Automated Pipeline Inspection Robot in Construction

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Abstract

This paper deals with a new type of automated inspection robots with the inch worm mechanism in particular, for inspecting pipelines from the outside of pipe surfaces of constructions during and after construction. Since pipelines are necessary for life lines, these are laid out in many constructions. Therefore, the inspection of pipeline is important for securing the good quality of construction. Newly developed robot, Mark III, can move vertically along the pipeline and move to the adjacent pipeline for the inspection. The sensors, infra ray proximity sensor and ultra sonic sensors and others, are installed to detect these obstacles and can move autonomously controlled by the microprocessor. The control method of this robot can be carried out by the dual control mode proposed in this paper. Furthermore, the path planning method for the inspection robot is also shown based on the PPES (Path Planning Expert System) employing the plant map and the priority information for inspection.

1. Introduction

Robotic technology has greatly been advanced for the production system and recognized as one of the useful technologies. Since then, this technology has been applied for not only the factory automation but also other sectors, such as inspection and maintenance works in a hostile environment, space works, services and others. This paper deals with one application of the technology to the inspection and maintenance field, particularly pipeline facilities.

Since pipelines are necessary for life lines, especially, for energy and other independable resources transportation, these are laid out in many constructions. Therefore, the inspection of pipeline is important for securing the good quality of construction. These maintenance operations under hostile environments have been done by human operators so far, but they are very dangerous and laborious to work for human operators and workers under these circumstances, such as a complicated area with pipelines or many machines, a higher locations, etc. Therefore, the remote inspection methods have been investigated and carried out/1,2,3/, but sometimes there happened some accuracy problems by these method. Thus, the direct inspection method is still desired and so our purpose of this study is to design and make a robot with which human workers can be replaced and furthermore, to increase the precision and the efficiency of the inspection procedures by the cooperation with such an intelligent robot.

There are two methods to inspect the pipelines by robots: one method is to inspect them from inside of a pipe/7/, while another is from outside/4,5,6/. There have been several works on the inspection from inside of the pipeline/7/, because the former is rather simpler than the latter. But there are few robots which can move and inspect along the outside of a pipe and avoid obstacles such as the flanges and the valves. Therefore, it is important to make robots which inspect them from outside. This kind of autonomous maintenance robots, moving along the pipe and inspect it from outside, need to have multifunctions: to detect the obstacles or T-joint, to understand what it is, to pass it , to inspect the pipelines, and to make planning by itself when accidents happen. Toward this direction, the intensive research works have been carried out for several years to make such an intelligent robot equipped with these multifunctions, and so far two types robots, Mark I and II with the wheel mechanism have been built and tested/4,5,6/. The first prototype robot, Mark I, can inspect a horizontal pipe (diameter=90mm) and pass a flange when it is detected/4,6/. The second prototype robot, Mark II, has more functions; to move with the spiral locus along pipelines and to pass T-joints to any desired direction.

This paper deals with a new type robot, Mark III, with an inch worm moving mechanism. This robot has abilities which the previous prototypes had and, in addition to these functions, can move vertically along the pipeline and move to the adjacent pipeline for the inspection. The robot's basic structure, the movement, the Dual Mode Control as one method of the joint control and the the way to detect the obstacles are shown. Furthermore, the path planning method for the inspection robot is also shown based on the PPES (Path Planning Expert System) employing the plant map and the priority information for inspection.

2. Conditions of Design for the Robot

In designing a new type of the maintenance robot, the following conditions and requirements must be met:

1. It is an intelligent robot with the function to recognize the circumstance and make moving plan.
2. It can pass obstacles such as flanges or supports of a pipe.
3. It can pass a branch on the pipelines such as a L-joint or a T-joint and go to any desired direction.
4. It can move along the vertical pipelines, similar in the horizontal ones.
5. It can move to an adjacently located pipeline.
6. It has the function to detect or inspect the abnormal point of pipelines, such as defects, cracks, corrosion, fatigue, and others.
7. It moves along the pipeline with a diameter of 90 mm.
8. It has two pairs of holding gripper and a supporting body with a slide joint, moving along pipes like an inch worm.
9. It has detectors for the inspection in two directions independently: longitudinal and circumferential directions.

3. Structure of Mark III

The prototype of the maintenance robot, Mark III, is designed and made for the research and the test, taking those conditions and requirements stated in chapter 2 consideration. Its appearance is shown in Fig. 1, and the structural and system properties are shown in Table 1. The basic schematic structure of Mark III is shown in Fig. 2. It consists of a supporting body, two pairs of the holding arm unit with a gripper mechanism and the sensor unit.

3.1 Structure of the Holding Arms

In this paper,"Arm" means a gripper designed to fit a 90 mm diameter pipe. There are a hook and a tensioner at the end of each arm. When the arm is closed, it hooks itself and the tensioner tense the hook by wire and motor mechanism. Then the robot can hold itself on the pipe, owing to the friction force between the pipe and the rubber inside the arms. It needs less force when it uses hook and tensioner system.

3.2 Structure of the Supporting Body

The robot has two sliding joints. One is for forward or backward movements, and the other is for moving in the circumferential direction, called the "Side Slider" in this paper hereafter shown in Fig. 2. The supporting body and the two holding arm units are connected each other by the rotary joints, which can rotate 180 degrees.

3.3 Structure of the Sensor Unit

The sensor unit consists of a sensing unit and its circular guiderail. The sensing unit consists of a motor as an actuator, detectors of the pipes and obstacle detector sensors.

This robot has nine actuators, all of which are pulse motors. It has four degrees of freedom with five links, except for one degree of the freedom of the sensor unit mobility and two degrees of the freedom of the holding grippers.

4. System Configuration

The system configuration of Mark III is shown in Fig. 3. It has the ultrasonic sensors and the infra ray sensors for obstacle sensing such as flanges, T-joints and so on. It also has an eddy current sensor for the pipeline inspection. These sensing results are transferred to the microcomputer which controls joint motors by pulse motor controllers.

5. Movement of Mark III

5.1 Straight Driving Mode

This robot consists of the supporting body and two holding arms as shown in Fig. 2, and moves like an inch worm, shown in Fig. 4. Though the speed of slider is 3.86 mm/s, the average velocity on forward driving is 0.22 mm/s at the present stage because it takes some time to open or close the holding arms and to give the predetermined tension of the hook by wire. But this is not a crucial problem for this robot and can be improved by the better actuators.

5.2 Flange Passing Mode

When the robot is in front of a flange and the sensing unit detects it, the robot can pass it by the mode shown in Fig. 5. The rear arm opens at first, the front rotary joint rotates 180 degrees and the rear arm closes (Fig. 5 No. 6). Then another arm opens and the rear rotary joint rotates 180 degrees again so it can pass the flange. Some experiments have been carried out for this mode successfully.

5.3 T-joint Passing Mode

Fig. 6 shows the mode when Mark III passes T-joint or L-joint. At first, the robot must be located the same position with a T-joint pipe, by the side slider(Fig. 6, No. 1). The front arm grasps the pipe as the base of this robot, the both rotary joints are controlled and the rear arm grasps the T-joint pipe, then the passing mode can be completed.

6. Motion Control with Transfer Matrix

6.1 Jacobian Matrix

This robot has five links and four degrees of freedom, and change its configuration suitably to the environment. Therefore, it is necessary to control joints as to suit its task or the environment. In this chapter, the control method is presented with the transfer matrix and the jacobian matrix methods. For the control purpose, Mark III may be considered as one kind of Manipulators during the application of this method.

This robot moves along the pipe by changing grasping points of the both holding arms sequentially and cooperatively, so that the sequential order of joints and the transfer matrix are different depending on which coordinate system of the Arm(A) and the Arm(B) is applied for the current robot motion control.

Then the Dual Mode Control is defined as follows: Control mode A is applied when Arm(B) grasps the pipe and Arm(A) is controlled to grasp another point. Control mode B is for the control of Arm(B). Control mode changes mutually like A, B, A, B, and so on sequentially when the robot moves like an inch worm. The coordinates on links and Jacobian matrix of both control mode are shown in Figs. 7 and 8 and by Eqs. (1)-(4).

$$\begin{bmatrix} dx \\ dy \\ dz \\ \delta x \\ \delta y \\ \delta z \end{bmatrix} = J_A \begin{bmatrix} dd_0 \\ d\theta_1 \\ d\theta_5 \\ d\theta_4 \\ dd_3 \\ d\theta_2 \end{bmatrix} \tag{1}$$

$$J_A = \begin{bmatrix} -C_2C_4S_5+S_2C_5 & a\{S_2S_5+C_2(1-C_5)\}S_4+C_2(d_3+d_4)S_4S_5 & aS_2(C_4-1)+C_2(d_3+d_4)C_4 & 0 & -S_2 & 0 \\ S_4S_5 & a\{(1-C_2)C_5+C_4(1-C_5)\}+(aS_2+d_3+d_4)C_4S_5 & -(aS_2+d_3+d_4)S_4 & a(1-C_2) & 0 & 0 \\ -S_2C_4S_5+C_2C_5 & a\{(1-C_2)S_5+S_2(1-C_5)\}S_4+S_2(d_3+d_4)S_4S_5 & a\{(1-C_2)C_4+C_2\}+S_2(d_3+d_4)C_4 & 0 & C_2 & a \\ 0 & -C_2C_4S_5-S_2C_5 & C_2S_4 & -S_2 & 0 & 0 \\ 0 & S_4S_5 & C_4 & 0 & 0 & 1 \\ 0 & -S_2C_4S_5+C_2C_5 & S_2S_4 & C_2 & 0 & 0 \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} dx \\ dy \\ dz \\ \delta x \\ \delta y \\ \delta z \end{bmatrix} = J_B \begin{bmatrix} dd_0 \\ d\theta_1 \\ d\theta_2 \\ dd_3 \\ d\theta_4 \\ d\theta_5 \end{bmatrix} \tag{3}$$

$$
J_B=\begin{bmatrix}
-S_2C_4C_5-C_2S_5 & -a\{S_2S_5+(1-C_2)C_5\}+S_2(d_3+d_4)S_4C_5 & -a(1-C_4)S_5-(d_3+d_4)C_4C_5 & S_5 & 0 & 0 \\
-S_2S_4 & a\{C_2(1-C_4-C_5)+(S_2S_5+1)C_4\}-S_2(d_3+d_4)C_4 & -S_4(d_3+d_4-aS_5) & 0 & -a(1-C_5) & 0 \\
-S_2C_4S_5+C_2C_5 & -a\{S_2(1-C_5)+(1-C_2)S_5\}+S_2(d_3+d_4)S_4S_5 & -a\{C_4(1-C_5)-1\}C_5-(d_3+d_4-aS_5)C_4S_5 & -C_5 & 0 & a \\
0 & -S_2C_4C_5-C_2S_5 & -S_4C_5 & 0 & S_5 & 0 \\
0 & -S_2S_4 & C_4 & 0 & 0 & 1 \\
0 & -S_2C_4S_5+C_2C_5 & -S_4S_5 & 0 & -C_5 & 0
\end{bmatrix} \tag{4}
$$

where

$$
\begin{aligned}
C_i&=\cos(\theta_i)\\
S_i&=\sin(\theta_i)
\end{aligned} \tag{5}
$$

Joint d0 and theta-1 are used to indicate the virtual position and attitude of the robot, though they do not exist.

The position and attitude at the end of the robot can be calculated by the transformation matrix, so that the slight change of its position and attitude can be obtained by calculating the Jacobian matrix.

6.2 Jacobian Matrix in Transition to Another Pipe

This robot can pass flanges and T-joints, furthermore it has another functions: Transition to an adjacent pipe, shown in Fig. 9. This passing mode is useful when it inspects many parallel pipes or transfer the other pipeline system. The Jacobian matrix in transition to another pipe is two dimensional problem when the robot is located between two pipes. Then eqs. (2) and (4) are simplified as Eqs. (6) and (7).

In the case of control mode A:

$$
\begin{bmatrix} dx \\ dz \\ \delta y \end{bmatrix}=\begin{bmatrix} C_2(d_3+d_4) & -S_2 & 0 \\ a+S_2(d_3+d_4) & C_2 & a \\ 1 & 0 & 1 \end{bmatrix}\begin{bmatrix} d\theta_5 \\ dd_3 \\ d\theta_2 \end{bmatrix} \tag{6}
$$

In the case of control mode B:

$$
\begin{bmatrix} dx \\ dz \\ \delta y \end{bmatrix}=\begin{bmatrix} -(d_3+d_4)C_5 & S_5 & 0 \\ a-(d_3+d_4)S_5 & -C_5 & a \\ 1 & 0 & 1 \end{bmatrix}\begin{bmatrix} d\theta_2 \\ dd_3 \\ d\theta_5 \end{bmatrix} \tag{7}
$$

Consider the situation that the distance between the robot and the pipe is 300 mm and transfer that pipe. In calculating jacobian, from Eqs. (6) and (7), the locus of the end of each arm can be drawn, shown in Figs. 10 and 11. On the other hand, the slight change of the robot position and attitude can be calculated from Inverse jacobian matrix, Eqs. (8) and (9).

In the case of control mode A:

$$\begin{bmatrix} d\theta_5 \\ dd_3 \\ d\theta_2 \end{bmatrix} = \begin{bmatrix} C_2/D & S_2/D & aS_2/D \\ -S_2 & C_2 & -aC_2 \\ -C_2/D & -S_2/D & 1+aS_2/D \end{bmatrix} \begin{bmatrix} dx \\ dz \\ \delta y \end{bmatrix} \tag{8}$$

In the case of control mode B:

$$\begin{bmatrix} d\theta_2 \\ dd_3 \\ d\theta_5 \end{bmatrix} = \begin{bmatrix} -C_5/D & -S_5/D & aS_5/D \\ S_5 & C_5 & aC_5 \\ C_5/D & S_5/D & 1-aS_5/D \end{bmatrix} \begin{bmatrix} dx \\ dz \\ \delta y \end{bmatrix} \tag{9}$$

where

$$D = d_3 + d_4 \tag{10}$$

7. Sensors for Obstacle Avoidance

These kinds of mobile robots need sensors to detect obstacles. The prototypes I and II are equipped with infra ray sensors as obstacle sensors, but it is difficult to detect objects more than 10 mm distance. Therefore, Mark III is equipped with both ultrasonic sensors and infra ray sensors, and composed the complex multiple sensor system, shown in Fig.12. Some experiments have been carried out for detecting flange, T-joint, support of a pipe and an adjacent pipe with this system. Fig. 13 show experimental results.

The experimental method is such that the robot moves the sensor unit to the circular direction and sensors detect forward 72 times in one loop. The distance between the object and the sensor can be measured by the ultrasonic sensor, the object's existence can also be measured by infra ray sensor, and then those two sensors outputs are processed by the OR logic in microcomputer. Thus, the relative relationship of the position between the robot and objects can be recognized.

Some experiments were carried out to detect the distance between sensors and the object at 70mm (a) and 30mm (b). When the robot locates near the flange, both of sensors detect object in (b), while, in longer distance only the ultrasonic sensor can detect it in (a), in very close distance, it can be detected by only the infra ray sensors . A T-joint in the distance of 70 mm was also detected. The response of the ultrasonic sensor is found to be sensitive in the search local area, so it can be said that it is a horizontal T-joint, but not a flange. Fig. 13 shows a result for the support of pipe.

The adjacently located pipe can also be sensed by these sensor systems. Sensors are faced to the normal direction of the pipe. It can be recognized that there is some object in the either side of the robot and furthermore that it is another pipe by matching this result with the plant map.

In this way, it is possible to detect obstacles in the large area with this combined multiple sensor system.

8. Path Planning Method

The path planning is very important for the pipe maintenance robot, because there are many obstacles on pipeline such as franges, T-joints and others, and because pipelines are constructed as a connected network in a very complicated way. A configuration of this system especially aimed for path planning, named PPES (Path Planning Expert System), is shown in Fig. 14. This system consists of a plant map editor for path planning, its graphic indicator and working part of path planning. Furthermore, this system has informations such as pipeline system, robot system, a kind of works and others as database.

A human-operator has only to give some tasks to this system. This system automatically replies the optimal path, which is based on the calculation of the task levels, and the list of some control commands. Task level is a criterion to determine one optimal path. It consists of the difference of potential energies, the static joint torques, velocity of the robot, step numbers of the grippers' or body's moving, which the robot requires in moving. This system also has the graphic illustrations, so that the operator can check and understand easily the plant map and the result of path planning. An example of simple pipelines is shown in Fig. 15 and a modelled plant map is shown in Fig. 16. When the start point and the goal point are given in Fig. 16, the result of path planning is shown in Fig. 17.

9. Conclusions

The basic structure and motion of the new type of pipeline maintenance robot, Mark III, was presented in this paper. The dual mode control is proposed here as one method of the robot control and the locus of robot arm was calculated for the demonstration by the jacobian matrix, as an example.

The combined complex sensor system for obstacle sensing with ultrasonic sensors and infra ray sensors was made and it was found that it can successfully detect various obstacles on pipelines. Although this robot is not completed as an autonomous maintenance robot without arms for repair works, it gives one of the mobile robot mechanisms, structures and control methods.

References

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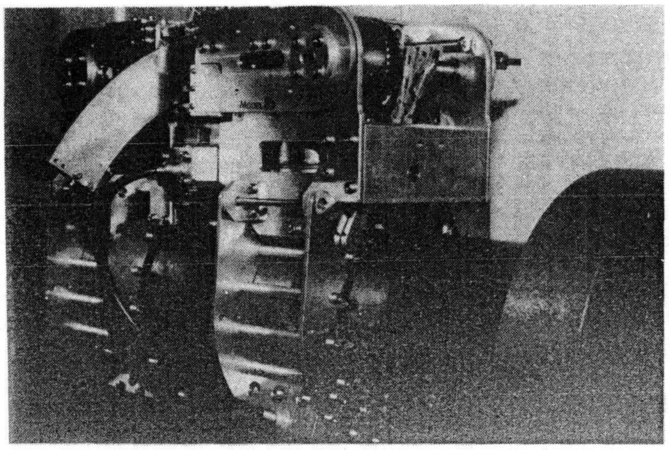

Fig. 1 Appearance of Mark III

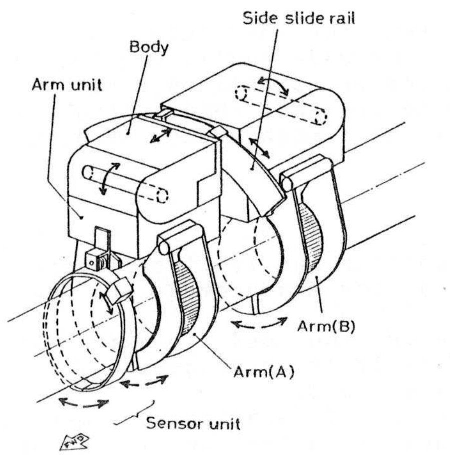

Fig. 2 Basic structure of Mark III

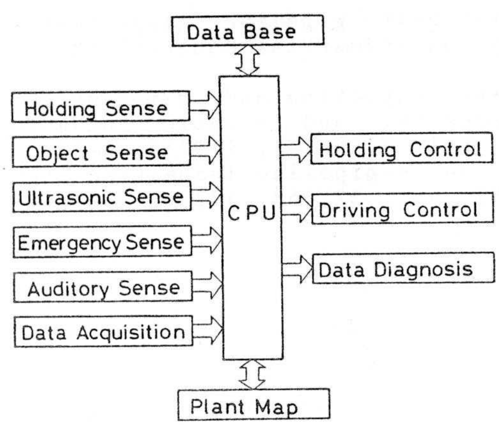

Fig. 3 System configuration

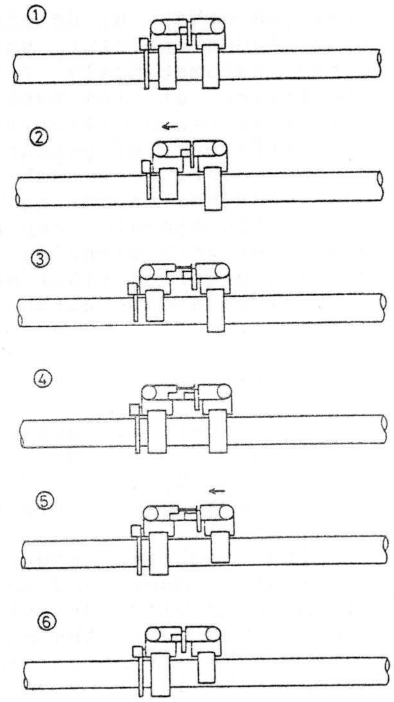

Fig. 4 Straight driving mode

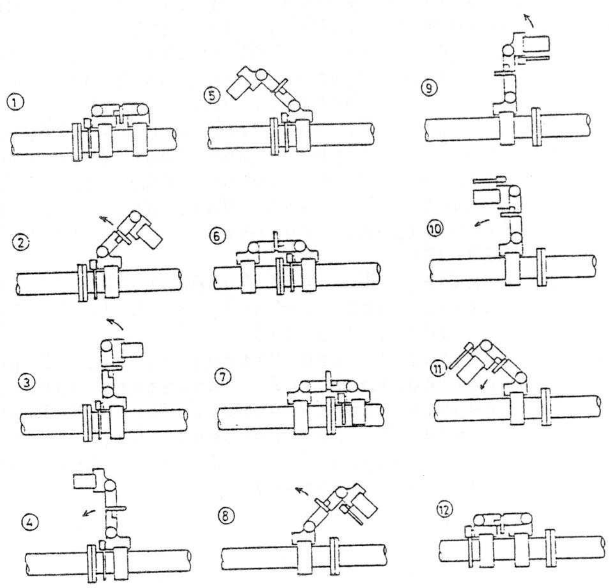

Fig. 5 Flange passing mode

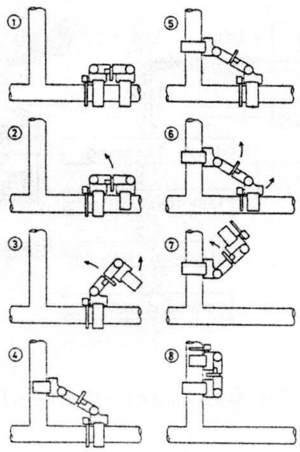

Fig. 6 T-joint passing mode

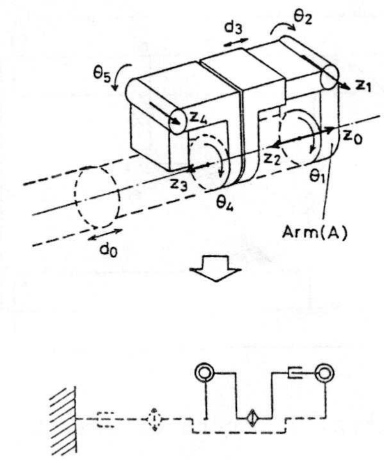

Fig. 8 Coordinates on links of control mode B

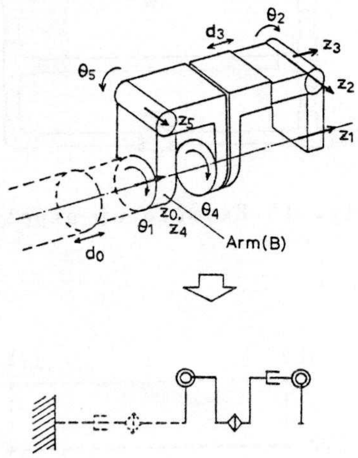

Fig. 7 Coordinates on links of control mode A

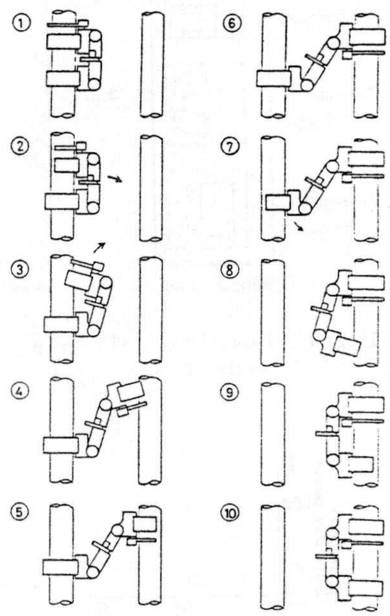

Fig. 9 Transition mode to an adjacent pipe

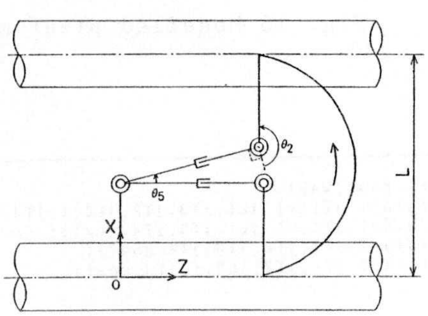

Fig. 10 Locus of arm (A)

Table 1 System properties

Height (max)	232 mm
Width	258 mm
Length	310 mm
Weight	5.0 kg
Holding torque	8.02 Nm
Velocity (average)	0.3 mm/s

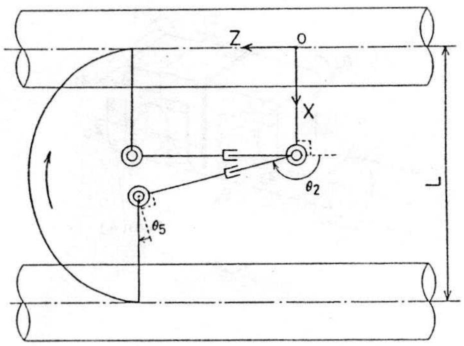

Fig. 11 Locus of arm (B)

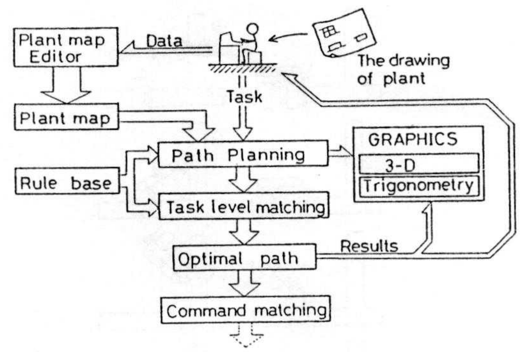

Fig. 14 Configuration of PPES

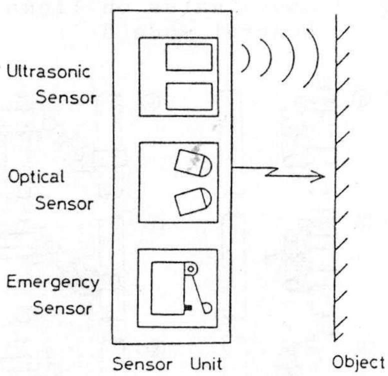

Fig. 12 Complex multiple sensor system

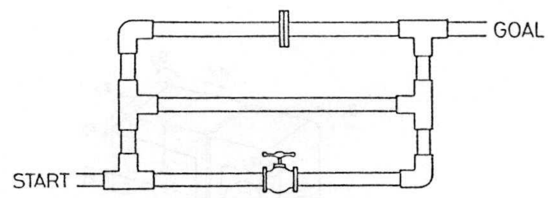

Fig. 15 Example of pipelines

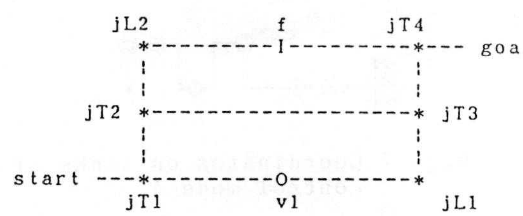

Fig. 16 Modelled plant map

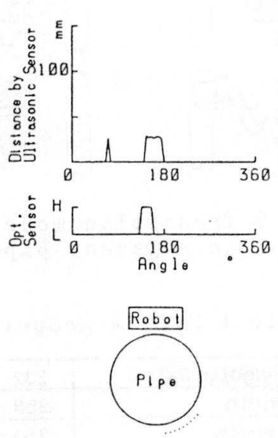

Fig. 13 Sensing result for a pipe support

```
| ?-go(start,goal,Way).
Way    = [start,jT1,v1,jL1,jT3,jT2,jL2,f,jT4,goal];
Way    = [start,jT1,v1,jL1,jT3,jT4,goal];
Way    = [start,jT1,jT2,jT3,jT4,goal];
Way    = [start,jT1,jT2,jL2,f,jT4,goal];
no
| ?-
```

Fig. 17 Result of path planning