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Development of a Pipeline Monitoring System by Bio-mimetic Robots

Seung You Na, Daejung Shin, Jin Young Kim, Joo Hyun Jung and Yong-Gwan Won

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***Abstract*—**To explore pipelines is one of various bio-mimetic robot applications. The robot may work in common buildings such as between ceilings and ducts, in addition to complicated and massive pipeline systems of large industrial plants. The bio-mimetic robot finds any troubled area or malfunction and then reports its data. Importantly, it can not only prepare for but also react to any abnormal routes in the pipeline. The pipeline monitoring tasks require special types of mobile robots. For an effective movement along a pipeline, the movement of the robot will be similar to that of insects or crawling animals. During its movement along the pipelines, a pipeline monitoring robot has an important task of finding the shapes of the approaching path on the pipes. In this paper we propose an effective solution to the pipeline pattern recognition, based on the fuzzy classification rules for the measured IR distance data.

***Keywords*—**Bio-mimetic robots, Plant pipes monitoring, Pipe pattern recognition.

I. INTRODUCTION

THERE are usually various kinds of machines and extremely long pipelines in manufacturing plant systems. As a result, many kinds of signals produce a large amount of data to be monitored. Besides complex and huge pipeline systems of large industrial plants, many areas such as between ceilings and ducts of common buildings need to be monitored. Periodical monitoring of a massive factory area, however, cannot be easily performed. Furthermore, system failures often start from a small leakage caused by years of the pipeline's gradual deterioration. While noticeable pipeline leakage and blockage are easy problems to resolve, a small leakage is difficult to spot simply by monitoring. In this paper, we present robots whose function is to collect data that will make sure to detect any obscure leakage and deteriorated pipelines. A set of modules for measurement sensors, navigation, actuators and communication is attached in the robot so that it can collect data with intelligence and a better maneuver.

Once a malfunction is recognized, the monitoring system enables a robot to formulate appropriate responses and movements [1]. There are several steps in the monitoring system, including collecting, saving, conditioning and analyzing data, but one of the most important tasks is to find in advance the shapes of the upcoming path on the pipes while the robot moves along the pipelines. Among many different shapes of pipe patterns are bends, ramification and crosses. In this paper, an effective method of the pipe pattern recognition for pipeline monitoring robots is presented. We propose our solution based on the fuzzy classification rules for the measured IR distance data [2].

II. BIO-MIMETIC ROBOTS MOVING ON PIPES

To find abnormal conditions of a pipeline, the monitoring system collects, saves, and examines data. Some of the systems that are currently used include DAS (Data Acquisition System), SCADA (Supervisory Control And Data Acquisition System), and MAP (Manufacturing Automation Protocol). These systems collect monitored data and transfer the data to a computer through LAN to save and examine them.

The biggest disadvantage in the conventional monitoring system is that the observed and monitored spots are fixed. It needs to pick the most appropriate area as its standard measuring points so that it can distinguish normal conditions from abnormal [5]. The proposed monitoring method has an advantage of active searching due to mobility and instant analysis. When an abnormal condition is recognized, the robot reports the data to prevent further problems and system failure. The monitoring system, in addition to fixed sensors, adds moveable observatory points, which are the robots on the pipelines. The robot, which is equipped with a set of modules, can report the measured data while searching its path autonomously based on the real-time location of the robot.

In a factory environment, pipe monitoring robots are used to locate abnormal conditions caused by depreciation and deterioration of the factory machines. The robot as an assistant to a professional engineer replaces a person who inspects hard-to-reach areas including pipelines. The robot also collects data and reacts to its sensors. These bio-mimetic robots are useful not only in industrial environments but also in skyscrapers and any buildings where a regular checkup is essential. The robot collects enough data to locate troublesome areas and even predict a possible malfunction in advance.

A factory pipeline as well as water supply and drainage, gas pipes, or an air duct would be the most appropriate environment for this bio-mimetic robot. Since deterioration is relatively fast and the replacement is extremely costly, these areas require a periodic checkup. Because of the complexity of the pipelines, a

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S. Y. Na is with the Electronics and Computer Engineering Department, Chonnam National University, Gwangju 500-757 South Korea (corresponding author to provide phone: +82-62-530-1753; fax: +82-62-530-1759; e-mail: syna12@jnu.ac.kr).

Daejung Shin is with BK21 and ETTRC, Chonnam National University, Gwangju 500-757 South Korea (e-mail: djshin71ha@hotmail.com).

J. Y. Kim, J. H. Jung and Y.-G. Won are with the Electronics and Computer Engineering Department, Chonnam National University, Gwangju 500-757 South Korea (e-mail: beyondi@jnu.ac.kr, jupiter@hanmail.net, ykwon@jnu.ac.kr).

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small, delicate robot would be much more appropriate for examining the areas than a man.

To inspect the areas, the robot must be able to move freely throughout the pipelines. A suitable type of robot should also be able to withstand factory pipeline's condition and structure. The measured data of a pipeline are collected and transmitted to a server to find any abnormality such as leakage, vibration, or a temperature change. Since it should perform properly as a mobile agent, the robot needs to be built in a proper shape and attached with driving module and interface including a battery pack as well as position and path-finding algorithms. Besides, a server is necessary to report the exact location of the robot and communicate information to each other.

III. CONSTRUCTION OF A MONITORING ROBOT SYSTEM

Our proposed bio-mimetic robot can collect the data by moving freely along the pipelines. The robot as an assistant to a professional engineer is the monitoring system which finds abnormal conditions of the pipeline by collecting and processing the relevant data. These robots are useful especially in large buildings, let alone in industrial environments, where complex facilities are operated. The monitoring robot should be able to collect enough data to locate a variety of system failures and predict the data patterns so that the monitoring system can prevent any possible malfunction beforehand.

A. Microcontroller Units

Serving as the robot's main intelligence part, the microcontroller exchanges information and commands with the server by using the Bluetooth module connected to the serial communication ports. In order to control many servo motors of the robot while recognizing its path on a pipeline, more than one separate motor controller is used and other serial communication ports are used so that they can exchange appropriate commands. In that way, the microcontroller is able to avoid heavy loads and collect and analyse the sensor data such as vibration, noise and temperature. Figure 1 shows a microcontroller unit playing the role of the robot's brain.

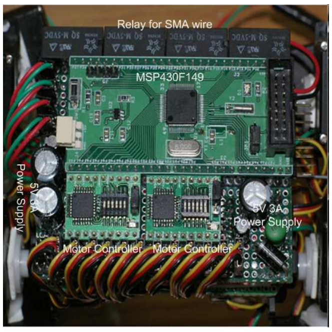

Fig. 1 A microcontroller unit for a pipe robot

B. Grippers

The gripper is an implementation device to firmly grip the pipe and a set of relays is used to provide or disconnect the electricity to the shape memory alloy wires. The gripper using the shape memory alloy is placed at the end of the four arms of each robot. The end-effector of the robot, actually holding a grip of the pipe, is depicted in Figure 2. The gripper is made up of the gripping part, the joints, and the shape memory alloy wires used to move the joints. As the temperature rises, the alloy contracts when consistent electricity is provided. The contraction of the wire makes the joint move and makes the ends of the gripper separated from each other. When the electricity is cut off, the shape memory alloy returns to its normal and the gripper grips the pipe by the power of springs which form the joints. Basically, the pipe climbing robot holds a grip of the pipe by spring force when no current is supplied to the shape memory alloy wires. In order for the robot to move, the gripper moves one of its four arms forward by taking the ends apart and moving the angle of the joints connected to the servo motor. For the moved arm to stick to the pipe, the electricity to the shape memory wire is disconnected. Once the sufficient power to grip the pipe is applied, the other arms are moved either forward or backward of the pipe, according to the given commands. The pipe climbing robot weighs about 570g with the batteries included; at the initial state, the wire is 52mm in length. The gripper has the angle of 30° but, when the wire contracts and reaches to 49mm, the angle is 45°.

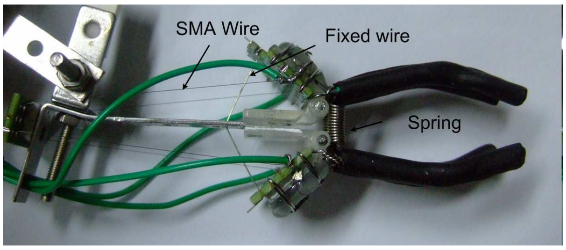

Fig. 2 Gripper structure of a pipe robot

C. Shape Memory Alloy Wires

The elasticity of the spring is so strong that it can withstand the weight of the body. The fixed wire is used to prevent the unnecessary power from adding to the shape memory alloy wires, as shown in Figure 2. The fixed wire sustains the elasticity of the spring at the initial status so that the SMA wires are not loosened. At this status, the shape memory alloy wire is pulled enough not to allow no additional power so that the highest power can be obtained when contracted.

The shape memory alloy which was used for the robot grippers has the radius of 0.004 inches and it has resistance of about 3 Ω per unit. If the electricity is provided to the alloy, the temperature of the wire rises and there will be about 3-5% contraction. At this time, tension for the unit inch is about 150g. To increase the tension, several wires are used in parallel. The alloy wire, which was used in the experiment, shows the largest contraction at 70°C, and the excessive rise in temperature harms the nature of the shape memory alloy. It has the dimension of 320×180×190mm when expanded by operating the joint motor of the robot. On the other hand, it has the dimension of 180×160×170mm when contracted.

Two wires, which are about 10 inches long, are installed at four places where force is applied. Therefore, each connected wire has the tension that can handle a weight of 150g*8= 1200g.

The set of wires is installed at both ends of each gripper; the total power comes to approximately 2.4Kg. The entire wire has the resistance of 14Ω, and when the voltage of 5V is given, it has 0.37A and the contraction shows the variation of 15° at one joint of the gripper and indicates about the variation of 30° in total. The constructed gripper structure for the pipe climbing robot is shown in Figure 2.

D. Body Integration

The robot collects data on leakage, vibration, or temperature changes as it moves along the designated courses. It immediately reports them to the server system. Thus the systems should include the proper robot structure, sensors, and the interface with actuator modules, which can resolve the problems with the robot’s movement and performance. Since our robots move autonomously, the power, location recognition sensors and algorithms, and the communication module with the server are needed.

The robot takes the routes according to the rules so that maintenance of the pipelines can be ensured. As it identifies the existence of the pipeline which it needs to move along, the robot’s sensors recognize the complex pipelines.

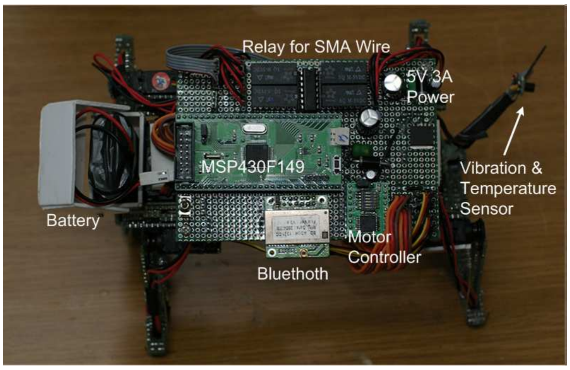

Fig. 3 Integration of functional units for a pipe robot

E. Sensor Module

Unlike the conventional methods of pipeline monitoring which collect data by sensors attached on fixed posts, the proposed method depends on mobile robots having a fundamental advantage of mobility over the conventional fixed monitoring posts. Because of free movements of the bio-mimetic robots on the pipes while collecting measurements, it is possible to track directions that have higher possibilities of malfunction in real time modes. Practically, this kind of real time dynamic monitoring method is crucial when investigating possible future failure and protecting the plants.

Sound data collection of pipelines is described as a typical sensing data for diagnosis. A variety of methods of sound source localization have been developed, based on audio-visual information [12]. The basic features of the sound signals to determine the directions and distances of sound sources are the interaural time difference(ITD) and the interaural level difference(ILD) from a sound source to each microphone.

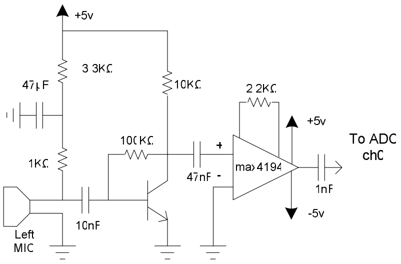

Fig. 4 Circuit of a stereo microphone system

We use a simple estimation method of sound directions with microphones only, due to the restriction of computation time and resources in a mobile robot system. The calculations of the interaural time difference(ITD) and the interaural level difference(ILD) from a sound source to each microphone or the analysis of the average magnitude difference function(AMDF) signals for short-time intervals are not applied to get the estimation quickly. Only sampling of microphone signals, A/D conversion and simple algebraic calculations are applied to obtain the differences of the right and left microphone measurements, which are directly related to the sound directions.

Besides sound data by similar methods, acceleration and temperature data associated with possible leakage, vibration, or temperature changes are typical signals collected by the monitoring robot.

The robot operates either automatically or by remote control, and collects and analyzes data before transmitting them to a server. A diagram of microcontroller and peripheral equipment for the robot is shown in Figure 5.

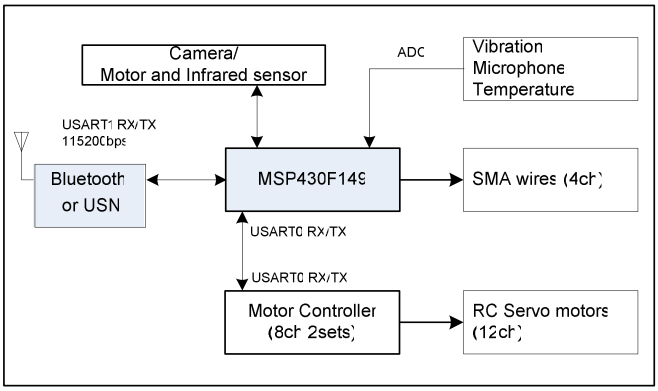

Fig. 5 Functional block diagram of a pipe monitoring robot

F. Noise Rejection

Two main sources of noise are environmental sound around the robot and noise from actuating motors inside a robot body. Since the main spectrum of the motor noise has a much higher range than that of signals from pipelines, it is easy to filter out the effect from the motor sound. The sound of environmental noises, however, has a similar spectrum range to that of interested signals. The environment signals are rather uniform around the robot, and the measured signals due to ambient noises are similar at each microphone. Therefore, when the

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measured signal at the left microphone is subtracted from that of the right one, noise components due to ambient noise are nearly cancelled out. The subtraction can reveal the interested component that arrived at the left and right microphones differently due to different approaching angles.

When the sound direction of the interested signals is estimated, a mobile robot turns its head to the near direction which is possible on the pipelines. Sound distances from the sources to microphones are not estimated due to the randomness of sound source levels.

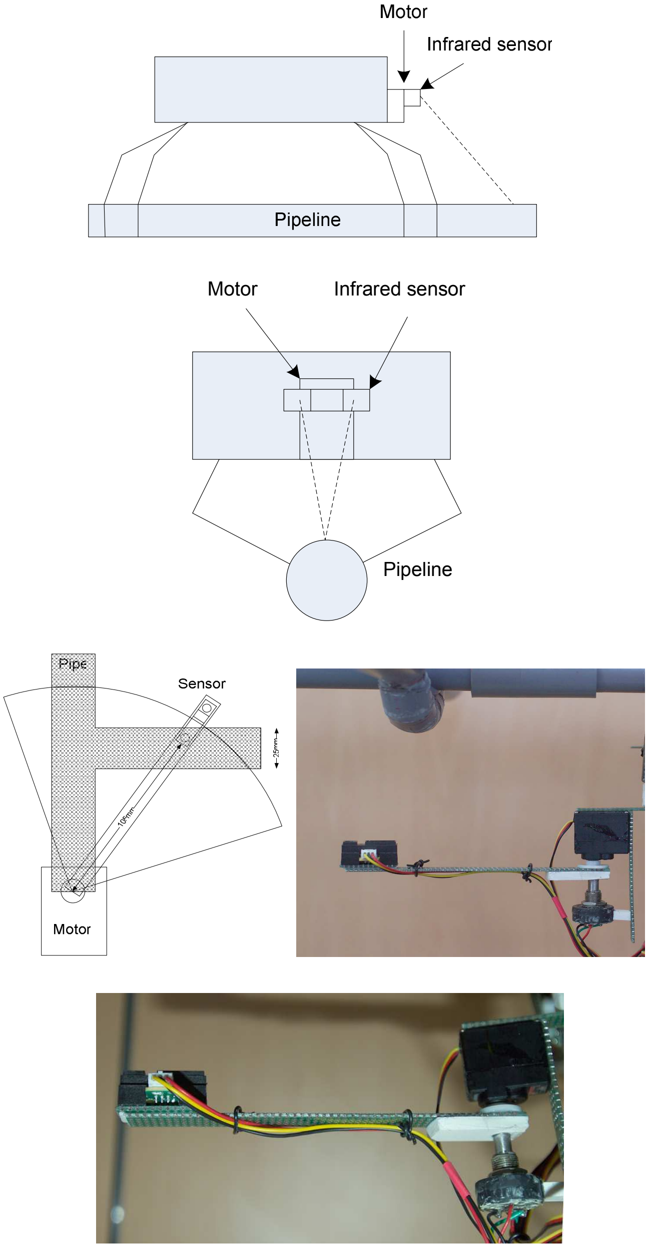
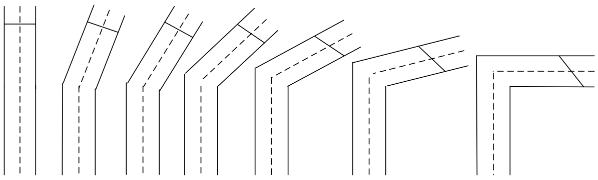


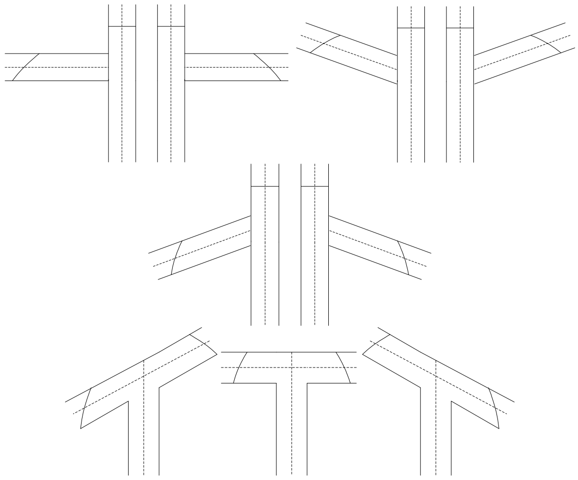
Fig. 6 Scanning IR sensor module

IV. PIPE PATTERN RECOGNITION

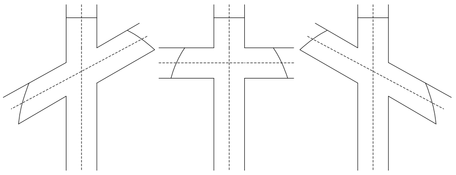
The pipeline monitoring process includes several steps, such as collecting, saving, conditioning, and analyzing data. Nevertheless, one of the most important tasks for a robot during its movements along the pipelines is to find the shapes of the approaching path on the pipes. The recognition of the pipe shapes beforehand determines the gait commands for the movement of a robot. There are many shapes of pipe patterns such as bends, ramification or crosses. An effective solution is proposed to the pipe pattern recognition for pipeline monitoring robots. Our solution is based on the fuzzy classification rules for the measured IR distance data.



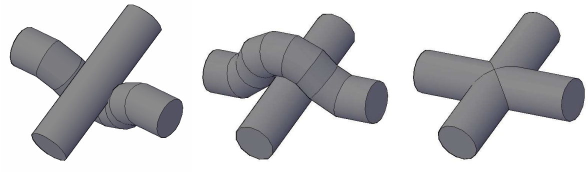
(a) Bend: one detection



(b) Ramification: two detections



(c) Cross: three detections



(d) Different cross shapes

Fig. 7 Pipeline patterns

A. *Scanning IR Sensor*

Figure 6 describes the basic sensor module. It is a scanning IR distance sensor. The moving rod is connected through a potentiometer at the head of a robot.

The scanning range is from -75 ° to 75° and then back to -75 ° to complete one cycle. The scanning time for the first half cycle is 9.5 sec. including distance measurements. The scanning time for the second half cycle is 1.4 sec. without measurements. The IR distance measurement time is 1/20 sec. so that 190 sets of distance and angle can be obtained during a scan cycle.

B. Pipeline Patterns

We assume that the pipeline patterns to be classified are shown in Figure 7. Since the crawling robot can rotate at the same location on a pipe into different positions, the patterns are assumed to be in two-dimensional.

C. Sensor Specifications

The sensors on the scanning module are an IR distance sensor and a potentiometer. The IR measures distance data to the pipelines; a potentiometer measures the angle of the scanning rod at the instance of IR distance measurement.

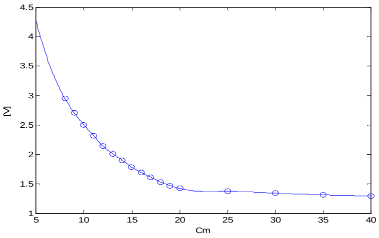


Fig. 8 IR distance sensor specification

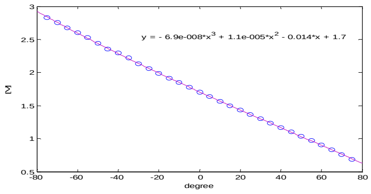


Fig. 9 Potentiometer specification

D. Sensor Data

The measured data are signal conditioned through filters and an amplifier. Figure 10 shows a typical example and the pipe shape is the case of an angled cross.

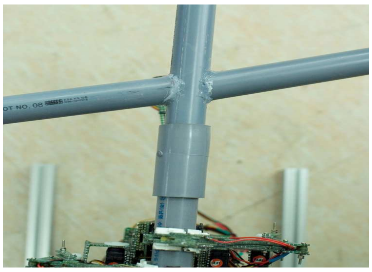
The measured data sets of distance and angle are shown in (b), and the corresponding data set for the fuzzy classifier input are shown in (c). Only the measured IR sensor output voltages of (b), which are greater than a certain level, are shown in (c) where background noises are eliminated.

E. Fuzzy Classifier

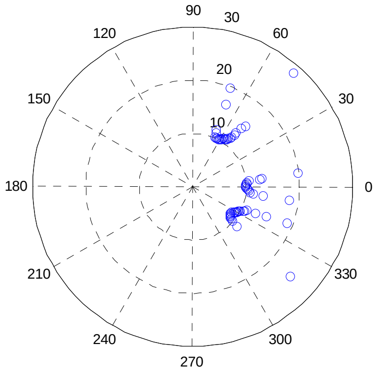
There are two steps of the classification. The first step is to find the number of pipelines from the grouped sampling data. One, two and three groups of sampling data represent the cases of bend, ramification, and cross, respectively, as shown in Figure 7 (a), (b), and (c).

The second step is to find the angle of pipelines for each case of Figure 7 (a), (b), and (c). The degree of discrepancy in symmetry corresponds to the angles of the each case of Figure 7 (a), (b), and (c).

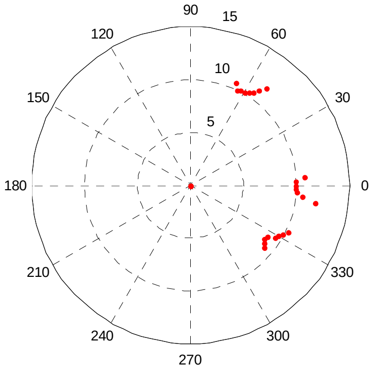
As shown in Figure 10, for example, the group of three unsymmetrical samples conforms to the pipeline shape of an angled cross. The fuzzy rules are typically based on ANFIS(Adaptive-Network-based Fuzzy Inference Systems) to infer pipeline shape recognition.



(a) Angled cross pipeline



(b) Measured data set



(c) Input data for fuzzy inference

Fig. 10 Measured and fuzzy classifier input data

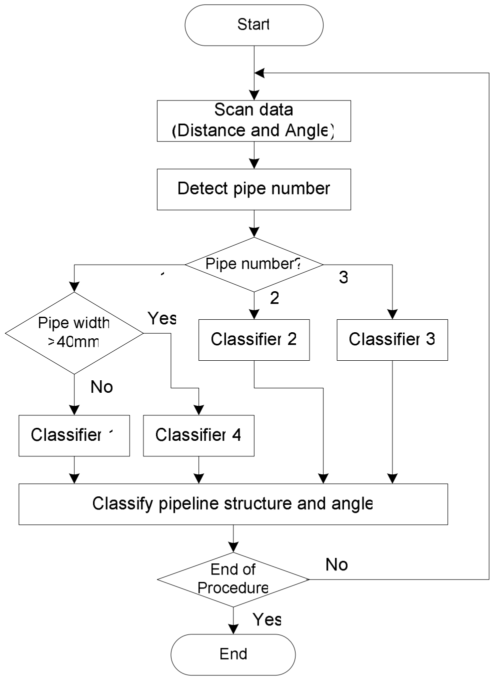
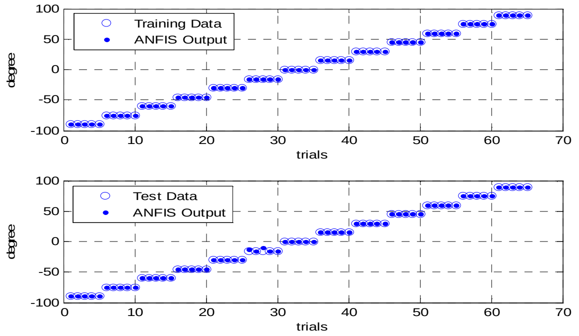


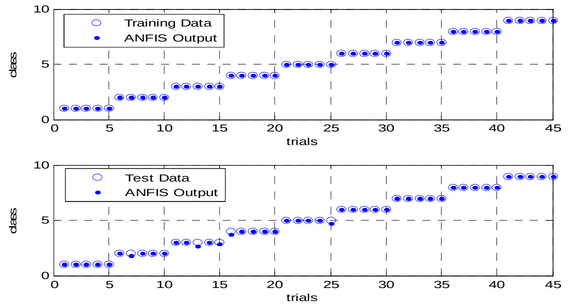
Fig. 11 Fuzzy logic flowchart for pipe pattern classification

F. *Recognition Results*

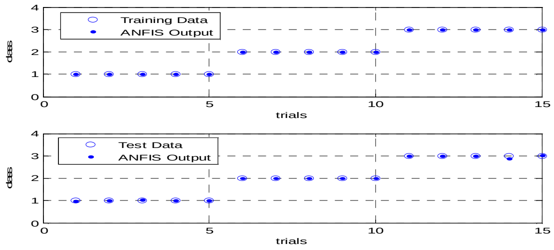
Figure 12 and Table 1-4 show the recognition results of the fuzzy inference rules. The classification of the pipe patterns of (a), (b), (c) and (d) in Figure 7 are shown in Figure 12, respectively. The test results of 28 pattern cases in total are quite satisfactory in terms of safety margin and low degree of standard deviations as shown in Table 1-4.



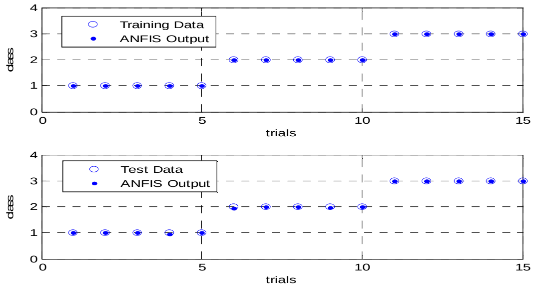
(a) Case 1 (one detection)



(b) Case 2 (two detections)



(c) Case 3 (three detections)



(d) Case 4 (Cross sections)

Fig. 12 Test results of ANFIS inference

TABLE I RECOGNITION RESULTS FOR CASE 1

	Error	Standard Deviation
-90	-4.8199e-6	3.5655e-6
-75	-9.3913e-6	2.7576e-6
-60	-7.4995e-6	2.3301e-6
-45	-3.4581e-6	7.4083e-7
--30	-2.1448e-6	1.5991e-6
-15	-1.4285e+0	2.2016e+0
0	9.9782e-20	2.2312e-19
15	2.4353e-6	1.6215e-7
30	1.8687e-6	1.7738e-6
45	2.5959e-6	3.3552e-7
60	1.5175e-6	0
75	2.1249e-6	0
90	6.1897e-6	1.8378e-6

TABLE II RECOGNITION RESULTS FOR CASE 2

	Error	Standard Deviation
Class 1	6.2125e-8	1.8875e-8
Class 2	0.0347	0.0776
Class 3	0.0947	0.1412
Class 4	0.0500	0.1118
Class 5	0.0625	0.1398
Class 6	2.0863e-7	1.3748e-7
Class 7	1.1184e-7	1.6381e-7
Class 8	2.7889e-7	1.3100e-7
Class 9	1.1179e-7	9.8018e-8

TABLE III RECOGNITION RESULTS FOR CASE 3

	Error	Standard Deviation
Class 1	-0.0066	0.0235
Class 2	-0.0043	0.0088
Class 3	0.0255	0.0577

TABLE IV RECOGNITION RESULTS FOR CASE 4

	Error	Standard Deviation
Class 1	9.3455e-3	2.7514e-2
Class 2	1.9586e-2	3.2044e-2
Class 3	8.7662e-4	6.9162e-3

V. CONCLUSION

Several steps of collecting, saving, conditioning, and analyzing measured data constitute the pipeline monitoring process. One of the most important tasks for a robot moving along the pipelines is to find out what shapes the upcoming path has on the pipes. Among many different shapes of pipe patterns are bends, ramification and crosses. Recognizing the pipe shapes ahead of time determines the route commands for the movement of a robot. Based on the fuzzy classification inference rules for the measured IR distance data, we propose an effective solution of the pipe pattern recognition for pipeline monitoring robots.

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