Research article

Development of an autonomous in-pipe robot for offshore pipeline maintenance

Zhongwei Wang
Research Institute of Robotics, Shanghai Jiao Tong University, Shanghai, China, and

Qixin Cao, Nan Luan and Lei Zhang
Institute of Welding Engineering, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, China

Abstract

Purpose – The purpose of this paper is to develop a novel autonomous in-pipe robot to perform the preventive point reparation for long-distance offshore oil pipelines.

Design/methodology/approach – The autonomous in-pipe robot performs online ultrasonic inspection for pipe wall thickness, and the original inspection data are stored in large capacity hard disk. Through the offline data analysis by the data analysts and the software tool, the pipeline health status is known. If server defects lie there, the in-pipe robot is introduced into the pipeline once more to indicate the defect's location to the maintenance ship.

Findings – The laboratory tests and the field tests prove the feasibility and validity of the developed autonomous in-pipe robot. Furthermore, the application of intelligent control techniques ensures the mission completion by the autonomous in-pipe robot, which worked in the awful pipeline environment.

Practical implications – The developed autonomous in-pipe robot helps eliminate lost production costs and pipeline downtime caused by leakages and guarantees the safe run of offshore oil pipelines.

Originality/value – For the application of the autonomous in-pipe robot, there are no special requirements for maintained pipelines themselves, so it is applicable to the point reparation for most long-distance welded offshore pipelines.

Keywords Pipelines, Maintenance, Robotics, Ultrasonic devices, Inspection, Intelligent sensors

Paper type Research paper

1. Introduction

Recently, offshore oil pipelines are the most energy-efficient, safe, environmentally friendly, and economic way to transport crude oil over long distance from an oil well/oil terminal in the sea to an refinery/oil storage device on land. However, for the long-term erosion of transported materials and environmental effects, flaws can appear and grow on the walls of pipelines. As a result, there exist potential pipeline leakages. Any failure of these offshore pipelines will not only affect productivity negatively, but also cause tremendous environmental hazards. So, this issue has motivated the development of effective methods for leak detection and pipeline maintenance.

In the reviewed work, the pipeline leak detection systems were developed and successfully applied to detecting and locating the breaks in transport pipelines (*Journal of Offshore Technology*, 2004; Henrique *et al.*, 2005; Feng and Zhang, 2005; Lin and Zhang, 2006). The system works based on detecting an abrupt break-induced pressure wave. The pressure wave travels in both directions away from the break point and is reflected at the pipeline boundaries. Using the pressure wave, data measured at one location along the pipeline, the time of the initial and reflected transient waves induced by the break determines the location of the break. The pipeline leak detection system performs a continuous monitoring for pipeline operation and helps to find pipeline leakage in time to minimize the losses, but it cannot prevent and avoid pipeline leak. Besides, localization error of the leakage point is usually several hundred meters, and it brings tremendous difficulty to implement the offshore pipelines maintenance (Feng and Zhang, 2005; Lin and Zhang, 2006). To implement the preventive pipeline maintenance and then completely avoid leakage losses caused by metal corrosion, the pipeline inspection devices, commonly referred to the intelligent pig, were developed to implement the regular pipeline inspection (Okamoto *et al.*, 1999; Reber *et al.*, 2002; Yu *et al.*, 2005; Lopez and Sadovnychiy, 2007). The devices run through all the length of the pipelines to detect potential

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/0143-991X.htm

Industrial Robot: An International Journal
37/2 (2010) 177–184

[DOI 10.1108/01439911011018957]

This work was supported by National "863" High Technology Research and Development Program of China (2001AA602021) and partially by Natural Science Foundation of China (50705054).

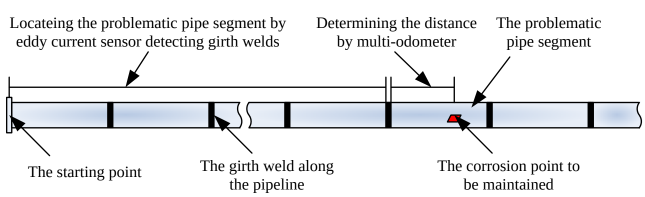
leaks and their location coordinates. According to the detection results, the point reparations for those severe defects are performed, which is a relatively cost-saving and easily implemented maintenance method. To adopt the maintenance method, the necessary precondition is that the detected pipelines must be equipped with magnetic markers every certain distance and their coordinate information is known. Correspondingly, the pipeline inspection device is equipped with special magnetometer and strap-down inertial navigation system (SINS). When performing pipeline inspection, the magnetometer can reliably detect magnetic markers along the pipelines and their known coordinate data are used for the correction of the SINS measurement. Consequently, the pipeline inspection device achieves the pipeline inspection and also acquires the precise location coordinates of those detected corrosion points (Yu *et al.*, 2005; Lopez and Sadovnychiy, 2007). However, most offshore pipelines are not equipped with magnetic markers because when laying pipelines, the business of maintenance in the future was not adequately taken into consideration. Therefore, the maintenance method cannot apply to most offshore pipelines.

Considering that most offshore oil pipelines are welded from fixed-length steel pipe segments and the girth welds along the pipeline can roughly indicate the locations relative to the starting point of the pipeline, A novel approach for precisely locating the corrosion inside the pipelines is proposed, which first locates the problematic pipe segment by eddy current sensor detecting girth welds, and then determines the distance from the forward girth weld of the problematic pipe segment to the corrosion point by multi-odometer. Based on the localization method, an autonomous in-pipe robot is developed to detect the potential leaks in long-distance offshore pipelines and implement point reparation for them. This paper presents in detail the design and implementation issues related to the autonomous in-pipe robot. Also, intelligent control techniques are applied to ensuring the mission completion by the autonomous in-pipe robot, since it works in the awful pipeline environment (Figure 1).

2. General description of the autonomous in-pipe robot

The autonomous in-pipe robot is shown in Figure 2 and an overview of the design specifications is provided in Table I. The in-pipe robot's mechanical structure is composed of an electric crawler and nine cylindrical sealed cabins, and they are all connected together via hook joints, which allow the in-pipe robot to negotiate 3D bends. The sealed cabins are supported by tensioner wheels, which not only keep them centered in the pipe but also adapt to pipe diameter deformation in a certain extent. Three tensioner wheels are

Figure 1 The schematic of precisely locating the corrosion inside the offshore pipelines



also used as the odometer wheels to measure the traveled distance of the in-pipe robot inside the pipeline. Inside the sealed cabins are electric crawler controller, power supply which includes four cabins, intelligent controller, extra low frequency (ELF) emitter, data-processing module, and ultrasonic inspection module.

The electric connection among all units of the in-pipe robot is shown in Figure 3. The nine sealed cabins are interconnected by two power cables for 24 V DC supply and two signal cables for controller area network (CAN) bus. In addition, electric crawler controller supplies the driving current for the electric crawler and the ultrasonic inspection module transmits sensor data to the data-processing module with multi-cable connection. For the waterproof protection, the electric connection wires are all enclosed in sealed hosepipes. Furthermore, the detail about the in-pipe robot modules will be introduced in the following text.

2.1 Electric crawler and electric crawler controller

The electric crawler and the electric crawler controller are traction devices for the in-pipe robot moving through the inspected pipeline. The electric crawler, shown in Figure 4, has six wheeled driving arms fixed circumferentially with 60° apart on the outside of body frame. The driving wheels are located on the end of driving arms and there are motors built in the driving arms. The motors control the wheels, respectively, to form the driving mode of six independent driving wheels. The electric crawler features with compact structure, great transmission efficiency and big tractive forces, and provides the moving speed from 50 to 240 mm/s for the in-pipe robot. The electric crawler controller receives control instructions such as start-stop, moving direction, moving speed, etc. from intelligent controller and supplies the corresponding driving current for the electric crawler.

2.2 Power supply

The power supply module is fitted with Li batteries and provides 24 V, the maximum 30 A and over 40 h DC for the in-pipe robot system. The Li batteries are rechargeable for 20 times approximately and have an available period of two years. The power supply module monitors the battery energy utilization and the residual capacity, and feedbacks the battery working status to intelligent controller as the basis for its decision making.

2.3 Intelligent controller

The intelligent controller is the control center of the autonomous in-pipe robot. We adopted an embedded pc104 industrial computer as the core to meet the need of complex control calculation. To facilitate compiling program code and debugging them, the development of the intelligent control software is based on an embedded Linux system, which runs on the pc104 computer. Based on CAN bus, the intelligent controller sends control instructions to other modules and receives feedback messages from them, too. The feedbacks include the control instruction confirmation, the modules' working status and the sensor data. Before performing the pipeline maintenance, the mission objective and intelligent control algorithms are download into the intelligent controller, and then based on the receiving sensor data, it makes decisions to achieve the mission. Besides, when encountering an emergency, such as power supply failure and electric crawler malfunction, the instruction of emitting

Industrial Robot: An International Journal
Volume 37 · Number 2 · 2010 · 177–184

Figure 2 Outside view of the autonomous in-pipe robot

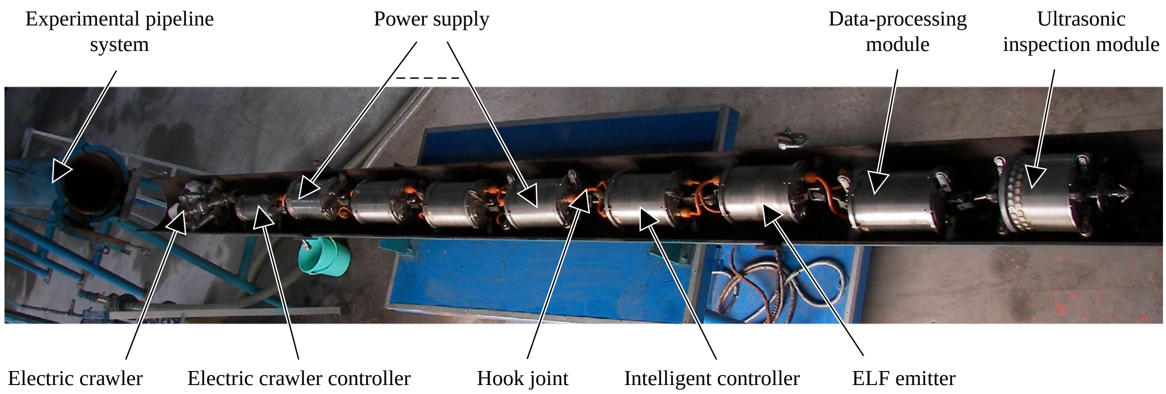


Table I The main design specifications of the autonomous in-pipe robot

The main design specifications	Data
Number of bodies	10
Length	Approx. 5,670 mm
Diameter	320 mm
Weight	Approx. 300 kg
Moving speed range	From 50 to 240 mm/s
Pipeline inspection distance range	Approx. 20 km at the speed of 150 mm/s
Minimum bend radius	3D
Permitted pipeline deformation	2 percent of the pipeline diameter

emergency signal is send to the ELF emitter module to get rescue for the in-pipe robot.

2.4 ELF emitter

The early offshore pipeline inspection devices used isotopes for tracking and locating the equipments. The restricted use and combined operational limitations of isotopes led to the development of a new tracing method – the ELF signal (ELF wave) for its better penetration capability (da Silva *et al.*, 2004; Chen *et al.*, 2006). Experiment showed the ELF signal has the characteristic of penetrating through metal pipe, subset sediments and seawater (Chen *et al.*, 2006). The characteristic meets the requirements in this application, so the in-pipe robot is equipped with an ELF emitter to indicate its location to the exterior – maintenance ship. The effective communication distance between the ELF emitter and the ELF signal receiver located on the maintenance ship is 11 m, approximately. The sealed cabin for the ELF emitter, shown in Figure 1, also contains batteries as emergency power for emitting emergency signal in case of power supply failure.

2.5 Ultrasonic inspection module and data-processing module

The ultrasonic inspection module contains 64 channel ultrasonic sensors to detect pipe wall thickness of the pipeline. As shown in Figure 5, the ultrasonic sensors are divided into two circles with 32 sensors for each circle, and the two circles of ultrasonic sensors are regularly staggered to ensure full circumferential coverage of the pipe. The ultrasonic sensors work in a pulse-echo mode with a selected center frequency. The acoustic wave, emitted by the ultrasonic sensors, travels in the liquid medium and is reflected at reaching the inner- and outer-wall of the pipe. The time of flight between the echoes from the inner- and outer-wall is related to the pipe thickness and can be used to evaluate the metal corrosion of the pipeline. The center frequency of the ultrasonic sensor relates to its detection resolution and detection distance. The greater the ultrasonic sensor frequency is, the shorter the wavelength is and

Figure 3 Schematic diagram for electric connection among the in-pipe robot units

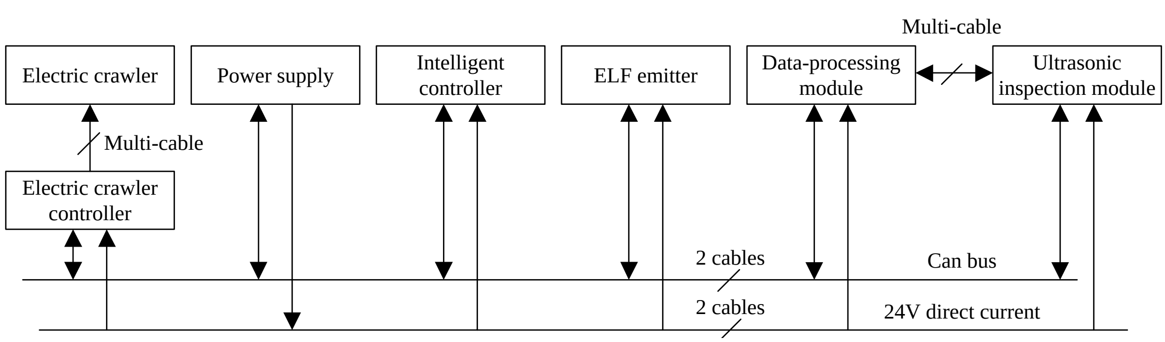


Figure 4 Mechanical model of the electric crawler

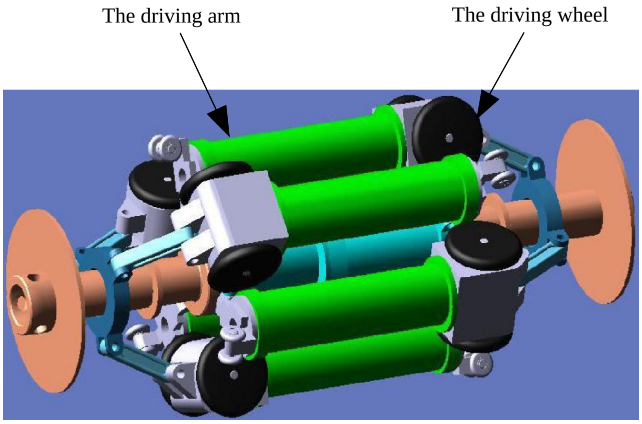
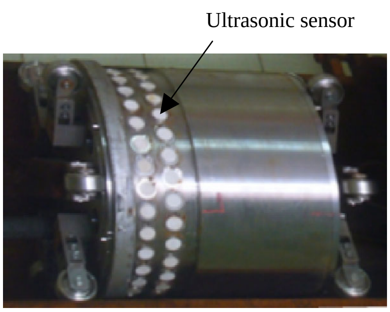


Figure 5 Actual photograph of the inspection sensor module



therefore the better is the detection resolution. However, the acoustic attenuation in the liquid medium exponentially increases with the frequency increase. So, as a compromise, 5 MHz ultrasonic sensor frequency is selected as the solution for this application. Then, the ultrasonic sensor equipped on the inspection sensor module has a beam width of 1.8 mm and its detection distance is 40 mm.

The ultrasonic inspection module also contains 1 eddy current sensor to detect the girth welds along the pipeline, whose induction coil, as shown in Figure 6, is located on the cross-section of the sealed cabin. Based on the sensitivity to different electromagnetism characteristics between girth weld material and steel pipe material, the eddy current sensor is utilized to detect girth welds.

The data-processing module compresses and stores the sensor data from the ultrasonic inspection module. Usually, the pipeline inspection devices online evaluate the defects and extract their features during the pipeline inspection, and only the defects' feature data and their location data are stored for performing the subsequent defect reparation (Okamoto *et al.*, 1999; Reber *et al.*, 2002). For this project, based on the digital signal processor + field-programmable gate array techniques, the high-speed data acquisition system is developed to AD-convert and compress the total inspection data, and then they are stored in large capacity hard disk. Later, the stored original inspection data can be used for the offline pipeline evaluation to investigate the pipeline's whole health status rather than the local defects. Besides, since the professional data analysts can participate in the offline evaluation work, so it is more precise and reliable than the automatic online evaluation mentioned above.

3. Operation process for the offshore pipeline maintenance

The entire operation process for performing the point reparation in offshore pipelines with the in-pipe robot includes four steps: preparations for the in-pipe inspection, online pipeline inspection, offline data analysis and point reparation for the defect, and the details of the operation process are shown in Figure 7.

As the preparation work for the in-pipe inspection, the cleaning operations for pipeline internal surface are performed with cleaning pigs, which is necessary to obtain good quality inspection data during the online pipeline inspection; then the geometry inspection is performed to measure the pipeline's cross-section by applying a caliper tool, which ensures the safe passage through the long-distance pipeline by the in-pipe robot. For the online pipeline inspection, the autonomous in-pipe robot passes through the whole pipeline at the speed of 150 mm/s. The pipe wall thickness is detected by the ultrasonic sensors, and the location is synchronously got by the eddy current sensor detecting girth welds along the pipeline and the multi-odometer detecting the precise position between adjacent girth welds. The original inspection data are stored for the subsequent offline data analysis. After the in-pipe inspection, the inspection data are retrieved from the in-pipe robot for the offline data analysis. The software tool is developed to automatically analyze the ultrasonic data to obtain defect candidates, which reduces the number of indications to be manually checked. As shown in Figure 8, the software tool not only visualizes multi-ultrasonic sensor data in 2D image with the pseudo color, which uses a dominant color for defect areas, but it also displays A-scan view of any channel for accessing the relevant portions of the defect. For better

Figure 6 The layout of the eddy current sensor's induction coil in the sealed cabin

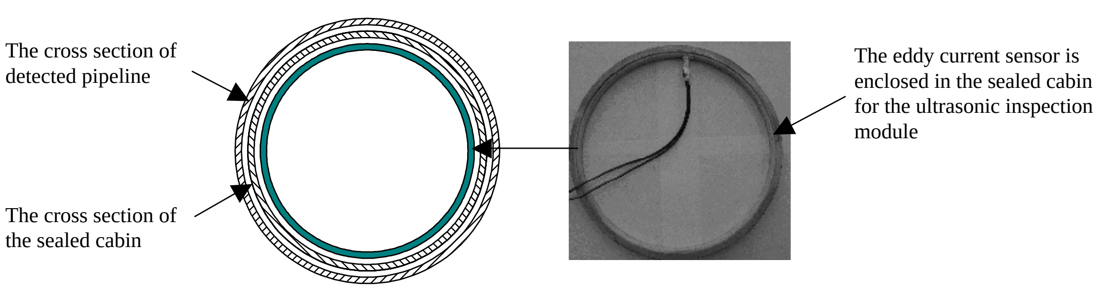


Figure 7 Schematic of the operation process for offshore pipeline maintenance

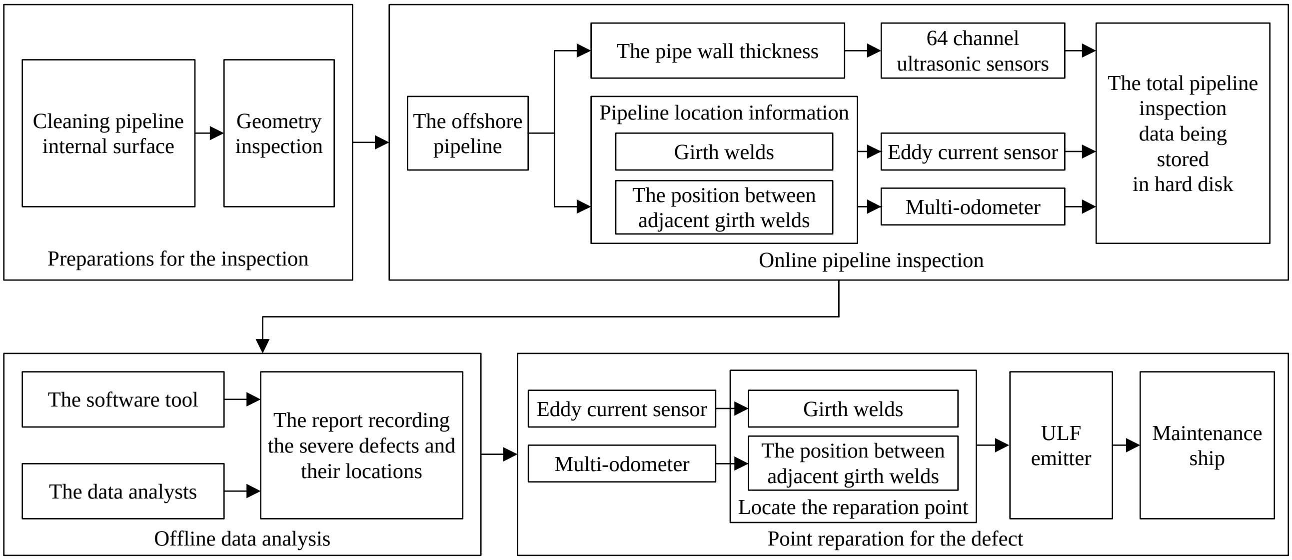
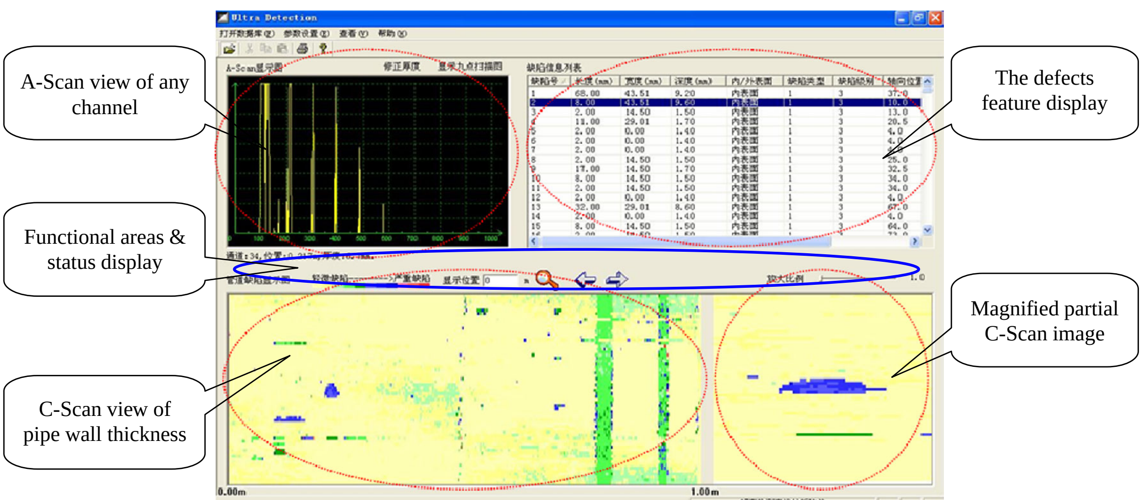


Figure 8 The screenshot of the software tool for inspection data analysis



accuracy, data analysts can check the feature of any defect candidate, such as its length, width, depth, and severity grade, which helps to the identification of the defects. When the offline data analysis is finished, the report of recording the severe defects and their location is got. To implement point reparation for the severe defect, their location data are downloaded into the intelligent controller and then the in-pipe robot is introduced into the pipeline again. By the eddy current sensor detecting the girth welds passed by and counting them, the autonomous in-pipe robot first locates the problematic pipe segment, and then by multi-odometer, it determines the distance from the forward girth weld of the problematic pipe segment to the reparation point. When arriving at the reparation point, the in-pipe robot stops to emit the ELF signal and the maintenance ship will receive it and therefore locate the reparation point. The reparation for the defect is done by the maintenance ship, and meanwhile, the in-pipe robot is taken out from the pipeline. Thus, the preventive point reparation for offshore pipelines is achieved.

4. The intelligent control techniques applied to the in-pipe robot

The autonomous in-pipe robot runs in the awful working environment of oil pipelines, where the detailed environment information is unknown even though the geometry inspection is performed in advance as described in section 3. After being introduced into the pipeline, the in-pipe robot runs autonomously and is no longer under the control of us. Some problems were exposed in the laboratory tests and field tests, which were induced by the awful pipeline environment and severely affected the in-pipe robot's usability. So it is necessary for the autonomous in-pipe robot to be provided with the adaptability and robustness to the interferential working environment, and the following intelligent control techniques are applied to achieve the purpose.

4.1 The intelligent localization technique

During performing the point reparation for the defect, to locate the problematic pipe segment depends on detecting the girth welds passed by. Therefore, whether the girth welds can be reliably detected determines the success or failure of the point reparation for the offshore pipeline. Plenty of underwater tests for detecting the girth weld by the eddy current sensor were dong, as shown in Figure 9, that when the sealed cabin of containing the eddy current sensor passed a girth weld, the gathered signal was converted into one pulse by converting circuit. And the test results indicate when the moving speed of the eddy current sensor, relative to the girth weld, is more than the threshold – 50 mm/s the girth welds can be inerrably detected. However, the jounce movement of the in-pipe robot and the abrupt drop of its moving speed, caused by the hindrance of welding beadings at girth welds, may induce the instantaneous speed to be less than the threshold. Therefore, the detection ability of the eddy current sensor is depressed and some girth welds may be undetected. Consequently, fault-tolerance processing for those undetected girth welds is performed to ensure correctly locating the problematic pipe segment by the in-pipe robot.

The fault-tolerance processing is based on the fact that after the in-pipe robot has moved a certain distance, there is one girth weld to be detected, so if not detecting girth weld, the judgment of one girth weld missed can be made and the counter of recording the girth weld passed by will be purposively modified to compensate the missed one. Here, we use production rule to represent the aforementioned fault-tolerance idea and the proposed rule is given as the following:

$$
\begin{aligned}
&\textbf{IF} < \text{Measured value by multi-odometer having passed} \\
&\qquad \text{the interval } (\alpha L, L/\alpha) > \\
&\quad \textbf{AND} < \text{Without detecting girth weld} > \\
&\textbf{THEN} < \text{One undetected girth weld occurs, the girth} \\
&\qquad \text{weld counter plus } 1 >
\end{aligned}
$$

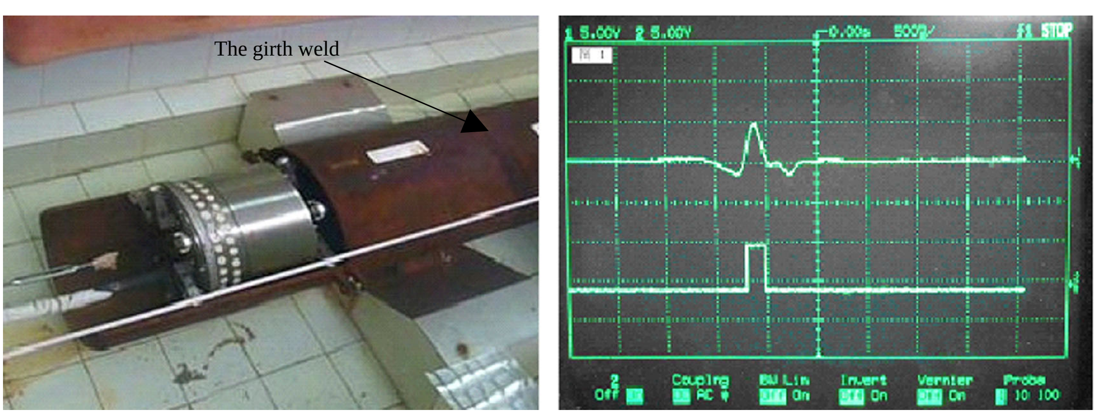
In the production rule, L is the length of steel pipe segments that offshore pipelines are made of and α ($\alpha \in (0, 1)$) is the reliability coefficient of the multi-odometer. The reliability coefficient means when the in-pipe robot moves L, the measured value is at least αL. Consequently, the following inferences are made for the case that one girth weld is detected and the next will be missed:

- when the in-pipe robot moves L, that is, it has not yet passed the next girth weld, the measured value by the multi-odometer must be in the interval (αL, L); and
- when the in-pipe robot moves L/α, that is, it has already passed the next, the measured value must be in the interval (L, L/α).

Therefore, when the measured value has passed the interval $(\alpha L, L) \cup (L, L/\alpha) = (\alpha L, L/\alpha)$, one girth weld is traversed by the in-pipe robot for certain, and if no girth weld is detected, then we infer one girth weld has been missed and the fault-tolerance is performed to compensate the missed. With the aforesaid method, we can perform fault-tolerance processing for successive multiple undetected girth welds.

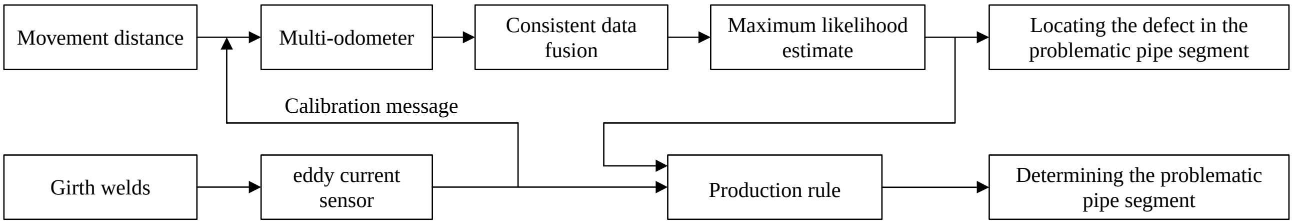
Generally, odometers are applied to the localization of automatic inspection devices inside the pipelines. Owing to the cumulative error effect, the longer the pipeline is, the lower the localization accuracy is. In this application, the girth welds along the pipeline are used as calibration messages for every L distance to insure high-localization accuracy by the odometers. That is, at detecting the girth weld, the register of recording the movement distance resets and anew records. So the odometers are applied to the localization between adjacent girth welds in most time and the fault-tolerance processing for the missed girth weld sometimes. For the point reparation of offshore pipelines, the more precise to locate the defect is, the easier the maintenance work is. To locate the defect precisely, three odometers are applied to obtaining the movement distance and the multi-sensor data fusion is adopted to merge the redundant movement distance data into more precise and reliable one. The odometers are easily disturbed in the awful pipeline environment, so the redundant movement distance data may be uncertain or not in agreement. Problems will arise in data fusion if any of sensor data are uncertain or contains biggish inaccuracy. Here, based on the consistent data fusion algorithm (Luo *et al.*, 1988; Mintz, 1990), the dubious sensor data are first eliminated before data mergence, so the rest are consistent or in agreement. Then the precise localization inside the pipelines is achieved by merging the consistent data with the maximum likelihood estimate algorithm (Luo *et al.*, 1988). Figure 10 is the schematic of data fusion for the multi-odometer and the eddy current sensor to achieve intelligent precise localization of the in-pipe robot inside the pipelines.

Figure 9 The underwater test of detecting girth welds



Industrial Robot: An International Journal
Volume 37 · Number 2 · 2010 · 177–184

Figure 10 The schematic of multi-sensor data fusion for the intelligent precise localization



4.2 Reactive self-rescue control for the autonomous in-pipe robot

The specially designed electric crawler, introduced in Section 2, can provide sufficient tractive forces for the in-pipe robot system; however, there still occurred the cases that it encountered the impassability inside the pipeline for unclear reason. When the emergency happens, the straightforward rescue method is to inform the maintenance ship by emitting ELF signals, and then the rescue activities is performed to locate the in-pipe robot, cut-off the pipeline and get it back. The rescue method can availably avoid the equipment loss, but the rescue activity is troublesome and meanwhile, it has to terminate the pipeline maintenance task. It expends many resources to perform the maintenance work with the in-pipe robot, and therefore the mission failure also means sever economic losses.

In the application field of autonomous mobile robots, researchers advocate that they should be provided with autonomous learning ability, which is to learn from self-exploration and observation without the need of examples or a teacher (Gachet *et al.*, 1994; Zalama *et al.*, 2002). Thus, the autonomous mobile robot will have certain adaptability for unstructured environment and unknown emergency. For this project, based on Q-learning algorithm (Watkins and Dayan, 1992), the motion control strategy of guiding the in-pipe robot through the impassability is proposed. When the emergency occurs, instead of immediately emitting the ELF signals for help, the autonomous in-pipe robot stops moving forward and falls back a certain distance, then it moves forward again at different speed to try to overcome the impassability. The trial process is repetitively performed. When one trial achieves good result that is, the in-pipe robot moves forward farther, the action is encouraged then, and the repetition of such action tend to problem solving. The self-rescue control skill of the autonomous in-pipe robot is got on line through the interaction between it and the pipeline environment, which helps to avoid the loss for the rescue activity and the mission failure. When the self-rescue strategy does not work, it is necessary to implement the mentioned rescue activity for the in-pipe robot.

5. Experimental results

The in-pipe robot was tested both in the laboratory and in the field. For the laboratory test, a 110 m length experimental pipeline system was constructed which was similar to the actual offshore transmission pipeline, and some artificial defects were made outside a pipe segment to determine the effectiveness of the ultrasonic inspection. The laboratory tests were implemented, using water as couplant medium. Figure 2 shows the in-pipe robot being introduced in the experimental pipeline. The test result was that the measurement error of pipeline wall thickness was less than 0.5 mm and the defects of corrosion area being more than $10 \times 10\,\mathrm{mm}^2$ could be reliably detected. Figure 11 shows the artificial defects on the experimental pipeline and their C-scan images for feature analysis.

The field tests, shown in Figure 12, were performed in a 3.5 km-length beach sea oil pipeline at Shengli Oilfield in Shandong Province, China. The test result was that by the intelligent localization technique, the in-pipe robot could reliably locate the repaired defect with the maximal localization error being less than 1 percent of the pipe segment. That is the maximal localization error approximates 20 cm when the maintained pipeline is made of 20 m length pipe segments. The location precision adequately meets the engineering requirement for implementing point reparation. Besides, the reactive self-rescue control technique helped to the passage through the pipeline by the in-pipe robot. In short, those tests showed the developed in-pipe robot was adequate to the preventive point reparation for the long-distance offshore pipeline.

6. Conclusion and future work

The development of an autonomous in-pipe robot for offshore oil pipeline maintenance was described in this paper. The test results showed the storage of original inspection data during the online inspection and the offline data analysis by data analysts combined with the software tool

Figure 11 The artificial defects outside a pipe segment and their C-scan images

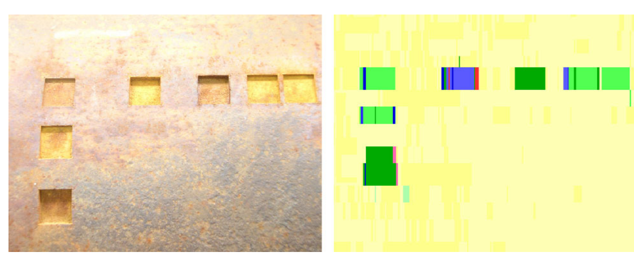


Figure 12 The in-pipe robot being introduced into the pipeline for field tests

Industrial Robot: An International Journal
Volume 37 · Number 2 · 2010 · 177–184

could achieve the reliable evaluation for pipelines' health status. To implement the point reparation for the severe defect, the intelligent localization technique was proposed to achieve reliable and precise localization for the defect, which was proven to meet the engineering requirement adequately. Besides, the reactive self-rescue control technique was adopted for the in-pipe robot to overcome the impassability in the awful pipeline environment, which effectively avoided the loss for the rescue activity and the mission failure. For the application of the in-pipe robot, there are no special requirements for maintained pipelines themselves, so it adapts to the point reparation of most welded offshore pipelines. Nevertheless, more tests in longer offshore oil pipelines will be conduced to verify the usability and reliability of the in-pipe robot before its practical application. And we will develop similar in-pipe robot for larger diameter offshore pipeline maintenance.

References

Chen, H.J., Zhang, X.H. and Li, J.Y. (2006), "Ultra low frequency electromagnetic wave localization and application to pipeline robot", *Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Beijing, China*, October, pp. 1201-5.

da Silva, J.A.P., de Jesus Ribeiro Afonso, O., Dos Santos, J.A.C., Matsuura, M., de Castro Antunes, R., de Freitas Santa Cruz, S. and Hashiguchi, D.I. (2004), "A smart location system", *Proceedings of the Biennial International Pipeline Conference, Calgary, Canada, October*, pp. 975-81.

Feng, J. and Zhang, H.G. (2005), "Diagnosis and localization of pipeline leak based on fuzzy decision-making method", *Acta Automatica Sinica*, Vol. 31 No. 3, pp. 484-90.

Gachet, D., Salichs, M.A., Moreno, L. and Pimentel, J.R. (1994), "Learning emergent tasks for an autonomous mobile robot", *Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Munich, Germany, September*, pp. 290-7.

Henrique, V.S., Morooka, C.K., Guilherme, I.R., Tiago, C.F. and Mendes, J.P. (2005), "Leak detection in petroleum pipelines using a fuzzy system", *Journal of Petroleum Science and Engineering*, Vol. 49 Nos 3/4, pp. 223-38.

Journal of Offshore Technology (2004), "Pipeline monitoring and control", *Journal of Offshore Technology*, Vol. 12 No. 5, pp. 15-17.

Lin, W.G. and Zhang, X. (2006), "A novel approach for dynamic pressure transducer based pipeline leak detection", *Proceedings of the 2006 World Congress on Intelligent Control and Automation, Dalian, China, June*, pp. 5299-303.

Lopez, J.M. and Sadovnychiy, S. (2007), "Small PIG for inspection pipeline", *Proceedings of the 2007 Electronics, Robotics and Automotive Mechanics Conference, Cuernavaca, Morelos, Mexico, September*, pp. 585-90.

Luo, R.C., Lin, M.H. and Scherp, R.S. (1988), "Dynamic multi-sensor data fusion system for intelligent robots", *IEEE Journal of Robotics and Automation*, Vol. 4 No. 4, pp. 238-41.

Mintz, M. (1990), "Comments on 'dynamic multi-Sensor data fusion system for intelligent robots'", *IEEE Journal of Robotics and Automation*, Vol. 6 No. 1, pp. 104-6.

Okamoto, J. Jr, Adamowski, J.O., Tsuzuki, J.C., Buiochi, M.G. and Camerini, F. (1999), "Autonomous system for oil pipelines inspection", *Mechatronics*, Vol. 9 No. 7, pp. 731-43.

Reber, K., Beller, M., Willems, H. and Barbian, O.A. (2002), "A new generation of ultrasonic in-line inspection tools for detecting, sizing and locating metal loss and cracks in transmission pipelines", *Proceedings of the 2002 IEEE Ultrasonics Symposium, Munich, Germany, October*, pp. 665-71.

Watkins, C. and Dayan, P. (1992), "Q-learning", *Machine Learning*, Vol. 8 Nos 3/4, pp. 279-92.

Yu, J., Lee, J.G., Park, C.G. and Han, H.S. (2005), "An off-line navigation of a geometry PIG using a modified nonlinear fixed-interval smoothing filter", *Control Engineering Practice*, Vol. 13 No. 11, pp. 1403-11.

Zalama, E., Gomez, J., Paul, M. and Peran, J.R. (2002), "Adaptive behavior navigation of a mobile robot", *IEEE Transactions on Systems, Man, and Cybernetics Part A: Systems and Humans*, Vol. 32 No. 1, pp. 160-9.

Corresponding author

Zhongwei Wang can be contacted at: wangzw@sjtu.edu.cn