$  (for the spiral spring with 3 mm in diameter, number of turn = 4, wire diameter=0.5 mm),  $\theta - \theta_0 = 13^\circ$ ,  $e=7 \text{ mm}$ ,  $l=25 \text{ mm}$ ,  $l_1=50.5 \text{ mm}$ ,  $l_2=30.9 \text{ mm}$ , and  $\theta = 73^\circ$ . The adhesive forces vary due to the forces generated by the spiral springs, and those are

$$F_5 = F_C - Q_2 = 3.36 - 0.16 = 3.2 \text{ [N]}$$

$$F_1 = F_C - Q_1 = 3.36 + 0.06 = 3.42 \text{ [N]}$$

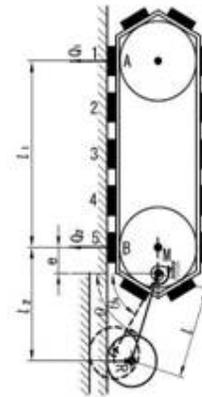


Fig. 8. Robot climbing the vertical wall.

Then, the friction force yields

$$\begin{aligned} F_f &= 2\mu F_1 + 2\mu(N-2)F_C + 2\mu F_5 \\ &= 33.4\mu [N] \end{aligned}$$

The weight of the robot is  $mg=1.79\text{N}$  (involving the weight of the camera), and so the friction coefficient should be greater than 0.05. Therefore, the adhesion is maintained because the friction coefficient in this system is greater than it ( $\mu = 0.6$ ). Since the posture of the robot is vertical ( $\phi = 0$ ), there is no moment due to the gravity force as mentioned above.

### 3.5 Analysis of the present robot climbing the T-shape connection piping

Since the wheels with the spiral springs give the restoring moment, which makes the posture of the robot vertical as shown in Fig.9, the adhesion is maintained when the friction force is greater than the gravity force:.

$$2\sum_{n=1}^N \mu F_C \sin \theta_n - 2\mu Q_1 - 2\mu Q_2 > mg \quad (14)$$

The angles in this case are

$$\theta_1 \cong \theta_2 \cong 80^\circ, \theta_3 = \theta_4 = \theta_5 = 90^\circ, \theta = 73^\circ$$

Substituting these values, we have

$$F_f = 19.9 [N]$$

The adhesion is maintained in this case, because the friction force is greater than the gravity force ( $mg=1.79\text{N}$ ).

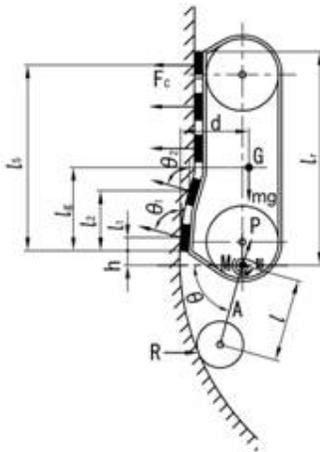


Fig. 9. Robot climbing T-shape branch.

### 3.6 Design formula for the robot on the ceiling

The relations in this case are (see Fig. 10).

$$mg(l_1 - l'_g) - Q_2 l_1 + R(e + l_1 + l \sin \theta) = 0 \quad (15)$$

$$-mg l'_g + Q_1 l_1 + R(l \sin \theta + e) = 0 \quad (16)$$

From which we have

$$Q_1 = \frac{mg l'_g - k(\theta - \theta_0) \left(1 + \frac{e}{l \sin \theta}\right)}{l_1} \quad (17)$$

$$Q_2 = \frac{mg(l_1 - l'_g) + k(\theta - \theta_0) \left(1 + \frac{e + l_1}{l \sin \theta}\right)}{l_1} \quad (18)$$

The adhesion is maintained under the following conditions:

$$2F_C > Q_1, 2F_C > Q_2 \quad (19)$$

In the present system, we have

$$Q_1 = 0.737[N] < 2F_C (= 6.72 [N])$$

$$Q_2 = 1.16[N] < 2F_C$$

Then the adhesion of robot is maintained on the ceiling surface of piping.

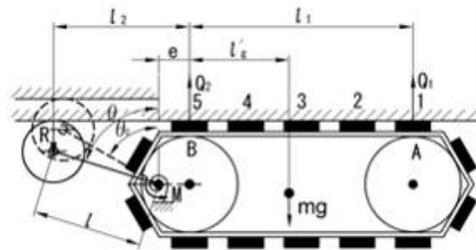


Fig. 10. Robot on the ceiling surface of piping.

### 3.7 Driving torque

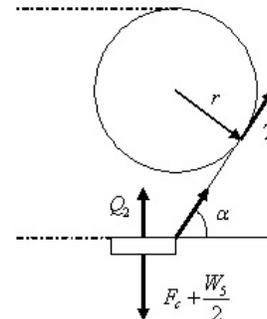


Fig. 11. Analytical model for the driving torque.

Fig. 11 shows the free body diagram for the driving magnet, and we have the following relation.

$$\frac{b}{2} \left( F_c + \frac{W_5}{2} - Q_2 \right) = \frac{T}{2} b \sin \alpha \quad (20)$$

where  $b$  is the width of the magnetic chip. The torque  $M_t$  when the robot climbs a slope with angle  $\theta$  is

$$M_t = \left( \frac{2F_c - 2Q_2 + W_5 \cos \theta}{2 \sin \alpha} + \frac{W}{2} \sin \theta \right) r + \frac{1}{2} M_f \quad (21)$$

where  $W_5$  is the force of the robot acting at the magnetic chip 5, and  $M_f$  the friction torque of the crawler. The dimensions of the present robot are as follows:

$$\begin{aligned} \alpha &= 60^\circ, W=1.79 \text{ N}(0.183\text{kgf}), W_5=1.0 \text{ N} \\ r &= 10.9\text{mm}, M_f=6.23 \times 10^{-3} \text{ N}\cdot\text{m}, F_c=3.36 \text{ N} \\ Q_2 &= 0.16 \text{ N}, \theta=90^\circ \end{aligned}$$

Substituting the values, the torque is obtained as  $M_t=0.05\text{N}\cdot\text{m}$ .

The torque for the motor is about  $M_d=3.46 \text{ N}\cdot\text{m}$ , in which the rating current=170 mA, rating torque=500g $\cdot$ cm, reduction ratio =1/97, and mechanical efficiency=73% (obtained by the experiment). In this case  $M_d(=3.46\text{N}\cdot\text{m}) > M_t(=0.05\text{N}\cdot\text{m})$ , and so the driving torque is enough.

#### 4. Running experiment in piping

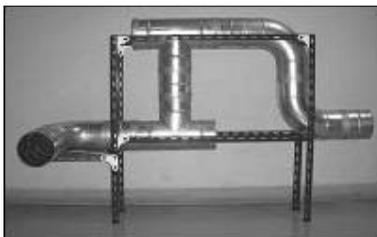


Fig. 12. Piping with vertical T-shape branch used in the experiment.

Fig. 12 shows the piping model used in this experiment, and Fig. 14 the crack model in the inner surface of the piping found by the monitor camera. The postures of the robot for climbing the vertical T-shape branch is shown in Fig. 13. In the figure, the robot changes its postures for climbing the branch in case of No. 1 and No. 2, then, climbs the T-shape branch in case of No. 3 through No. 5. It can be seen that the robot can climb the vertical wall of the pipe without falling.

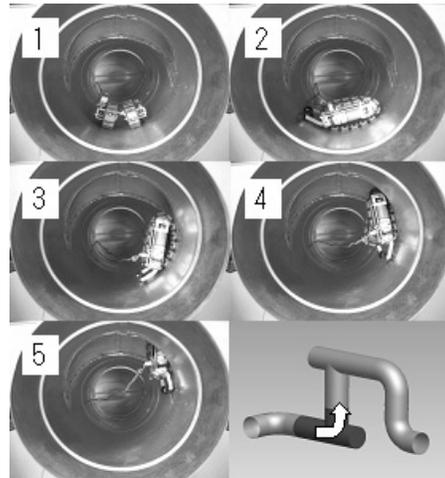


Fig. 13. Postures of the robot when climbing the T-shape branch.



Fig. 14. Crack model found by the monitor.

#### 5. Conclusion

An inspection robot in piping is developed, which can move piping networks with vertical T-shape connections and vertical crossings of piping. The robot consists of crawler with magnetic chips, wheels with spiral springs, driving motor, LED lights and camera. The design formulae are given, and the robot is produced by reference to the designed values. It is ascertained that the present robot can move freely in a pipe with vertical T-shape connections, and the cracks can be found by the monitor camera.

#### References

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