A Control Method of the Maneuverability of an Autonomous Pipeline Diagnostic Robot*

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A newly designed diagnostic robot, Mark II, basically consisting of three modules with a joint between modules has capabilities of straight and spiral movement along the outside of pipelines, and of freely passing over obstacles such as flanges, *T*-joints and other plant equipment by sensing and recognizing obstacles in front of it; and of controlling its attitude automatically. By calculating the position and orientation of the robot using a transformation matrix, a method of motion control in the passing of *T*-joints is shown. A method of compensating for the torque generated by gravitational forces is also applied for each module, independently, to keep the holding torque constant, which leads to less vibrations in movement and, hence, yields better diagnostic results. The Mark II equipped with diagnosis sensors can identify the location and depth of flaws on the surface by inspecting pipelines in the spiral-moving mode. The Mark II also has intelligent abilities, such as routing the most efficient path for inspection in plants, provided a plant map has been previously furnished.

Key Words: Application of Control, Transformation Matrix, *T*-Joint Passing, Intelligent Robot, Pipeline Inspection and Diagnosis, Flaw Detection, Plant Map.

1. Introduction

Flaw detection on the surface of pipelines and the subsequent repair are important for the prevention of accidents in petroleum and gas plants, chemical plants and the like. Under a hostile environment, an inspection of pipelines by an operator is difficult. Consequently, this automatic inspection is expected to improve the quality of inspection results.

The Mark I autonomous pipeline diagnostic robot has the capabilities of straight movement along the outsides of pipelines without a guardrail, of freely passing over flanges, and of proposing diagnostic systems to detect flaws on pipelines⁽¹⁾. However, it lacks the ability to automatically avoid *T*-joints and to detect flaws on pipelines. Few reports, in fact, have dealt with such a robot which can automatically avoid *T*-joints and detect pipeline flaws⁽²⁾. A newly designed, articulated mobile robot of variable-atti-

tude type, Mark II, basically consisting of three modules, with a joint between modules has capabilities of straight and spiral movement along the outside of pipelines, and free passage of obstacles, such as flanges, *T*-joints and other plant equipments. The robot senses and recognizes *T*-joints using the infrared proximity sensors installed in front of it and by calculating the positions and attitudes of each module of the robot using a transformation matrix⁽³⁾, a method of controlling maneuverability in the passage of *T*-joints is shown. To inspect a voluntary position on the pipelines, a method of compensating for the torque generated by gravitational forces for each module, independently, is proposed.

Based on the results of the inspection on a modelled pipeline including a *T*-joint and a flange, it has been clarified that the Mark II installed with the non-contact gap sensor as the diagnostic sensor can detect not only the position of flaws, but also the depth of flaws, leading to less vibrations in movement and yielding better diagnostic results. The Mark II also has intelligent abilities, such as routing the most efficient path for inspection plants, using an adjacency matrix⁽⁴⁾ obtained from a provided plant map.

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2. Specifications of the Design of the Mark II

(a) The robot, Mark II, consists of three modules, each equipped with three wheels capable of independent movement.

(b) A modelled steel pipeline including a flange and a T -joint is inspected, and its diameter is 90 mm. The flange diameter, 180 mm, is defined by Japan Industrial Standards.

(c) A microcomputer for maneuverability control and diagnosis can be loaded on the Mark II.

(d) The Mark II has a joint between modules to facilitate forward or backward movement at a constant speed, stopping, moving spirally along the outside of pipelines, and passing over obstacles freely, such as flanges, T -joints and others. The Mark II also has the capability of the control of these maneuverabilities and a diagnosis using diagnostic sensors such as a gap sensor of the non-contact type or an ultrasonic sensor.

(e) The Mark II is an intelligent movable robot with abilities such as routing the most efficient path for inspection in plants, provided that a plant map is previously furnished.

A photograph of the Mark II satisfying the above specifications is shown in Fig. 1. The system properties of the Mark II are shown in Table 1.

Table 1 System properties of Mark II

Height	355	mm
Width	350	mm
Length	670	mm
Mass	13.8	Kg
Holding Torque	630	N cm
Velocity (Max)	3.2	mm/s

Fig. 1 Photograph of Mark II

3. System Configuration

The system configuration of the Mark II is shown in Fig. 2.

3.1 Attitude-holding control of the robot

In the case of letting the robot move along a pipeline and holding the attitude after passing over flanges, the Mark I was required a holding torque control. The Mark II, on the other hand, can move spirally on pipelines by compensating for the torque generated by gravitational forces through the inclination angle of the robot.

3.2 Detection of obstacles on pipelines

The Mark II recognizes obstacles on pipelines, such as flanges and T -joints, using detection sensors, such as infrared proximity sensors, and avoids obstacles based on the avoidance control routine. In the case of failure of the infrared proximity sensors, damage of the robot by collision with pipeline obstacles such as flanges can be prevented by using the an additional mechanical tactile sensor.

3.3 Collection of diagnostic data

This robot has a exchangeable structure for diagnostic sensors, such as gap sensors, ultrasonic sensors and others, with the capability of diagnosis while moving along pipeline. In this study, the robot collected diagnostic data by an eddy-current-type gap sensor.

3.4 Routing the efficient inspection path for plants

Provided that a plant map has previously been made available an adjacency matrix⁽⁴⁾ of the pipeline connection is made from a graphical point of view, and the pipeline network in a given plant is automatically generated by a tree structure method, so that the inspection path can be built. If an edge must be passed by the robot more than twice, the path is ruled out because of inspection inefficiency. By

Fig. 2 System configuration

repeating these operations, the most efficient path for inspection in plants can be obtained. Supposing the plant map shown in Fig. 3, the subsequent adjacency matrix is shown in Fig. 4. To pass all the given nodes and edges, all the routes which pass all nodes without overlapping are generated, while the routes which pass the same edge more than twice are removed. Consequently, the six most efficient routes are obtained as shown in Table 2.

4. A control Method of Robot Maneuverability

4.1 A method of compensating for the torque generated by gravitational forces in a spiral movement

The Mark II has the capability of spiral movement for inspecting an arbitrary position on a pipeline. However, a control method of compensating for the holding torque according to the inclination angle of the robot is needed. The scheme of a robot with an inclination angle is shown in Fig. 5. The Mark II holds its attitude by pressing the free rolling wheel 2 and the two drive wheels 1 and 3 of each module to the surface of the pipeline. Movement on the pipelines can then be made by controlling the drive wheels. When the Mark II opens the legs of one module, the other two modules must hold the attitude with a holding torque T given by following equation:

$$T = 2[F_A + 2F_B + (M_A + M_B - 2M_X \sin \theta_X - 2M_Y \sin \theta_Y - 2M_Z \sin \theta_Z) \cos \varphi] \mu R \quad (1)$$

where F_A and F_B are forces of the pressed free rolling wheels and drive wheels to the surface of a pipeline, respectively. Also M_A , M_B , M_X , M_Y and M_Z are the

Fig. 3 Example of plant map

	1	2	3	4	5
1	0	1	1	0	1
2	1	0	1	0	0
3	1	1	0	1	0
4	0	0	1	0	1
5	1	0	0	1	0

Fig. 4 Adjacency matrix

respective masses of a holding gearbox, a free rolling wheel, a gearbox for the movement, a motor for the steering angle, and the motor for the movement. Also, θ_X is the angle between a horizontal plane and the line linking the center of the pipeline and the center of gravity of the gearbox for the movement in $\varphi=0$. In the same way, θ_Y and θ_Z are the angles between a horizontal plane and the line linking the center of the pipeline and the center of gravity of the motor for steering, and the center of gravity of the motor for movement in $\varphi=0$, respectively. Also, μ is a coefficient of static friction. R is the radius to the outside of the pipeline.

Using Eq. (1), calculated values of T needed to hold various attitudes are shown in Fig. 6. By changing the inclination angle of the Mark II, the holding

Table 2 Efficient route for inspection

1	1 - 2 - 3 - 1 - 5 - 4 - 3
2	1 - 2 - 3 - 4 - 5 - 1 - 3
3	1 - 3 - 2 - 1 - 5 - 4 - 3
4	1 - 3 - 4 - 5 - 1 - 2 - 3
5	1 - 5 - 4 - 3 - 1 - 2 - 3
6	1 - 5 - 4 - 3 - 2 - 1 - 3

Fig. 5 Scheme of Mark II

Fig. 6 Calculated result of holding torque

torque changes. Hence, a control of holding torque compensation is needed by the robot to keep its attitude and to be able to inspect at a constant speed, moving spirally along the pipeline. An error of holding force $f(\theta)$ is given by the following equation:

$$f(\theta) = f_i^* - f_i(\theta) - f_i \quad (2)$$

where f_i^* is a holding force at $\varphi=0$, $f(\theta)$ is the change of the holding force occurred by the inclination angle of the Mark II, and f_i is a measured value of the holding force for $i=1, 2, 3$. The block diagram of a holding torque control is shown in Fig. 7.

4.2.1 Passing mechanism of T -joints

The Mark II has a joint between modules to pass T -joints, and the joint angle is controlled by a pulse motor. The schema of the Mark II in the passing mode for T -joints is shown in Fig. 8, where the modules are numbered to 1, 2 and 3, starting from the last module. As the Mark II passes T -joints by opening and closing its legs and rotating the joints

Fig. 7 Block diagram

Fig. 8 Scheme of moving mode in passage of T -joint

between modules to reduce the load of pulse motors at the joints, the Mark II rotates 90° to the side of the pipeline. For processing diagnostic data, it was desirable that module 3, installed with a diagnostic sensor, moved along the pipeline at a constant speed. The trajectory of module 2 after module 3 has passed T -joints is given in Fig. 9, where it can be seen that the rotation angles of module 3 and module 2 can be controlled to maintain equal velocities. A photograph of the Mark II in passing a T -joint is shown in Fig. 10.

4.2.2 A control method of maneuverability in the passing of T -joints

In the case of the passing of T -joints by a mobile robot, motion control is required by using articulated structures, such as manipulators. The Mark II has three links and two joints, in the case of the passing of T -joints, a Jacobian matrix can be obtained to determine a differential change of the joint angle of each module, giving a differential change of position and an attitude to module 3. The coordinate system of the robot is shown in Fig. 11, where the length of modules 1, 2 and 3 are l_1 , l_2 and l_3 , respectively, θ_1 is an angle formed by module 1 and module 2; θ_2 is an angle formed by module 2 and module 3; and C_n , S_n , C_{ij} and S_{ij} are defined by $C_n = \cos \theta_n$, $S_n = \sin \theta_n$, $C_{ij} = \cos(\theta_i$

Fig. 9 Trajectory of module 2 in passage of T -joint

Fig. 10 Photograph of Mark II in passage of T -joint

Fig. 11 Coordinate system

$+\theta_j$) and $S_{ij}=\sin(\theta_i+\theta_j)$. The Mark II has a degree of freedom due to its movement by wheels. This mobile freedom can be expressed by the prismatic joint in this formulation. The link parameters of the Mark II are shown in Table 3.

A coordinate transformation matrix between modules, is given by a matrix of Eq. (3). When a T -joint is recognized in the coordinate system $O-xyz$, a coordinate transformation matrix T can be given by Eq. (4), where α is an angle formed by the z -axes between joint 1 and joint 2

$$A_1 = \begin{bmatrix} 1 & 0 & 0 & q_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = T_1$$

$$A_2 = \begin{bmatrix} C_1 & -S_1 & 0 & l_2 C_1 \\ S_1 & C_1 & 0 & l_2 S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = {}^1T_2$$

$$A_3 = \begin{bmatrix} C_2 & -S_2 & 0 & l_3 C_2 \\ S_2 & C_2 & 0 & l_3 S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = {}^2T_3$$

$$(3)$$

$$T_1 = \begin{bmatrix} 1 & 0 & 0 & q_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^1T_3 = {}^1T_2 {}^2T_3 = \begin{bmatrix} C_{12} & -S_{12} & 0 & l_3 C_{12} + l_2 C_1 \\ S_{12} & C_{12} & 0 & l_3 S_{12} + l_2 S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3 = T_1 {}^1T_3$$

$$= \begin{bmatrix} C_{12} & -S_{12} & 0 & l_3 C_{12} + l_2 C_1 + q_1 \\ S_{12} & C_{12} & 0 & l_3 S_{12} + l_2 S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$(4)$$

Table 3 Link parameters

Link	Variable	α	a	d	$\cos \alpha$	$\sin \alpha$
1	q	0	0	q_1	1	0
2	θ_1	0	l_2	0	1	0
3	θ_2	0	l_3	0	1	0

(when the z axes are parallel in the Mark II, α is zero), a is the length of modules (in a prismatic joint of translation, the length a is set as zero), d is a distance between modules (the state of $d=0$ is defined as the zero position for a joint of translation), θ is a joint parameter of a joint of rotation and q is a joint parameter of a joint of translation.

When three parameters of a robot, q , θ_1 and θ_2 , change slightly by $d\theta^T = (dq, d\theta_1, d\theta_2)$, a Jacobian matrix ${}^T J$ accordingly gives the differential relationship of a slight change of the position and attitude of module 3 by $dX^T = (dx, dy, \delta z)$. A small translation vector ${}^T d$ and a rotation vector ${}^T \delta$ in a coordinate system T are given by a small translation vector d and rotation vector δ in the base coordinate system. Considering that d_i is zero in rotation joints, δ_i is zero in translation joints and the rotation joint of the Mark II rotates only around the z -axis in passing T -joints, a Jacobian matrix is given by Eq. (5).

$${}^T J = \begin{pmatrix} C_{12} & l_2 S_2 & 0 \\ -S_{12} & l_3 + l_2 C_2 & l_3 \\ 0 & 1 & 1 \end{pmatrix} \quad (5)$$

Consequently, a differential change of module 3 is computed by Eq. (6).

$$dX = {}^T J d\theta \quad (6)$$

To pass over the T -joints, the Mark II needs to obtain not only the position and attitude of module 3, but also the positions and attitudes of module 2 and module 1. When a trajectory path is given, in order to obtain the positions and attitudes of module 2 and module 1, the following inverse Jacobian matrix is used.

$${}^T J^{-1} = \frac{1}{l_2 C_1} \begin{pmatrix} l_2 C_2 & -l_2 S_2 & l_2 l_3 S_2 \\ S_{12} & C_{12} & -l_3 C_{12} \\ -S_{12} & -C_{12} & l_2 C_1 + l_3 C_{12} \end{pmatrix} \quad (7)$$

Given a small change of module 3, $dX^T = (dx, dy, \delta z)$, small changes of module 2 and module 1, $d\theta^T = (dq, d\theta_1, d\theta_2)$, are computed using Eq. (8).

$$d\theta = {}^T J^{-1} dX \quad (8)$$

4.2.3 Control mode sequence in passing T -joints

A control mode sequence is explained according to the moving mode shown in Fig. 8.

1) The Mark II detects a T -joint by infrared ray proximity sensors, and stops at s distance l away

from the T -joint. Then, by steering the wheels at each module by ninety degrees, the Mark II is rotated by ninety degrees to the side of the pipeline. Then, each module is steered by ninety degrees to return to its original direction.

2) The legs of module 3 are opened over $D/2$ (D is an outer diameter of a pipeline) and given a small change, $d\theta^T = (0, 0, d\theta_2)$, the position and attitude of module 3 are given by Eq. (6) as $dx=0$, $dy=l_3 d\theta_2$. For small, continuous changes to $\theta_2 =$ ninety degrees, the position and attitude of module 3 are given by $x=0$, $y=l_3$, $\delta_z =$ ninety degrees.

3) Then given a small change $d\theta^T = (dq, 0, 0)$, the position and attitude of module 3 are given by Eq. (6), such that $dq=dx$, $dy=0$, and $\delta z=0$. By giving small changes continuously up to $dq=1+(D/2)$, the position and attitude of module 3 become $x=1+(D/2)$, $y=0$ and δz . The Mark II reaches a new pipeline keeping an inclination angle of ninety degrees. Then the legs of module 3 must close, and can be controlled to hold the pipeline with the same attitude using a holding force given by Eq. (2).

Fig. 12 Change of link parameters in passage of T -joint

Fig. 13 Scheme of artificial flaws

In the passage of the T -joint by module 2, as moving distances of module 1 and module 3 differ from each other for small $d\theta_1$ or $d\theta_2$, module 2 cannot pass a T -joint using the same control method as module 3. According to a small change of module 3, the positions and attitudes of module 1 and module 2 can be computed by Eq. (8), and module 2 can pass T -joints by controlling $x=1+(D/2)$, $y=0$, $\delta z=0$ obtained in the above computations.

4) The legs of module 2 are opened over $D/2$, and given a small change $dX^T = (dx, 0, 0)$ to module 3, the position and attitude of module 2 are given by $dq=dy$, $d\theta_1=dy/l_2$ and $d\theta_2=-dy/l_2$, as computed by using Eq. (8). Given a small, continual change up to $dq=l_2$ and $d\theta_1 =$ ninety degrees, module 2 reaches the new pipeline.

5) Then, the legs of module 2 are closed and the attitude can be controlled by using the holding force computed in Eq. (2).

6) The legs of module 1 are opened over $D/2$, and given a small change $dX^T = (dx, 0, 0)$ to module 3, a small change of module 1 is given by $dq=0$, $d\theta_1=dy/l_2$ and $d\theta_2=-dy/l_2$, as computed in Eq. (8).

A small change is given continuously up to $y=l$.

7) Given a small change, $d\theta^T = (0, d\theta_1, 0)$, to module 1, a small change of module 3 is given by dx

Fig. 14 Results of flaw detection

Fig. 15 Experimental results of depth of flaws

Fig. 16 Shape and location of artificial flaws

$=0$, $dy=(l_1+l_2)d\theta_1$, and $\delta_z=d\theta_1$, computed by Eq. (6). However, as the legs of module 2 and module 3 are fixed on the pipeline, module 1 rotates by $-d\theta_1$. Given a small change continuously up to $d\theta_1 =$ ninety degrees, module 1 reaches the new pipeline. Then, the legs of module 1 are closed, and the attitude can be controlled by a holding force computed by Eq. (2).

By computing the positions and attitudes of each module using a Jacobian matrix and an inverse Jacobian matrix, and by controlling the translation and rotation, the Mark II can pass the T -joints, as shown in Fig. 12.

5. Experimental Results of Mobility and Diagnosis

To compare the inspection capabilities of the Mark II with articulation and the Mark I without articulation, diagnostic experiments were carried out using a gap sensor as the diagnostic sensor. The artificial flaws provided on the surface of the pipeline are shown in Fig. 13. Experimental results for the round flaws with diameters of 4 mm are shown in Figs. 14 and 15. Figure 14 shows the experimental results carried out three times, under the same conditions. Figure 15 shows the mean values of the depth of each flaw. Both figures show reliable experimental results. A depth of flaw of up to 4 mm can be accurately detected for flaws 4 mm in diameter. The artificial flaws grooved on the surface of the pipeline are shown in Fig. 16, and the corresponding experimental results of flaw detection are shown in Fig. 17. The locations of two flaws in the model of flaw detection correspond to the locations of the two peaks in the experimental results. These results show that the Mark II can detect not only the position of flaw, but also the depth

Fig. 17 Results of flaw detection

of flaw. In comparison with the Mark I, data trends generated by the eccentricity of moving wheels are smaller, and the capability of flaw detection of the mobile robot, Mark II, is improved.

6. Conclusions

(1) A control method of the passage of a T -joint of an articulated mobile robot, Mark II, is shown by computing and controlling the positions and attitudes of each module using a coordinate transformation matrix.

(2) A control method compensating for the torque generated by gravitational force is shown for the robot to move spirally on the pipelines.

(3) By controlling a holding force in motion, in comparison with the Mark I, the capabilities for flaw detection are improved.

References

- (1) Hosokai, H. and Fukuda, T., A Study on an Autonomous Diagnostic Robot for Pipelines, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 51, No. 467, C (1985-7), p. 1655.
- (2) Vertut, J. and Marchal, P., Vehicles with Wheels and Legs- The In-Pipe Remote Inspection Vehicle and His Family, The 3rd Symposium on Theory and Practice of Robots and Manipulators, (1978), p. 476.
- (3) Paul, R. P., Robot Manipulators, (1980), p. 41, The MIT Press.
- (4) Busacker, R. G., and Saaty, T. L., Finite Graphs and Networks an Introduction with Applications, (in Japanese), (1970), p. 106, Baifukan.