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Paper

Mobile robots on cylindrical surfaces

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Abstract—This paper proposes some basic structures of mobile robots which can run on cylindrical surfaces. This type of robot is utilized to inspect such cylindrical components as oil pipe lines, electricl power lines and so on. The key functions, which such robots should have, are to run on cylindrical surfaces smoothly and to avoid many obstacles autonomously. This paper shows some possible structures for these two functions.

1. INTRODUCTION

There exist many types of cylindrical components in various fields: oil pipelines, gas pipelines, chemical plants' pipelines, electric power lines, communication cable networks and so on. Such lines have to be inspected periodically for maintenance, but manual inspections are almost impossible due to long distances. Thus it is necessary to develop robots which perform the automatic inspections. The key functions, which such robots should have, are to run on cylindrical surfaces smoothly and to avoid many obstacles autonomously.

There have been several trials to develop such robots running on cables or pipelines [1–8]. Those are all excellent ideas, but many of them have not yet been in practical use due to engineering problems. However, this type of robot is absolutely necessary and we should collect every possible idea to realize such robots. Thus, this paper shows some other possible structures for such robots. In our research, we especially pay much attention to the following three properties:

(1) Robots run smoothly on cylindrical surfaces.

(2) Robots hold cylindrical surfaces firmly.

(3) Robots avoid any obstacles on cylindrical surfaces without adding extra bypasses.

The first property, 'smooth movement', is necessary for inspecting whole cylindrical surfaces. The series of pipeline maintenance robots studied by Fukuda *et al.* [6] realize excellent flexible movements on any configuration of pipelines, but the touching points are discrete. That means continuous smooth movement for inspection is not accomplished by such robots. The second property, 'firmly holding', is absolutely necessary for autonomous robots. While the cable maintenance robot developed by NTT [7] can move smoothly on cables, the robot hangs on the cable without robust connecting devices. The third property, 'obstacle avoidance', is also necessary for long distance inspection. The inspection robot for power transmission lines [3] requires specially designed bypasses to pass through the supporting pillars. However, to attach such bypasses to every supporting pillar is an extraordinary difficult and costly task.

With this in mind, we have tried to develop robots having the above three properties. This paper proposes three kinds of robots. The first half describes a robot running on cables which have many supporting pillars in the vertical direction. The original purpose of this robot is the maintenance of feeder cables for railroads.

The second part of this paper proposes two new types of robots which can run on a cylindrical surface with continuous spiral rotation. One robot has a spiral main frame with small wheels facing the cylindrical surface. The wheels are supplied to support the main frame against the cylindrical surface and to drive the frame forward or backward by spiral rotation. The other robot consists of a spiral tube, rudder chain and small wheels. The rudder chain is driven by motors attached at both ends of the tube, and it run on a closed trajectory through the tube and around the cylindrical surface. The chain winding motion causes a force to drive the main body forward or backward. As an inborn ability, these two robots can avoid various obstacles on the cylindrical surface by their spiral structure.

2. MOBILE ROBOT ON FEEDER CABLES

Feeder cables hang beside the railway and supply electric power to contact wires which are touching the pantographs of trains. In order to supply stable electric power, feeder cables are inspected periodically, while contact wires are replaced regularly. However, the long distance of cable implies the difficulty of manual inspection. Thus, inspection robots have been desired to execute automatic inspection. The feeder cables have many irregular points, but almost all of them are vertical pillars used for hanging. We show a new structure for such robots.

2.1. Mechanical structure

The basic mechanical architecture is a multi-car structure with joint connections. The robot consists of a symmetric pair of several connected cars as shown in Fig. 1. Each car except the last one has two motors; one is for driving and the other is for controlling the connection joint. Each symmetric pair is connected by a magnetic lock system.

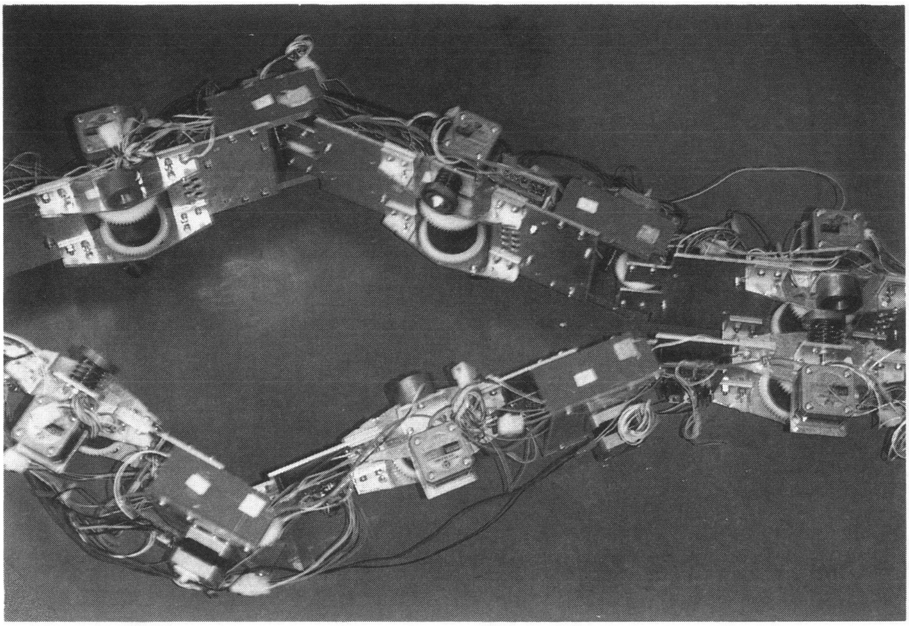

Figure 1. Appearance of prototype.

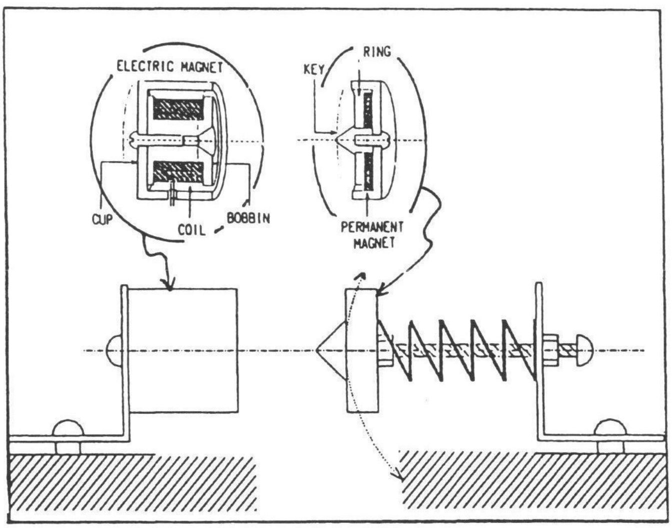

Figure 2. Structure of magnetic lock.

Figure 2 shows the structure of this magnetic lock system mounted on the prototype. This magnetic system consists of two parts; one is a permanent magnet and the other is an electrical magnet. The iron core and bobbin of the electrical magnet is a shape such that it makes a closed magnet circuit for the permanent magnet. One part is attached at the left-hand side and the other is mounted on the right-hand side of the car.

The permanent magnet is mounted by using a spring so as to have some flexibility. The head shapes of the keys attached to these magnets are the same; thus, when both side cars are in parallel, both parts slip into complete connection and connect both sides firmly. The holding force is about 20 kg in this case. Furthermore, this magnetic lock system has a failsafe structure, because the robot can hang on the feeder cable even when its electrical system is out of order.

Each car has a rubber wheel driven by a geared motor. By joining the rubber wheels of both side cars, the robot grasps the feeder cable and holds on it. Each rubber wheel rotates with the same constant speed, thus the robot can run along the cable smoothly.

The cars of the robot have their own connection joint. Each joint is driven by the motor attached beside the car, whose joint angle can be controlled arbitrarily. The motors have high ratio gears, thus the joints are driven with enough torque and high precision. Both sides can be separated into the left-hand side and right-hand side by decoupling the magnetic locks. By separating its body, the robot can avoid the vertical irregular points.

2.2. *Basic control strategy for obstacle avoidance*

As an original concept, we utilize a concept of biological autonomous systems. Let us consider the movement of our heart. A cell shrinks and passes the stimulating pulse for shrinking to the next cell; the cell shrinks and transmits the signal in turn. This small movement is done sequentially cell by cell. Atony is also done in the same 'cell-by-cell' manner. All of these small movements make the total pump-like movement. The first application of this motion into robotics was done by Hirose *et al.* [9]. They utilized this motion for a snake robot.

We also try to utilize this mechanism: the first car generates a control signal and moves by following this signal, and transmits the signal to the next car with some time delay. The second car executes the same motion with the delay and passes the same signal to the third car by adding another time delay. This motion is executed sequentially car by car and it causes a snake-like motion.

Here, we have to mention the following superior point when we adopt this mechanism to our robot. In the usual case, this mechanism is a kind of 'open loop control', thus the timing of each action is very important. If motion timing of a subsystem is slightly changed, the total motion is seriously disturbed by this slight changing. However, in our case, we can utilize the *distance along the cable* in place of *physical time.* Namely, each subsystem can precisely determine its timing by measuring the distance. Thus, even if the speed is changed randomly, the system acts the specified motion.

The strategy to avoid irregular points is as follows:

(1) The driving wheels of all of the cars are rotating at the same speed (the robot runs with constant speed).

(2) If the first car finds an obstacle, it release the magnetic locks of both sides of the cars and opens the connecting joint.

(3) The first car adjusts the joint angle such that it keeps the appropriate space from the obstacle.

(4) After passing over the obstacle, the car closes the connecting joint and locks both sides by the magnets.

(5) During obstacle avoidance, the first car transmits the generated joint control signal to the second car with some time delay.

(6) The second car and the following car can pass over the obstacle by sequentially repeating the manner as the first car.

Figure 3 shows the transition of the robot when it passes over the irregular point.

2.3. *Joint angle control*

The wheels for going forward are rotating with constant speed, thus trivial speed control is enough for this motion. The serious control problem is the joint angle control for obstacle avoidance.

2.3.1. Nominal trajectory. At first, we determine the nominal trajectory which bypasses the obstacle. It must be considered that at least three pairs of cars must hold the feeder cable in any given case. Naturally the nominal trajectory depends on the

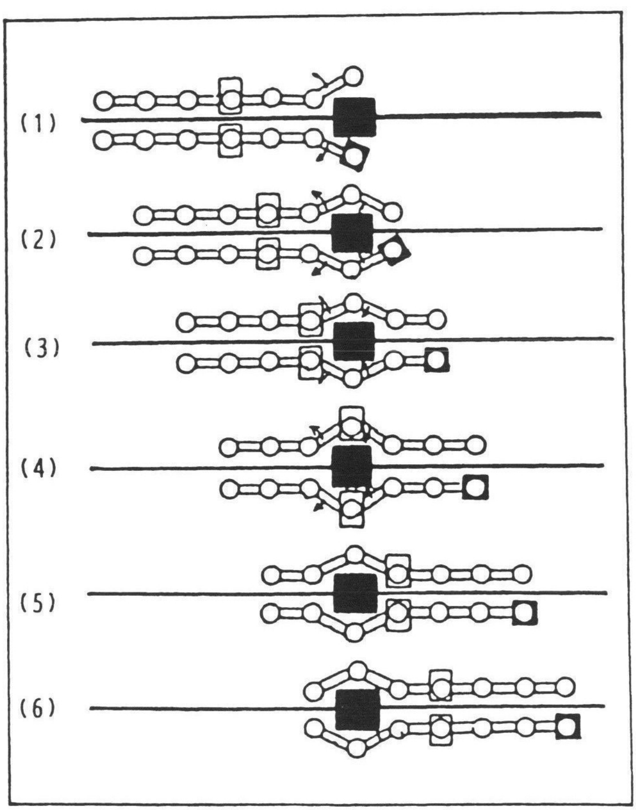

Figure 3. Basic strategy for obstacle avoidance.

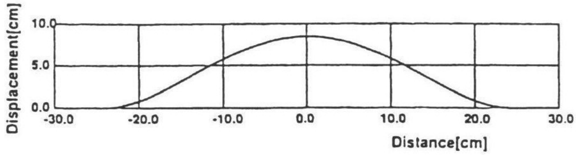

Figure 4. Nominal trajectory.

size of the robot and the obstacle. If the fore edge of each car tracks the following fourth order algebraic curve, more than three pairs can hold the feeder cable

$$f(x) = \begin{cases} \dfrac{1}{a^2 p^3}\{x^2 - (a+1)p^2\}^2 & \text{if} \quad |x| < \left(2+\sqrt{2}\right)p, \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where x is the distance along the cable and $f(x)$ is the displacement from the center axis of the cable. a and p are constants as $a = 5{+}4\sqrt{2}$ and $p =$ (length of a car)$/\sqrt{8}$. The obstacle is assumed to be at $x = 0$. Figure 4 shows the outline of the nominal trajectory. This trajectory is half the actual, the other half part is a symmetric form.

It is mathematically clear that no more than two points can exist on the curving region, where the distance of the points is equal to the length of the car. Therefore, of the robot follows this trajectory, more than three pairs of cars can hold the feeder cable.

2.3.2. Joint angle and car position. Let the relative angle between the i-th car and $(i+1)$-th car at step k be $\theta_i^*(k)$ and $u(k)$ is the control input at step k. The discrete state equation of each angle is written by the following simple equation

$$\begin{bmatrix} \theta_1^*(k+1) \\ \theta_2^*(k+1) \\ \theta_3^*(k+1) \\ \theta_4^*(k+1) \\ \theta_5^*(k+1) \end{bmatrix} = \begin{bmatrix} \theta_1^*(k) \\ \theta_2^*(k) \\ \theta_3^*(k) \\ \theta_4^*(k) \\ \theta_5^*(k) \end{bmatrix} + \begin{bmatrix} u(k) \\ u(k-d) \\ u(k-2d) \\ u(k-3d) \\ u(k-4d) \end{bmatrix} \tag{2}$$

Where d represents the delay time, namely the control for the first car at step k is equal to the control for the j-th car at step $\left(k + (j-1)d\right)$.

Let assume the final car (6th car) holds the cable and $\theta_i(k)$ be the absolute angle of the i-th car at step k concerning the coordinate system attached at the cable. The relation between the relative angle and absolute angle is given by the following equation:

$$\begin{bmatrix} \theta_1(k) \\ \theta_2(k) \\ \theta_3(k) \\ \theta_4(k) \\ \theta_5(k) \end{bmatrix} = J \begin{bmatrix} \theta_1^*(k) \\ \theta_2^*(k) \\ \theta_3^*(k) \\ \theta_4^*(k) \\ \theta_5^*(k) \end{bmatrix}, \qquad J = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

Let the fore position of the $(j+1)$-th car be (x_j, y_j). x_j is the distance along the cable and y_j is the displacement from the cable. (x_j, y_j) is described successively.

Where L is the length of each car.

$$x_0 = x_1 + L\cos(\theta_1) \qquad y_0 = y_1 + L\sin(\theta_1) \tag{4}$$

$$x_1 = x_2 + L\cos(\theta_2) \qquad y_1 = y_2 + L\sin(\theta_2) \tag{5}$$

$$x_2 = x_3 + L\cos(\theta_3) \qquad y_2 = y_3 + L\sin(\theta_3) \tag{6}$$

$$x_3 = x_4 + L\cos(\theta_4) \qquad y_3 = y_4 + L\sin(\theta_4) \tag{7}$$

$$x_4 = x_5 + L\cos(\theta_5) \qquad y_4 = y_5 + L\sin(\theta_5) \tag{8}$$

The state equation concerning the absolute angles is written as follows:

$$\begin{bmatrix} \theta_1(k+1) \\ \theta_2(k+1) \\ \theta_3(k+1) \\ \theta_4(k+1) \\ \theta_5(k+1) \end{bmatrix} = \begin{bmatrix} \theta_1(k) \\ \theta_2(k) \\ \theta_3(k) \\ \theta_4(k) \\ \theta_5(k) \end{bmatrix} + J \begin{bmatrix} u(k) \\ u(k-d) \\ u(k-2d) \\ u(k-3d) \\ u(k-4d) \end{bmatrix} \tag{9}$$

2.3.3. Joint angle control. Let us consider the situation at step k. Since only the first car makes a decision for control, it is enough to make the control $u(k)$ for the first car. The position (x_1, y_1) at the next step $(k+1)$ is determined previously, because it only depends on the control input till step $(k-d)$. The angle $\theta_1(k+1)$ is given from the state equation

$$\theta_1(k+1) = \theta_1(k) + u(k) + u(k-d) + u(k-2d) + u(k-3d) + u(k-4d) \tag{10}$$

The fore position of the first car at step $(k+1)$ is described by using this $\theta_1(k+1)$

$$x_0(k+1) = x_1(k+1) + L\cos\left(\theta_1(k+1)\right) \tag{11}$$

$$y_0(k+1) = y_1(k+1) + L\sin\left(\theta_1(k+1)\right) \tag{12}$$

We determine the $u(k)$ such as $\left(x_0(k+1), y_0(k+1)\right)$ be on the reference trajectory.

At first, we determine the angle $\theta_1(k+1)$ numerically. The procedure is as follows:

1 $\theta_0 = \theta_1(k)$

2 $x_0 = x_1(k+1) + L\cos(\theta_0)$

$y_0 = y_1(k+1) + L\sin(\theta_0)$

3 $f_0 = f(x_0)$

4 if $|y_0 - f_0| < \varepsilon$ $\theta := \theta_0$, END
if $y_0 > f_0 + \varepsilon$ $\theta = \theta_0 - 0.01$
if $y_0 < f_0 + \varepsilon$ $\theta = \theta_0 + 0.01$
5 $x = x_1(k+1) + L\cos(\theta)$
$y = y_1(k+1) + L\sin(\theta)$
6 $f = f(x)$
7 if $|y_0 - f_0| < \varepsilon$ END
else $\theta^* = \dfrac{\theta(y_0 - f_0) - \theta_0(y - f)}{(y_0 - f_0) - (y - f)}$
8 $y_0 \leftarrow y$ $f_0 \leftarrow f$
$\theta_0 \leftarrow \theta$ $\theta \leftarrow \theta^*$
9 goto **5**

If $\theta_1(k+1)$ coincides with θ found by the above procedure, the fore edge of the first car will be just on the nominal trajectory at step $(k+1)$. Therefore the control $u(k)$ is determined by the following equation

$$u(k) = \theta - \theta_1(k) - u(k-d) - u(k-2d) - u(k-3d) - u(k-4d) \tag{13}$$

The control value may be calculated previously, thus these data is stored in the memory of the first car. If the first car find an obstacle, it uses this control data in succession and transmits them to the following cars.

2.4. Simulation results

In the case of our prototype, the length of each car is 20 cm and it runs at a constant speed 10 [cm/s]. The sampling period for control is 100 [ms], thus the delay time (step) should be $d = 20$. It is calculated by the following equation

$$d = \frac{\text{(car length)}}{\text{(speed)} \times \text{(sampling period)}} \tag{14}$$

Figure 5 shows the control signal for the first car when it finds an obstacle. This control signal is transmitted to the next car with 2 s delay, to the third car with 4 s delay and so on. The relative joint angle between the first car and the second car is shown in Fig. 6. The angles between other cars are also of the same form but different time delay. Figure 7(a and b) shows the position of each car. The number (i) means the tail position of the i-th car. The number (0) means the fore position of the first car. Figure 7(a) shows the distance along the feeder cable. We know that the robot runs with the same speed (about 10 [cm/s]) even when it avoids the obstacle. Figure 7(b) shows the displacement from the feeder cable. The robot splits into both sides, thus the width of the robot will be double this value. Figure 8 shows the total transition when the robot passes over an obstacle.

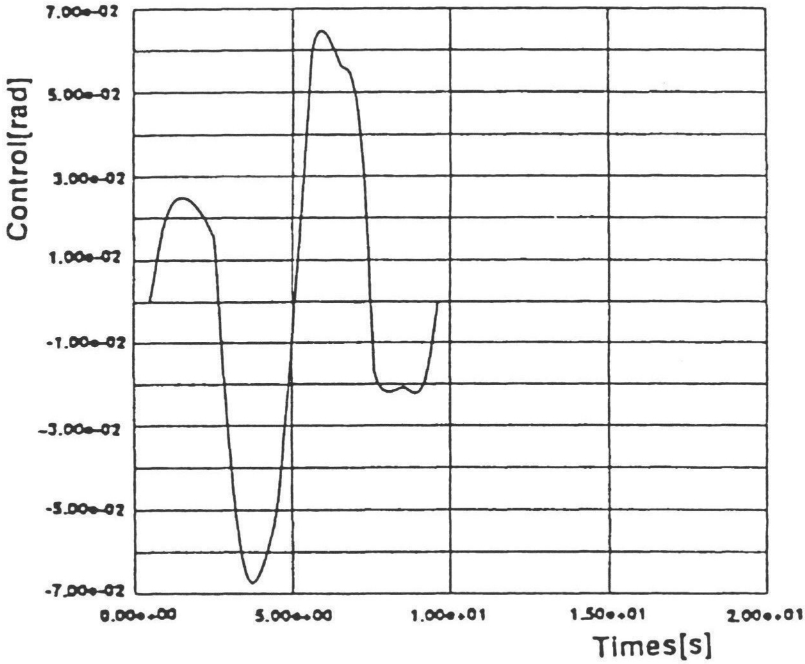

Figure 5. Control signal.

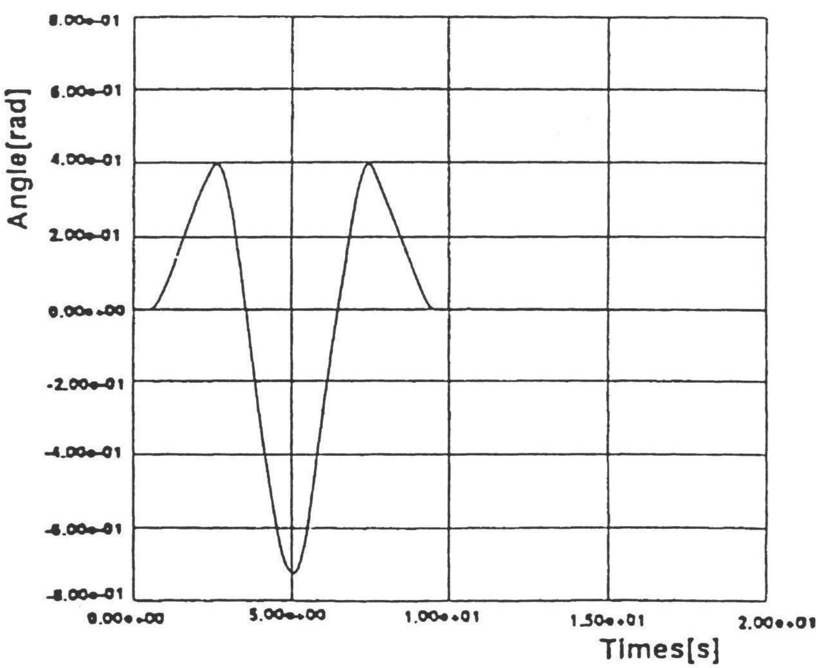

Figure 6. Relative joint angle 1–2.

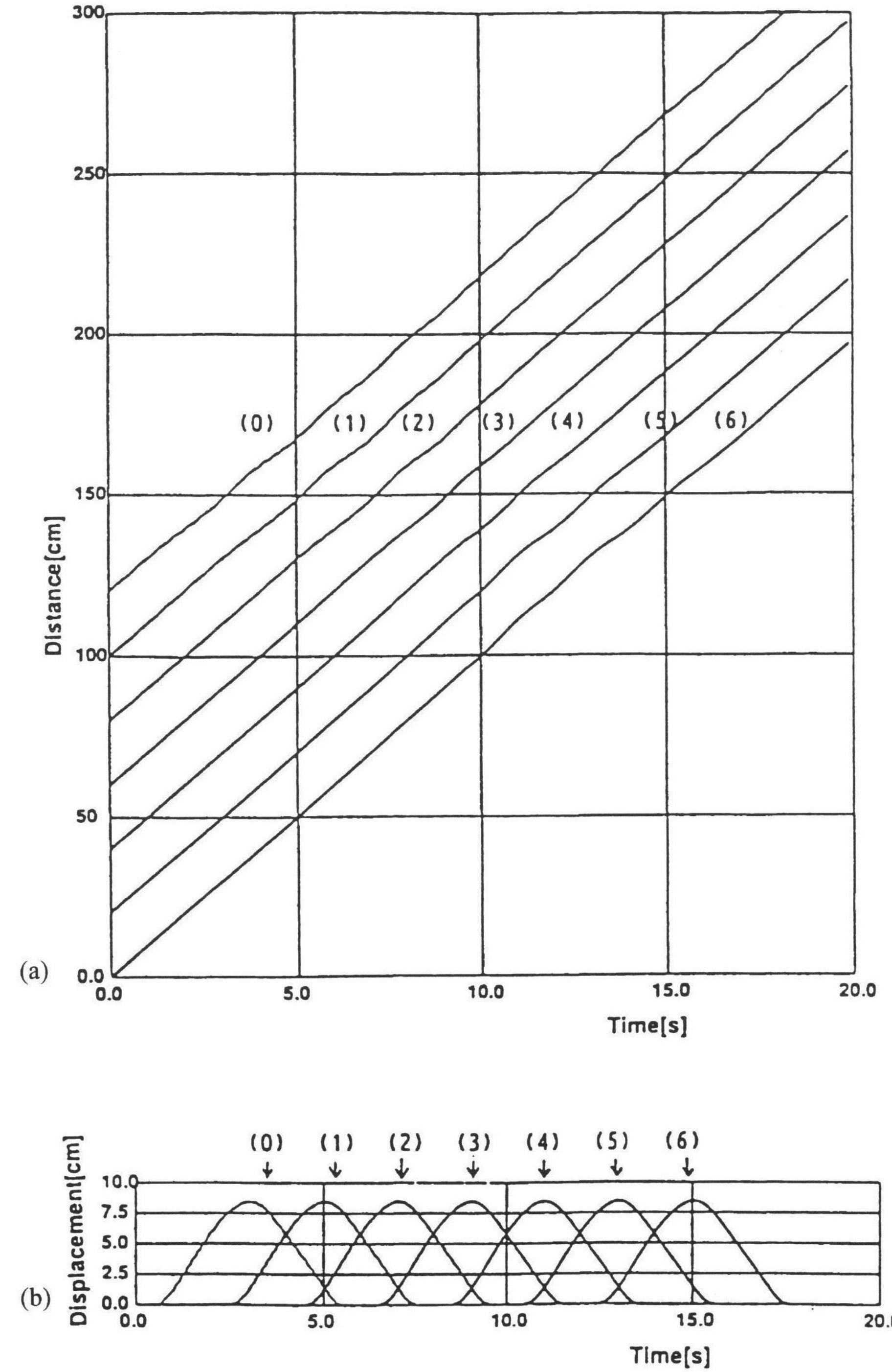

Figure 7. Distance along cable; displacement from cable.

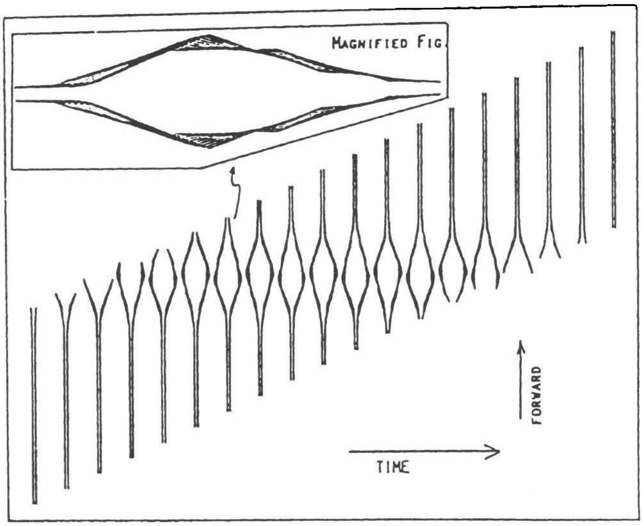

Figure 8. Transition of obstacle avoidance.

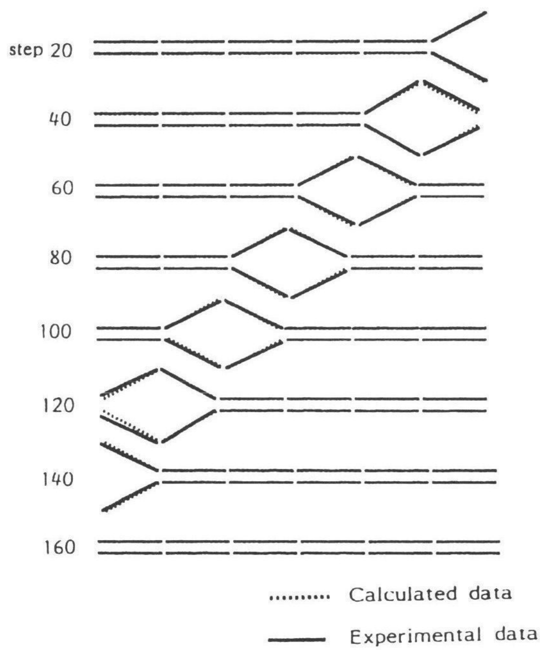

Figure 9. Experimental results.

2.5. Experimental result

We have applied the above stated control law to the prototype as shown in Fig. 1. The experiment was done fairly well as shown in Fig. 9. There exists a small error between the calculated data and experimental data. This error may depend on the stepping motors which we have used in place of conventional servo motors. However, the error is negligible and the robot can perform the specified motion as in laboratory experiment. However, through several experiments, we have found the robot has several practical problems to be solved. We summarize these problems in the next section.

2.6. Problems

This type of robot has the following problems to be improved:

(1) The robot is too heavy to hang on conventional cables. The magnetic connections are not able to guarantee its stablity in some case.

(2) Each car of the robot should be flexible to compensate for the errors of motions or to run on the curved cables.

(3) The robot should have actuators for vertical movements in order to compensate for the gravity effects.

Since these problems depend on the fundamental structure of the robot, the improvements may be theoretically possible but practically impossible. With this in mind, we propose a completeus different structure for robots in the next section.

3. SPIRAL MOBILE ROBOT

We propose two types of spiral robots which can run on a cylindrical surface. Since the robot main frame has a spiral architecture, it can avoid obstacles on the cylindrical surface by rotating its body as shown in Fig. 10. The spiral structure also means that the robot is always touching around the cylindrical surface even if every system becomes out of order. This means the system has no necessity to consider final satefy problems. Moreover, if we make the robot with a flexible body, the robot can move even on curved pipelines or curved cables without any artificial devices. Thus, the spiral robot has the required three properties stated in the introductory section and it can overcome the problems that arose in the development of the previous robot.

To avoid an obstacle at any position, the obstacle should be just between the pitches of the spiral frame. We can overcome this problem by the following two approaches.

(1) Move the robot in two directions: movement in a spiral direction and linear movement along the cable. By combining these two motions, the robot adjusts its position to contain the obstacle just between the pitches of the spiral frame.

(2) Make the robot flexible and slippery, and move the robot only in a spiral direction. If the robot meets an obstacle, the obstacle slips between the pitches of the spiral frame. Since the robot can also change its own pitch, it can always contain obstacles between the pitches of the spiral frame without any artificial movements.

We adopt the first approach for prototype A and the second approach for prototype B.

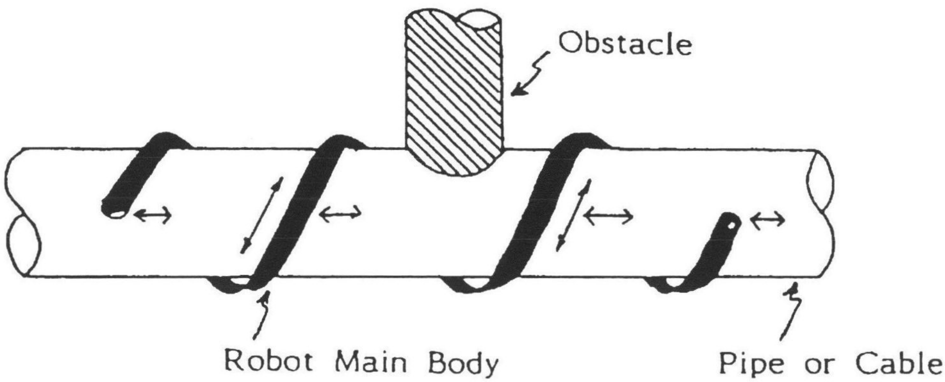

Figure 10. Concept of obstacle avoidance.

3.1. Prototype A

The starting problem for this approach is the method how to move the robot in a spiral direction and along the cable axis direction. A robot with spiral movement is not a new idea, e.g. Dr Masahiro Mori made such a prototype named 'Neji-Geji' which had been demonstrated in the Communications Museum at Tokyo.

The developed prototype has a spiral main frame with small wheels facing the cylindrical surface. The wheels are supplied to support the main frame against the cylindrical surface and to drive the frame forward or backward by spiral rotation or linear movement. The prototype is made under the condition that the pipeline's diameter is 10 cm. In order to keep its position and not to fall from the pipeline, the robot should wind its body at least three times around the pipe. Thus, we make the body by using 10 same size parts; these parts are connected in series. Each part, except the first and last, has only a rubber wheel. These rubber wheels should exactly face the cylindrical surface, in order to keep the body at the appropriate position and to move smoothly. The steering angle of each rubber wheel is not fixed — its direction can change freely. By attaching spring coils to the each connection joint, each car has some flexibility and produces a force to keep winding around the pipeline.

The driving motors of this robot are attached at the first part and the last part. Since this robot is made from light materials such as aluminum plate and small rubber wheels, the motor torque is enough at 1 kg-cm. We adopt a high speed small motor with a gear ratio of 65. The steering direction of these driving wheels is controlled by another small size motor. Naturally theses two driving wheels are controlled to be in the same direction. The fundamental rule of the robot's motion is as follows.

(1) In a normal situation without any obstacles, the driving wheels are steered in the direction along the cable. Thus the robot runs linearly along the cable.

(2) If the robot meets an obstacle, the robot moves backward a little.

(3) The robot changes the mode to the spiral movement and it goes forward by spiral rotation.

(4) If the robot cannot pass over the obstacle, it repeats the above two steps by changing the backward distance until it succeeds in avoiding the obstacle.

(5) After passing over the obstacle, it returns to the linear the mode by steering the direction of the driving wheels.

As the first step of development, we have made a simple prototype. With this prototype, we have been able to verify the fundamental motion of this robot. However, this simple prototype has no sensor or controller with it — a practical robot may have several problems for sensors and controllers on it.

3.2. Prototype B

Next, we shows another robot designed by a novel idea, which has a new mechanism consisting of a spiral tube and a rudder chain and small wheels. The main body of the robot is a spiral vinyl chloride tube of 1 cm diameter, which is coiled loosely with a constant pitch of 20 cm along the cylindrical surface. The robot has small wheels at a constant interval of 120° around the cylindrical surface. These wheels are not connected to the driving shaft of any actuators. These play only the roles of supporting the main frame at the appropriate position against the cylindrical surface. The rudder chain makes a closed loop which winds around the cylindrical surface several times and passes through the inside the tube. This rudder chain is driven by motors attached at the both ends of the tube and the motors also give a tension to the chain to keep it taut. By the winding motion of the motors, the chain runs on a closed trajectory through the tube and around the cylindrical surface. However, on the cylindrical surface, the chain cannot move due to the frictional force while the rudder chain can slip smoothly inside the tube. This phenomena causes a relative motion of moving the robot's main body in a continuous spiral rotation. Therefore, the robot goes forward along the axis direction of the pipe, on the same principle of 'the rule of the right screw'. Figure 11 shows the outline of this robot. This robot has flexible body, thus if it has a slipping head at the top of the body, it can avoid obstacles naturally. This inborn property is very robust and reliable against unknown natural circumstances. We have made a simple prototype of this mechanism and we have verified the ability of this mechanism.

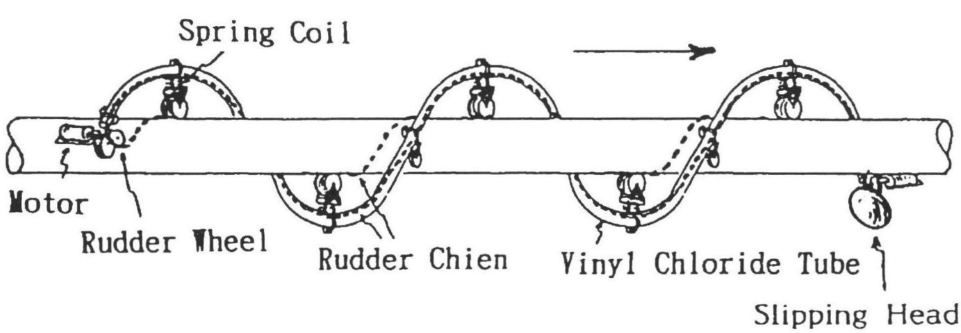

Figure 11. Outline of robot.

5. CONCLUSION

In this paper, we have reported outlines of the development process for new robots which can run on cylindrical surfaces. We have ensured the basic functions of these robots by elemental experiments. However, there are many engineering problems to be solved to make such robots practical, because the actual situation is not so simple. We think the last one, i.e. the spiral robot with rudder chain actuation, may be realizable for practical use for the following reasons.

(1) It can be applied even to thin cables, because the chain wrapped around the cable causes enough friction to move the robot body forward or backward.

(2) The robot has a simple structure and thus it is relatively easy to make it in a small size with light weight.

(3) This robot has a flexible body—it can avoid obstacles naturally by slipping out of the obstacle. This inborn property is very robust and reliable against unknown natural circumstances when compared with an artificial mechanism.

(4) The robot has a closed frame structure consisting of a spiral tube and rudder chain — it can never be released from the cables at any accident.

Future work will be to improve this mechanism into a practical form. We should mount sensors, data recorders, communication devices, controllers and energy source such as a solar battery on the practical robot for autonomous movement. However, this simple mechanism will release us from complicated motion control problems.

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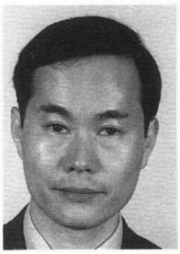

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