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Basic study on ultrasonic remote leakage position estimation method for underwater exploration

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Leakage from the reactor containment vessel has become an issue related to the decommissioning of TEPCO HD Fukushima Daiichi Nuclear Power Station, and it is required to investigate the leak location from inside the containment vessel. The performance of CCD cameras used for in-core exploration deteriorates in muddy water environments. Also, long arm robots and underwater robots, which are expected to be used for exploration, have a problem of low positioning accuracy. Therefore, as a survey method, we focused on ultrasonic measurement, which has radiation resistance and applies to turbid water and made it an issue to investigate leak points and estimate self-position. Therefore, we have developed a sensor self-position estimation method using ultrasonic distance measurement. Also, flow mapping measurement was performed using the ultrasonic flow velocity distribution measurement (UVP) method to grasp the position of the leak location. We proposed a method to estimate the rough location of leakage points by weighting the intersection points of the obtained two-dimensional flow velocity vectors and creating a weighted histogram. We conducted a mock test using a robot to verify the validity and adaptability of the proposed method. From the experimental results, it was confirmed that the leak location can be estimated.

Keywords: Localization, UVP, Decommissioning, ultrasonic measurement, detecting locating

1. Introduction

The decommissioning of all units from Unit 1 to Unit 6 of TEPCO's Fukushima Daiichi Nuclear Power Station has been decided due to the damage caused by the massive tsunami following the March 11, 2011 earthquake in the Tohoku region. In Units 1-3, where core damage has occurred, decommissioning is underway in accordance with the medium- to a long-term roadmap published by TEPCO HD. The main decommissioning tasks are fuel removal from the spent fuel pools, fuel debris removal, and dismantling of the facilities. In fuel debris removal, emphasis is placed on the in-air method, and it is necessary to investigate and repair the leaking points of the containment vessel cooling water in order to remove the fuel debris.

In order to identify the location of the leak, it is still impossible to enter the reactor building 10 years after the accident because of the high radiation environment. Therefore, remote measurements using robots and engineering endoscopes are being conducted. Outside the containment vessel, several leaks have already been found by the leak location survey. However, it is difficult to detect all the leaks only from the outside. In order to detect and repair all the leaks, it is necessary to identify the leaks from inside the containment vessel.

Conventional methods of leak detection have been proposed, such as investigation of cracks on the wall surface by image analysis using CCD cameras [1], and investigation of suspected leaks by spraying tracer particles around the area and detecting the movement of the particles [2]. However, image analysis using a camera is insufficient because the target is in a dark and turbid water environment. In addition, the CCD camera is not radiation-resistant, so it is not possible to investigate the inside of the containment vessel for a long time.

On the other hand, remote measurement technology using ultrasonic waves has been attracting attention. Ultrasonic devices have been used to survey the distribution of fuel debris under high radiation conditions during the accident at the Three Mile Island Nuclear Power Plant Unit 2 [3], and are characterized by their high radiation resistance. In addition, it has been demonstrated that it can be used in turbid water environments. The Ultrasonic Velocity Profiler (UVP) [4] has been developed to measure the flow of tracer particles in a liquid by using ultrasonic echo signals. The UVP method can be used to measure the flow inside a containment vessel and to estimate the location of leaks from the flow pattern.

The position and orientation of the ultrasonic sensor in the measurement environment are important factors for estimating the location of the leak from the flow direction. However, the positioning accuracy of long arm robots and underwater robots, which are expected to be used for the survey, is low. In normal environments, posture recognition using cameras and laser surveyors is used, but as mentioned earlier, the inside of the containment vessel is a turbid water environment and a high radiation environment, so it is expected to be difficult to use conventional posture estimation mechanisms. In this study, we focused on SLAM (Simultaneous Localization and Mapping), which can simultaneously estimate the self-position and generate an environmental map, because the environment inside the reactor is unknown. The purpose of this paper is to explore the technical possibilities of self-localization and remote flow mapping measurement by applying ultrasonic sensors to SLAM technology.

2. Algorithm of leak detection method using ultrasound.

2.1 Development of location estimation technology

The objective of this study is to use ultrasonic sensors for self-positioning estimation to compensate for the amount of movement measured inside the robot. ICP [5] is an intuitive method that performs scan matching between two measurement results by alternating the mapping of measurement points and position estimation.

Initially, at a certain sensor position x_t^k, the distance of the surrounding horizontal surface is measured by TOF (Time of flight) using an ultrasonic sensor, and the measurement result is converted into measurement data. In this study, we use a stage to move a single−element ultrasonic sensor from the initial rotation position ϕ_0 to $\phi_0 + 2\pi - d\phi$ by $d\phi$, and measure the distance at each position. n is the number of sampling in the rotation direction.

The measured distance d_k in k steps is obtained as shown in Equation 1.

$$d_k = [d_k^1 \quad \cdots \quad d_k^i \quad \cdots \quad d_k^n] \tag{1}$$

By using the rotation matrix R^k and the translation vector t^k of x_t^k, we can obtain the position matrix p_i^k of the scan point in the sensor coordinate system from Equation 2.

$$p_i^k = R^k d_k + t^k \tag{2}$$

Next, find the point $q_{j_i}^k$ in the reference scan s_{t-1} that is closest to p_i^k for mapping. That is, find the point where the Euclidean distance from p_i^k is the smallest as shown in Equation 3, and make it $q_{j_i}^k$. Here, denote the point number j of s_{t-1} corresponding to the point number i of of s_t.

$$q_{j_i}^k = argmin\|p_i^k - q_j^k\| \tag{3}$$

To evaluate the position estimation, the mean square of the distance between each point is calculated from Equation 4 according to the obtained correspondence.

$$G_1(x_t^k) = \frac{1}{N}\sum_{i=1}^{N}\left\|(R^k p_i + t^k) - q_{j_i}^{k-1}\right\|^2 \tag{4}$$

To estimate the robot position, we use the steepest descent method to find x_t^k where the evaluation function $G_1(x_t^k)$ is minimized.

To determine the end of the ICP iteration, the difference between the minimum value of $G_1(x_t^k)$ and the minimum value of $G_1(x_t^{k-1})$ is less than a threshold value according to Equation 4.

2.2 Ultrasonic velocity distribution measurement method

Ultrasonic Velocity Profiler (UVP) is a measurement technique that uses ultrasonic waves to measure the velocity distribution of a liquid. When small particles are dispersed in a liquid and ultrasonic pulses are transmitted from a sensor along a measurement line, echo signals are reflected from the small particles moving in the liquid. This reflected wave is continuously acquired by the sensor. The acquired echo signal is affected by the Doppler effect caused by the velocity of the reflector. The Doppler frequency can be obtained from the continuously acquired echo signals. The Doppler frequency $f_D(i)$ is related to the velocity of the particle, and the velocity $V(i)$ of the particle at a certain position i can be calculated from Equation 5.

$$V(i) = \frac{cf_D(i)}{2f_0} \tag{5}$$

f_0 is the fundamental frequency of the ultrasonic wave, α is the angle of incidence, and c is the speed of sound in the liquid. The distance $x(i)$ from the ultrasonic sensor is calculated using Equation 6.

$$x(i) = \frac{ct(i)}{2} \tag{6}$$

The flow velocity measurement in UVP has a problem of uncertainty of the measured value near the wall. In other words, it is sometimes difficult to measure the flow velocity accurately near the wall because the reflected ultrasonic wave becomes noise. In particular, it is difficult to cope with this problem when measuring the velocity distribution over a wide area such as in the case of in-core exploration. In this study, we propose a method to estimate the rough location of leakage points by using kernel density estimation based on the intersection distribution of the measurement results.

Kernel density estimation [6] is one of the non-parametric methods to estimate the establishment density distribution of a random variable. In the reactor environment, it is difficult to obtain an appropriate parametric model because the number and spacing of leaks are unknown. Therefore, we adopted this estimation method, which has fewer processes for the distribution. Since the accuracy of kernel density estimation decreases with high-dimensional data, we decided to perform the estimation in one dimension in this study.

Suppose that n two−dimensional flow velocity vectors are obtained by measurement. The intersection points $(x_{i,j}, y_{i,j})$ on the extension line of two arbitrary velocity vectors $V_i, V_j (0 \leq i, j \leq n, i \neq j)$are calculated and the weight $w_{i,j}$ is calculated. This time, the weighting is the product of the magnitudes of each velocity vector. However, if there is no intersection point, the weight is 0.

Since the absolute value of the velocity vector near the leakage point is large and its contribution to the estimation is considered to be high, we assume that $w_{i,j}$ points exist at the intersection points $(x_{i,j}, y_{i,j})$, and create a histogram for each of the x and y axis. This is treated as a weighted histogram $m^w = (m_x^w, m_i^w)$. For the weighted histogram, we estimate the kernel density distribution as in Equation 7.

$$\hat{f}_h(m^w) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{m^w - m_i^w}{h}\right) \tag{7}$$

As the kernel function, we adopted a Gaussian function with 0 mean and 1 variance as shown in Equation 8.

$$K(x) = \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \tag{8}$$

This method is expected to provide a rough estimation of the location of leaks over a wide area.

3. Leakage point investigation experiment

3.1 Equipment and method of leak point investigation experiment

To validate the methods proposed in Section 2.2 for measuring the flow velocity distribution and estimating the location of leaks, an experiment simulating a robotic survey is conducted. A polyvinyl chloride pipe (O.D. 26 mm, I.D. 20 mm) is attached to the wall of the tank as a simulated leak point. A pump was used to draw water from the leakage point, and a discharge outlet was placed on the other side of the tank to circulate the water and construct a flow field. A pulse receiver (JPR-600C, National Instruments) was used to transmit and receive ultrasonic waves, and an A/D converter (NI USB-5133, National Instruments) was used to store the received signals in a PC. A robot was used to control the position of the sensor.

The sensor-transport robot used in this experiment was designed as a mock-up of a long arm robot [7], which is being studied for decommissioning in the Suzumori-Endo Laboratory of the Tokyo Institute of Technology. This robot consists of a body and a robot arm. The payload of this arm robot is 1.94 kg, and the paw is equipped with a rotating stage and an ultrasonic sensor. The payload of the robot arm is 1.94 kg. We used this robot to control the position and direction of the sensors and perform measurements.

3.2 Equipment and method for leak point investigation experiment

Figure 1 shows the results of the position estimation of the arm in the simulated test, and the error between the hand position calculated from the forward kinematics and the actual position based on the encoder values mounted on the robot. The error means, error deviation, and maximum error of each result are shown in Table 1. It was confirmed that the position estimation was much more accurate than the hand position recognized by the robot.

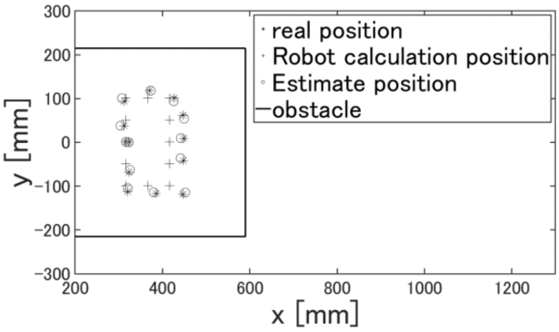


Fig. 1 Results of localization and Robot calculation

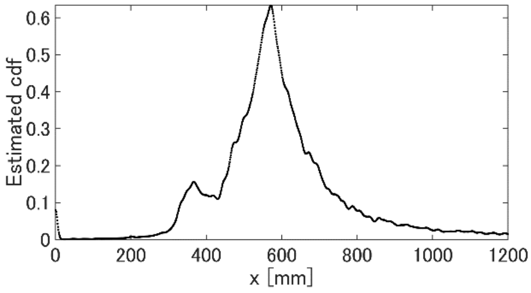
Table 1: Localization Result

	Average error[mm]	Standard deviation of error[mm]	Maximum error [mm]
Localization	9.61	10.3	9.89
Robot calculation	17.52	21.7	16.5

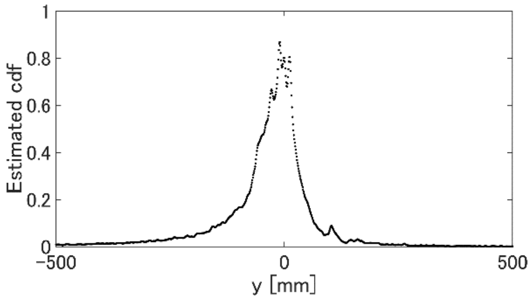
Table 2: Parameter configuration of UVP systems

Parameter	Value
Basic frequency	2 MHz
Pulse repetition frequency	0.5 kHz
Number of repetition	256
Spatial resolution	1.5mm

The parameters of the UVP measurements are shown in Table 2. As a result, 1031 two-dimensional velocity vectors were obtained by synthesizing the velocity vectors from the measurement results on the measurement lines of each UVP measurement. The weighted histograms on the x and y axes were obtained by weighting the intersection points of the obtained two-dimensional velocity vectors by the product of the magnitudes of the vectors.



(a) x-axis



(b) y-axis

Fig. 2 Results of localization and Robot calculation

Kernel density estimation was performed on this histogram. We then normalized the overall probability to obtain the estimated establishment density for each axis. The results are shown in Figure 2. While the actual leakage points were $x = 600$ mm, $y = -13$ mm, the estimated leakage points obtained from the probability density estimation were $x = 570 \pm 20$ mm, $y = -10 \pm 10$ mm.

6. Summary

In this study, a basic study of an underwater ultrasonic exploration system for decommissioning of nuclear reactors was conducted. Long-arm robots and underwater exploration robots used for decommissioning have a problem of low accuracy in position estimation. In addition, because of the high radiation environment in the reactor, the number of sensors that can be used is limited. Therefore, we developed a self-positioning system using a mechanical encoder with high radiation resistance and an ultrasonic sensor. In the experiment, it was confirmed that the self-position can be estimated with higher accuracy by using the ultrasonic distance measurement technique and correcting the error in the amount of movement.

In addition, we combined the results of the above self-position estimation with the flow mapping system using the UVP method and conducted a simulated leak location estimation experiment using an actual device. It is suggested that the rough location of the leak can be estimated by correcting the sensor position by self-position estimation and expressing the flow velocity measurement results as a weighted histogram.

Future work includes the development of a detailed in-vessel survey system by combining multi-dimensional UVP measurement and ultrasonic imaging technologies and a study of its applicability. In particular, since the in-vessel environment requires a three-dimensional measurement rather than a two-dimensional survey, we believe that extending the UVP method to three dimensions will enable fast and reliable measurements.

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