2008 IEEE International Conference on
Robotics and Automation
Pasadena, CA, USA, May 19-23, 2008

SLAM in Indoor Pipelines with 15mm Diameter

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Abstract— **As the need of well-being life becomes popular, one of important issues is clean drinking water. Delivery of clean water from the main water fountain to the end user is very crucial. However, typical pipelines are being contaminated by rust and several chemicals. And thus the water being delivered to house is not trustful as the drinking water. Thus, cleaning and inspection of the in-house pipeline becomes an important issue. However, it is hard to find a small-sized motor adequate to the robot for the inspection of the in-house pipeline with diameter of 15mm. Thus, this paper introduces a new semi-automatic pipeline inspection robotic system for small-sized pipelines. Three different types of inspection robot system were developed, which have different combination of sensors to realize SLAM. The robot system is carried by an extension cable, which is in advance being penetrated into the pipeline by a compressed air. The feasibility of the proposed SLAM using this semi-automatic pipeline inspection robotic system was verified through experimentation.**

I. Introduction

RECENTLY, many robot systems for pipeline inspection and monitoring have been developed. Such pipeline robotic systems range from the small-sized to the large-sized with different functionality.

Suzumori [1] developed a small-sized pipeline inspection robot with diameter of 13mm. A pneumatic power was employed to activate the CCD camera and the micro arm, but this design was not adequate for sharply curved pipeline and the cost is another problem for customization. Hirose [2] proposed several types of pipeline inspection robots whose diameters range from 25 mm, 50 mm, up to 150 mm. Muramatsu [3] and Roh [4-5] investigated pipeline robots for the underground urban to overcome the sharp curve inside the pipeline. Duran [6-7] developed an image processing algorithm to acquire the image of the pipeline using CCD camera and laser diode. Boudjabi [8] developed a tele-operation system for pipeline inspection.

However, most pipeline inspection robots in use have been developed for large-sized pipelines such as gas and oil pipelines. Most small-sized pipeline robots in use ranging from 50mm to 100mm are automatically driven by motor, but the motor-driven system cannot be implemented to 15mm pipeline because small-sized motor and sensor are not available for 15mm pipeline.

Recently, many SLAM algorithms based on various sensors such as infrared sensor, ultrasonic sensor and vision or laser range finder are developed. [11-14]

However, there is no prior work on SLAM of pipeline robot system with less than 15mm diameter, yet. In this paper, we introduce a semi-automatic pipeline inspection system and its SLAM algorithm. Three types of robot system are developed and the SLAM algorithm for each system is proposed, which uses different set of sensors. The performance of those pipeline inspection systems is shown through several experiments.

II. Working Principle of System

Semi-automatic pipeline inspection robotic system is a wire driven system. Figure 1 shows the working principle of the wire driving mechanism. First, the wire is connected to a sponge and the wire-connected sponge is inserted into the pipeline. Second, push the sponge in the pipeline by blowing the compressed air. As the sponge passes through the entire pipeline, the wire connected to the sponge penetrates the pipeline from the entrance to the exit location. Using a SLAM algorithm, the movement of the robot system can be identified along with the map building of the pipeline.

Figure 2 shows the wire and sponge being used in the wire driving system. The wire is made of a twisted stainless steel and moves smoothly in the metal pipeline. The stainless wire in use for the experimentation has the extensional strength of 68Kg and the thickness of 0.8mm.

The pipe inspection robot is connected to a stainless wire and then it is inserted into the pipeline by pushing in its structure made of spring. The pipe inspection robot carries many kinds of sensors to inspect the state of corrosion and water leakage and to develop the map of the pipeline

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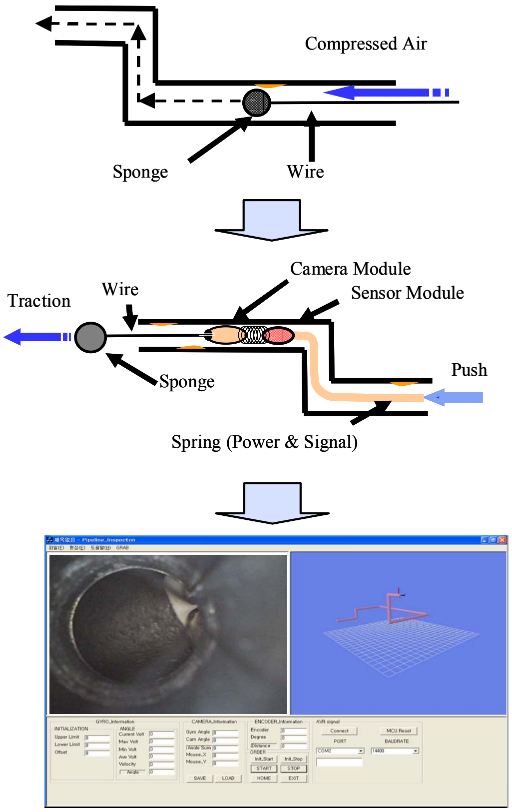


GUI (Map building)

Fig. 1. Wire driving mechanism

Fig. 2. Traction wire and sponge

The camera module is made small enough to pass through the pipeline with diameter of 15mm. It should pass through the curved pipeline as well. Several kinds of sensor fusion algorithms are used, which combines the information of vision sensor, gyro sensor, and accelerometer. Usually, the working environment of the indoor pipeline is well-structured because the indoor pipeline for water delivery always has 90 degree's turn at elbow or T-branch. This feature facilitates the SLAM in in-door pipelines.

III. Design and Components of Semi-Automatic Pipeline Inspection Robotic System

A. *Mechanism of Robotic System*

Three types of semi-automatic pipe inspection robot are introduced. Figure 3 is the appearance of Type 1, which consists of 3 single axis gyro sensors and a spring body. Both type 2 and type 3 consist of a camera module, a steering spring, a sensor module, and a spring body. However, they have different set of sensors. Type 2 employs just one single-axis gyro sensor, and Type 3 has additional accelerators. Figure 4 shows the structures of Type 2 and Type 3.

Fig. 3. Type 1 Inspection robot

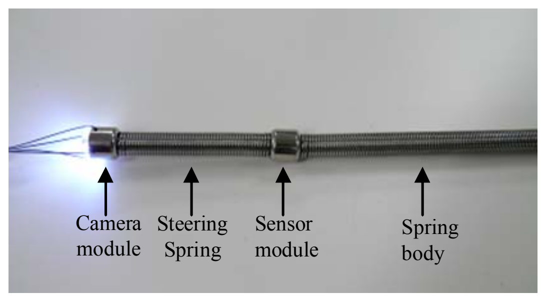


Fig. 4. Structure of Type 2 & Type 3 Inspection robot

Semi-automatic pipeline inspection system is designed suitable to inspect the indoor pipeline with diameter of 15mm. The diameters of both camera module and sensor module are 11mm, and the lengths are 11mm and 10mm, respectively. The camera module and sensor module are connected by a flexible steering spring whose length is 10mm. The length of spring body is 17m, and a signal line and power line are built in it. Figure 5 shows the dimension of the inspection robot. The major function of the steering spring is to provide smooth maneuvering of the semi-automatic robot system inside the pipeline.

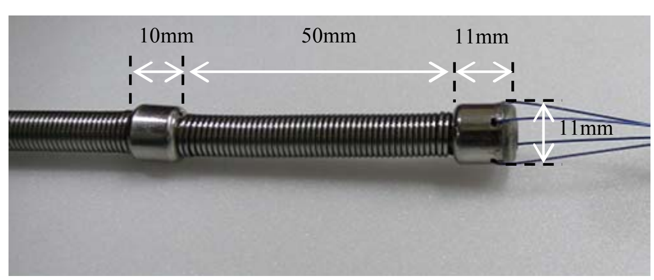


Fig. 5. Dimension of inspection robot

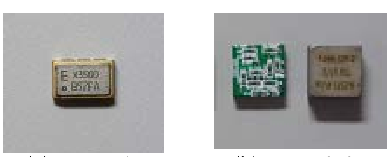
B. Vision System

The camera module contains eight high-luminance LEDs. General CCD camera module comparatively has a long circuitry part. So, it cannot pass through the elbow of pipeline with diameter of 15mm. Also the CCD sensor needs an amplifier in order to send the image information to the distance of 17m. So the head part of the robotic system is more difficult to pass through the elbow of pipeline due to the size of the amplifier part. To cope with this problem, a CMOS camera module is employed in this system. The COMS camera module has a simple circuit, its cost is inexpensive, and the required power is also reduced. In addition, it is possible to obtain the image information during inspection of more than 17m pipeline without using the amplifier. The CMOS camera module used for this experimentation is shown in Figure 6. Its diameter is 1/4 inch, its array size is 510□492, its frame rate of image is 30 frame/sec, and the minimum required illumination is 2 Lux.

Fig. 6. CMOS sensor

C. Sensor Modules

The single-axis gyro sensor used in Type 1 has dimension of 5 x 3.2 x 1.3mm. Three gyro sensors are placed in the three perpendicular directions of the sensor module. In Type 2 and Type 3, one gyro sensor with dimension of 7 x 7 x 3mm is employed. Figure 7 shows the gyro sensors of Type 1 and Type 2 or Type 3. Figure 8 shows a dual-axis accelerometer used in Type 3. Its dimension is 5 x 5 x 2mm.



(a) Type 1 (b)Type 2,3

Fig. 7. Gyro sensors

Fig. 8. Accelerometer

An encoder is used to measure the moving distance of the robot and it is located at the entrance of the pipeline. The encoder measures the length of the wire protecting spring being inserted from the entrance of the pipeline to the current location of the pipe inspection robot inside the pipeline.

Figure 9 shows the distance sensing module using an encoder. The cable protecting spring is bit by two rollers and an encoder is attached on the shaft of the bottom roller. The roller rotates as the cable protecting spring passes the roller and the encoder calculates the number of rotation. Then, the moving distance of the pipe inspection robot can be calculated by

$$d = R\pi\theta / 360 \,, \qquad (1)$$

where d, R, and θ denote the moving distance of the robot, the diameter of the roller, and the rotation angle of the roller, respectively.

Fig. 9. Distance sensing module

IV. Implement of SLAM using Sensor fusion in Pipelines

A. Experimental Environment

Figure 10 shows the experimental environment that imitates a real indoor pipeline. Usual indoor pipelines have many elbows and T-branches, which are commonly bent 90 degrees. Thus, each longitudinal pathway is always parallel to one of three axes in the global coordinate. When the pipeline inspection robot is moving along the pipeline, there are four possible moving directions at elbow or T-branch; turning to up, down, left, and right direction.

Therefore, the working environment is relatively simple as compared to that of autonomous mobile robot navigating an open environment. For SLAM of this pipeline inspection system, a proper sensor fusion is required to identify one of the four turning directions. Figure 11 shows four possible turning directions in elbow.

The pipe used in experiment is a galvanized steel pipe with diameter of 15mm used for real indoor water pipe. The pipeline has more elbows than the number of real indoor pipeline. Five to seven elbows are installed in general indoor pipeline. However, twelve elbows are used in this experiment. The total length of pipeline is 15m.

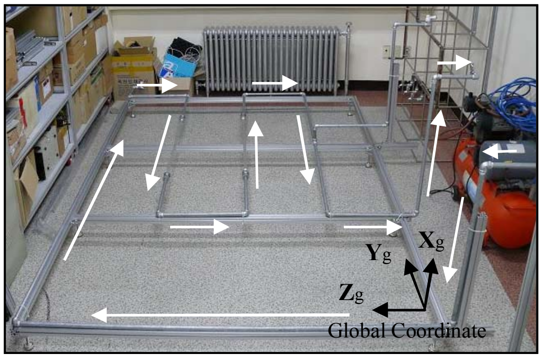


Fig. 10. Experimental environment

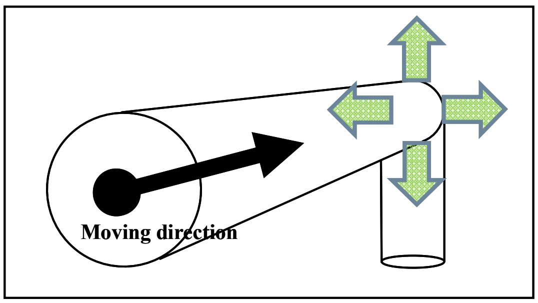


Fig. 11. Detection of the turning direction

B. Basic Concept of SLAM in pipeline

To build the map of the pipeline, the position and attitude of the pipeline inspection robot should be measured in real-time. The encoder information locates the pipeline inspection robot inside the pipeline. And the gyro sensor and accelerometer measure the roll motion, and the camera is able to detect the pitch and yaw angles by information of the camera image. Using those sensor data and the image information of the camera module, we can construct a complete map of pipelines.

Using the map, localization of the pipeline inspection robot can be simply made by measuring the moving distance of the robot. Figure 12 shows the robot coordinate system used to obtain the position and the attitude of the pipeline inspection robot.

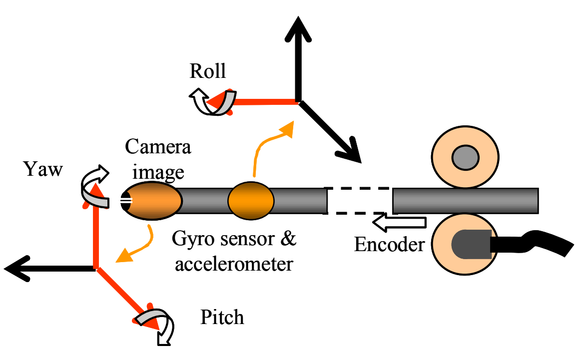


Fig. 12. Basic concept of map building

C. SLAM Algorithms

1) TYPE 1: SLAM by using 3 Single-axis Gyro Sensors

Type 1 uses a gyro sensor consisting of three single-axis gyro sensors. Figure 13 shows the arrangement of the three gyro sensors. However, the maximum dynamic range of the small-sized gyro sensor used in Type 1 is relatively small (i.e., 100 degree/s), and thus the error of the measured angle is accumulated for long pipeline. Each gyro sensor is aligned to the x-, y- and, z-direction of the robot coordinates. The z-direction is along the moving direction, and the roll angle of the inspection robot is measured by the gyro sensor aligned in the z-direction. The pitch and yaw angles with respect to the global coordinate are obtained by using coordinate transformation between the global coordinate system and the robot coordinate system.

The length of the pipeline used in this experiment is 5m, and it is a U-shaped pipeline consisting of two elbows. Fig. 14 shows the result of the map building algorithm. For inspecting a longer pipeline, it is necessary to employ more accurate gyro sensor.

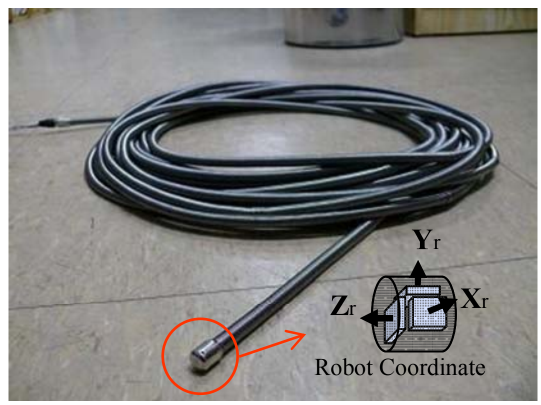


Fig. 13. Construction of 3 single-axis gyro sensor

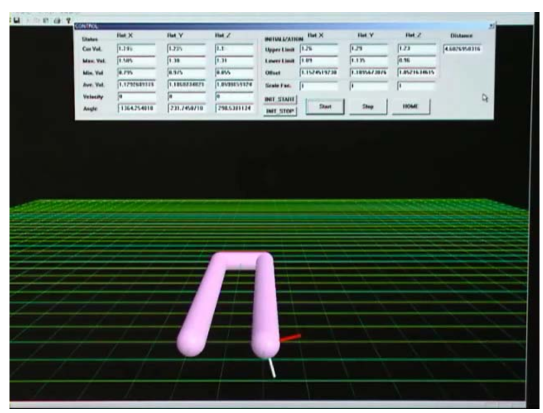


Fig.14. Map building of Type 1

2) TYPE 2: SLAM by using 1 Single-axis Gyro Sensor and Camera image information

Type 2 consists of a camera module, a steering spring, and a sensor module. One single-axis gyro sensor is installed in the sensor module along the z-direction of the robot coordinate. Its dynamic range of this sensor is 300 degree/s but its size is a little larger than the gyro sensor used for Type 1.

Figure 15 shows the method for detecting the moving direction of the robot by using the information of the gyro sensor and the camera. At first, we initialize the orientation of the robot coordinate relative to the global coordinate. After the robot system is inserted into the pipeline, the gyro sensor continuously measures the roll angle α of the robot coordinate. When the robot reaches the elbow or T-branch and starts to turn, the turning direction p is identified visually by the human operator. When the inspection robot turns at the elbow, a small circle at the edge of elbow is identified. The operator observes the motion through the PC screen and clicks the mouse on the center of the circle. The angle θ denotes the rotation angle of the inspection robot relative to the camera coordinate system. Thus, the global roll angle of the vector P is calculated by

$$\Phi = \alpha + \theta, \tag{2}$$

where

$$0^\circ < \Phi \leq 360^\circ.$$

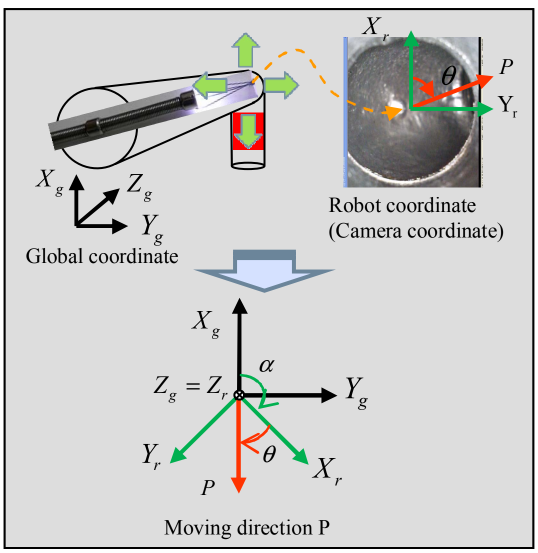


Fig. 15. Detection of the moving direction

In the real experiment, the measured roll angle is not exactly scalar multiple of 90 degrees because of some noises. Thus, Table I is employed to identify the real roll angle.

TABLE I

P_{Global} ANGLES IN TERMS OF THE RANGE OF Φ

Range of Φ	P_{Global} angle
$45^\circ < \Phi \leq 135^\circ$	90°
$135^\circ < \Phi \leq 225^\circ$	180°
$225^\circ < \Phi \leq 315^\circ$	270°
$0^\circ < \Phi \leq 45^\circ$ & $315^\circ < \Phi \leq 360^\circ$	0°

SLAM in pipeline is realized by using the above method repeatedly; find the orientation of the robot by gyro sensors and calculates the moving distance by encoder. However, similar to Type 1, sometimes it builds an incorrect map by error accumulation of the gyro sensor for the pipeline longer than 5 m. Figure 16 shows the pipeline with 6 elbows and the length of 5 m. In this experimental environment, Type 2 was able to perform SLAM without error, and Fig. 17 shows the result of map building.

In the operation of Type 2, the turning direction can be estimated by the image information of the camera because sometimes it is inconvenient to click on the screen by the operator. For this, we attach a sponge in front of the camera module and fix the focal length so that better image can be provided. When the inspection robot turns at the elbow, the sponge deflects toward the turning direction as shown in Figure 18. The moving direction of the inspection robot can be automatically identified by using a proper image processing algorithm. This algorithm uses the state that the sponge is divided into four sections created by the four wires connecting the sponge to the camera module. However, the performance of the image processing algorithm varies depending upon the condition of the inner pipelines. The color of the inner surface of the pipeline is not identical. Thus, adaptive change of illumination is one important issue. Current system employs a high illuminant LED for illumination. Optimal choice of LED is a future research topic.

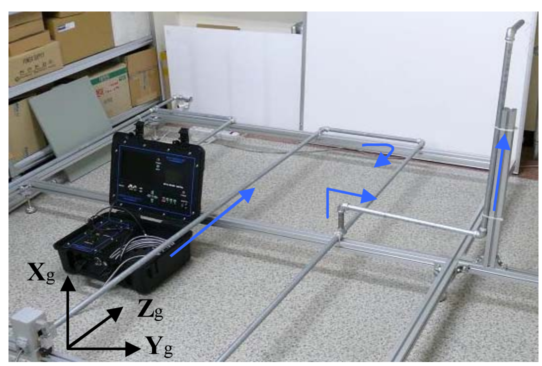


Fig. 16. Experimental environment of Type 2

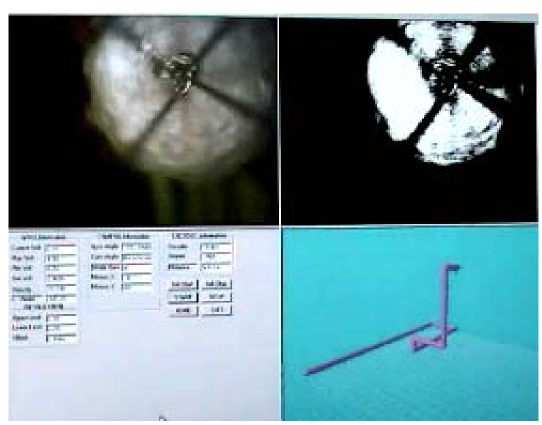


Fig. 17. Map building of Type 2

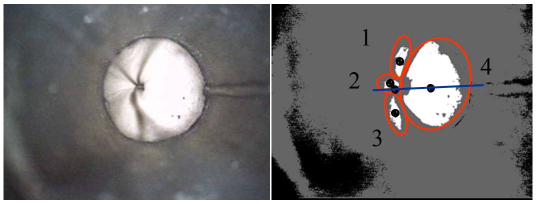


Fig. 18. Image processing with sponge

3) TYPE 3: SLAM by using 1 Single-axis Gyro Sensor, 1 Dual-axis Accelerometer and Camera image information

In Type 1 and Type 2, it is hard to build the accurate map of pipelines longer than 5m due to the error of gyro sensors measuring the rolling angle. To cope with this problem, Type 3 employs a dual-axis accelerometer to assist measuring accurate rolling angle. Fig. 19 shows the sensor module equipped with a gyro sensor and a dual-axis accelerometer.

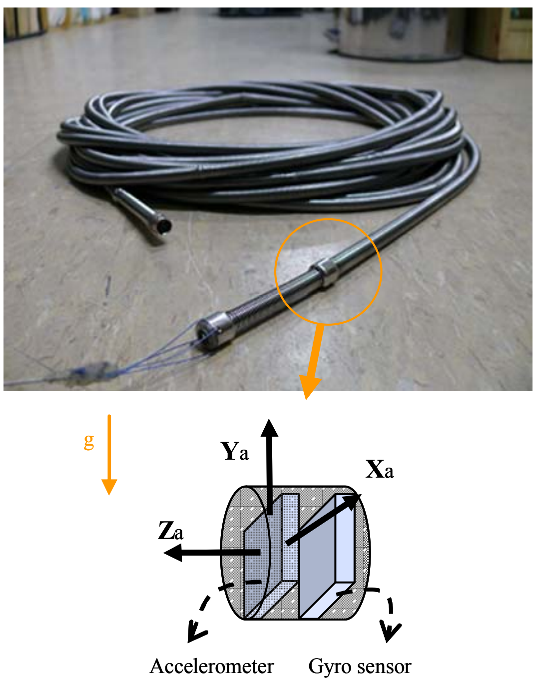


Fig. 19. Sensor module of type 3

The dual-axis accelerometer senses the acceleration in the X_a - axis and Y_a - axis of the camera coordinate system. They have the maximum values when their directions are opposed to the gravity direction, and have 0 values when it is perpendicular to the gravity direction. The rolling angle θ of the sensor module is obtained by

$$\theta = A\tan 2(\ddot{X}_a, \ddot{Y}_a), \qquad (3)$$

where $\ddot{X}_a$ and $\ddot{Y}_a$ denote the gravitational acceleration measured by dual-axis accelerometer.

However, the dual-axis accelerometer cannot measure the rolling angle when the Z_a axis is along the gravity direction. Thus, in the vertical pathway of pipelines, only gyro sensor measures the rolling angle. It is remarked that in the indoor pipeline, there are not many vertical pathways longer that 5 m. Thus, the sensor fusion algorithm provided by the dual-axis accelerometer and the gyro sensor provides the operator with the information of current position and pipe condition as well as the map of the pipeline under inspection

Figure 20 is the experimental environment for Type 3 and the length of the pipeline is 7m, and the number of the elbows is 8. Figure 21 shows the result of the map building. We performed several experimentations for the same test-bed. The success rate of the map building is 95%, which is fairly satisfactory.


Fig. 20. Experimental environment of Type 2

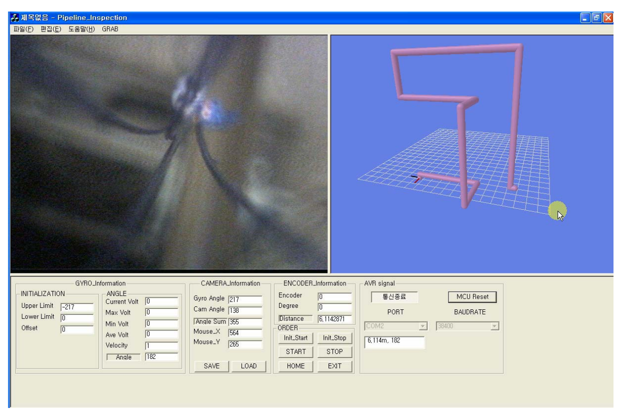


Fig. 21. Map building of Type 3

V. Conclusion

This paper introduced a new semi-automatic pipeline inspection robotic system, which can be used for inspection of the in-house pipeline with diameter of 15mm.

Three types of inspection methods were proposed and tested in order to implement SLAM in the pipeline during inspecting.

However, it is difficult to build the accurate map due to the error accumulation when using only one gyro sensor. This problem can be resolved by adding a dual-axis accelerometer sensing the absolute roll angle.

Also, unlike SLAM applied to the existing mobile robot, the working environment of the pipeline inspection robot is relatively simple. Using a sensor fusion algorithm based on a couple of sensors, we were able to provide the operator with an accurate map and the state of any damaged location of the pipeline in real time. In addition, providing the real time image of the inner pipeline, we are able to provide the home residence with comfort so that they can drink water without any worry.

ACKNOWLEDGMENT

This work was financially supported by MOCIE & ETEP (Electric Power Technology Evaluation & planning Center) through EIRC program, Republic of Korea. (I-2007-0-267-0-00)

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