ABSTRACT

A vehicle system based on a new concept is developed for narrow space inspections in nuclear power plants. The system is named the tandem underwater vehicle system and it consists of a small inspection ROV (Remotely Operated Vehicle) and a support ROV which supports movement of the inspection ROV. The support ROV needs a hovering control function which consists of detection sensors for position and attitude angle. In this system, the self-position is detected by a light sectioning method and an image correlating method. Evaluation experiments showed that position can be detected accurately, and the hovering control function is confirmed to be sufficiently applicable in narrow sections.

INTRODUCTION

When inspections in the reactor vessel of nuclear power plants are carried out, sometimes ultrasonic testing and eddy current testing are carried out after visual testing (VT). When VT is carried out, an underwater camera system or a remotely operated vehicle (ROV) may be used. Especially, in the narrow sections, such as the bottom of the vessel, a small ROV is needed. However, since the weight of the motor which the small ROV can carry is restricted, it becomes difficult to get sufficient driving force for pulling a long cable. So, we developed a tandem underwater vehicle system which consists of a small inspection ROV which carries the camera, and a support ROV which supports the movement of the inspection ROV [1]. Although tandem underwater vehicles have already been developed for oceanic uses, they are premised on use in open spaces. Therefore, the vehicle thrusters and stabilizers, etc. are placed in an ideal arrangement without much concern for a final large vehicle size. Application of these tandem vehicles to reactor vessel inspections with manoeuvring size restrictions would be difficult. Then, we developed the tandem underwater vehicle system with a form and size applicable in reactor vessels. Moreover, after the inspection ROV is separated from the support ROV, the latter carries out hovering operations while handling the cable connecting it to the inspection ROV until the two are rejoined. In this case, the hovering control function must be able to detect the self-position and to hover in a fixed area. In this report, we show evaluation results on movement of the manufactured vehicle system, and evaluation results on the position detection function and the hovering control function.

PROTOTYPE OF THE TANDEM UNDERWATER VEHICLE SYSTEM

COMPOSITION OF THE SYSTEM

The form and size of the ROV are designed according to the environment. Fig. 1 shows a schematic drawing of a reactor vessel and an application of the tandem underwater vehicle system carrying out VT in a narrow section of the shroud support lower part. The tandem vehicle first approaches the bottom of the vessel. The inspection ROV is released from the support ROV, and the latter guides the inspection ROV to the narrow section where the inspection is to be carried out. A winch for handling the cable linked to the inspection ROV is installed in the support ROV, and the cable delivery length is adjusted so that the tensile force of the cable does not hinder movements of the inspection ROV.
THE INSPECTION ROV

Fig. 2 shows a schematic of the inspection ROV. To allow movement in three dimensions, the inspection ROV has three built-in actuators, the thruster for order movement, the screw for right-and-left revolution, and the weight balance adjustment mechanism for pitch angular transformation. Moreover, it carries a CCD camera and lighting (in the form of LEDs). When moving, the CCD camera is used for monitoring the surroundings of the inspection ROV and for carrying out VT. The camera can view a wire with a diameter of 25 micrometers which is sufficient performance for VT in the reactor vessel.

THE SUPPORT ROV

Fig. 3 shows a schematic of the support ROV. The circular hole in the reactor core plate (Fig. 1) is the item restricting the size of the support ROV. The hole is 270mm in diameter and the support ROV was designed with a diameter of 250mm. Furthermore, one CCD camera is carried in the front and another in the back for viewing the surroundings when moving, and for implementing the self-position detection function described later. The support ROV has two kinds of thrusters, one kind for vertical movement and the other for horizontal movement. Fig. 4 shows their arrangement. There are two thrusters for vertical movement and three thrusters for horizontal movement. The horizontal movement thrusters are arranged around the central winch which handles the cable linking the support ROV and the inspection ROV. These three thrusters are also used for yaw rotation. The rotational frequency of the horizontal movement thrusters is adjusted using the vector control mentioned later.
The cable is a flexible neutral buoyancy type which does not interfere with movement of the small inspection ROV. Since the cable is a signal line, it signals between the two ROVs. The cable length is controlled by the winch and a pulley and drum mechanism. After the inspection ROV has been separated from the support ROV, the support ROV must handle the cable (i.e. change its length) according to the inspection ROV movements. Therefore, the support ROV must have a hovering control function in order to hover in a fixed area while the inspection ROV is working. The hovering control function consists of a function which detects self-position and attitude angle, and a control function which determines the amount of operation of the thrusters. The attitude angle in the position detection function is detected by a 3-axis gyroscope and a geomagnetic sensor and a tilt meter installed in the sensor unit (Fig. 3). On the other hand, the self-position is computed by the optical cutting method and the picture correlating method using the slit laser light source and the CCD camera.

EVALUATION OF THE TANDEM VEHICLE SYSTEM OPERATION

Fig. 5 shows a sample picture taken during operation of the tandem underwater vehicle system; the inspection ROV has just left the support ROV. The following items were confirmed in the evaluation.

1. The support ROV is able to move in three dimensions, while the inspection ROV remains in its stored position in the support ROV.
2. The support ROV is able to release the inspection ROV from the stored position and make it stop and start.
3. The winch of the support ROV is able to release and retract the cable and signals are transmitted through the cable.

HOVERING CONTROL FUNCTION

CONFIGURATION OF THE HOVERING CONTROL SYSTEM

Fig. 6 shows a configuration block diagram of the hovering control system. The initial position and attitude angle are taken as the position and attitude angle of the support ROV at the time hovering control is started. The present position and attitude angle are computed by the control unit using information obtained by the support ROV sensor and CCD camera. The initial position and the attitude angle are compared to the present position and attitude angle, the controlled variable of each thruster is computed, and the voltage to be sent to each thruster motor is determined. The hovering operation is realized by repeating these steps to keep the support ROV at the initial position and attitude angle. In designing the hovering control system, the targeted movement from the control start position had to be less than 0.1m based on size restrictions of the spaces in the reactor vessel. Moreover, in order to
attain this target, the positioning error had to be less than 0.05m, and the attitude angle error had to be less than 5 degrees.

POSITION AND ANGLE DETECTION

The inside of the reactor vessel has many structures, and since it is difficult to apply an absolute position detection system using external sensors, such as ultrasonic sensors, we examined an inertial navigation system using an inner sensor. Fig. 7 shows a block diagram of the position and angle detection function. The attitude angle (roll, pitch, and yaw) is detected using the gyroscope, tilt meter, and geomagnetic sensor. Usually, when computing an angle using a small gyroscope without a processing circuit, there is a problem that the error generated when integrating the detected angular velocity is accumulated. So, in this system, we used the method of presuming the optimal value using a Karman filter. The position is computed by processing a camera image. The back and front position is computed by the optical cutting method which uses the slit laser. Moreover, the position of the upper and lower sides and the position right and left are computed from the speed computed using the picture correlating method.

Fig. 8 shows a block diagram of the attitude angle processing which used the Karman filter. The gyroscope, tilt meter, and geomagnetic sensor are used in this process. Among them, although it causes an accumulation error, the gyroscope is not influenced by a magnetic field environment, and since it has a rapid response, it is used as the main sensor. On the other hand, although the tilt meter and the geomagnetic sensor have a systematic error under the influence of a magnetic field and there is a problem that their response is bad, since there is no accumulation error, they are used as sensors for compensation of the gyroscope. In addition, the geomagnetic sensor is set for yaw detection and the tilt meter is set for roll and pitch detection. In Fig. 8, the signal which is assumed measurement noise of the detection angular velocity of the gyroscope is superimposed first, and an attitude angle is computed by mathematical integration. Next, the output of the sensor for compensation is presumed...
using the defined sensor model and the computed attitude angle. The model for the tilt meter and the geomagnetic sensor is an angle-voltage conversion factor, and it is a constant peculiar to each sensor. Next, virtual noise is superimposed on the actual output detected by each sensor for compensation, and the difference with the output of the sensor for compensation presumed previously is taken. Correction of the attitude angle is repeated so that this value becomes the minimum, and the optimal value of the attitude angle is output. Fig. 9 shows the results obtained in the attitude angle detection. The true results were measured results obtained by fixing a jig to a unit which carried three kinds of measurement sensors, and rotating the jig ±30 degrees for roll, pitch, and yaw movements. We confirmed that the maximum error is less than 5 degrees in this range.

The position of back and front is computed using an optical cutting method. In the method, the distance to a target is measured based on the laser position in a picture which was previously irradiated by the slit laser light. Fig. 10 shows the principle. The axis of a slit laser light source is parallel to the optical axis of the camera. The position (pic1 pixel) of a laser image from the vertical direction center in a picture is computed. Next, the distance between the optical axis of the laser light source and the camera is set to ‘d’, the vertical field of view angle of the camera is set to ‘β’, half of the total number of pixels of the vertical direction of the picture is set to ’pic2’, and the distance ‘L’ to the target is computed using formula (1). Finally, the position of back and front is computed by adding the amount of change of distance ‘L’ to the initial position.

\[
L = \left(\frac{d}{\tan \frac{\beta}{2}}\right) \cdot \left(\frac{\text{pic2}}{\text{pic1}}\right) \Lambda (1) \\
\delta y = L \cdot \tan \frac{\alpha}{2} \cdot \left(\frac{\xi}{\text{pic3}}\right) \Lambda \Lambda (2) \\
\delta z = L \cdot \tan \frac{\beta}{2} \cdot \left(\frac{\eta}{\text{pic2}}\right)
\]

On the other hand, the vertical and horizontal position is computed using the picture correlating method. Fig. 11 shows the principle. First, the template pattern used for picture correlation is cut out of the picture taken at Time ‘i-1’. Next, a search area is specified in the picture taken at Time ‘i’, correlation processing is performed, and the shift amount (\(\xi, \eta\)) for which the correlation value becomes the largest is calculated. Using formula (2), the speeds \(\delta y\) of the right-and-left direction and \(\delta z\) of the vertical direction are computed, and the vertical and horizontal position is computed by integrating in the initial position. In this formula, ‘pic2’ is the half value of the total number of pixels of the vertical direction of the picture, and ‘pic3’ is the half value of the total number of pixels of the right-and-left direction, and ‘\(\alpha\)’ and ‘\(\beta\)’ are the horizontal and vertical angles of fields of the camera.
In addition, when computing y and z using formula (2), the back and front distance ‘L’ is used. Therefore, the laser image used for the optical cutting method sets up the domain that it may be contained in the template pattern. Fig. 12 shows the results of the position detection. Moreover, Fig. 13 shows an example template picture obtained in an evaluation examination. In this examination, the mock-up of the structure in a reactor was installed in front of the sensor unit, and it was made to move in the front and rear, and right and left vertical directions by 0.3m, for each. We confirmed that the error of position detection is a maximum of 0.05m.

CONTROL FUNCTION

Since horizontal movement, rise and fall movements, revolution, etc. are simultaneously done in order to get the support ROV to hover, it is necessary to control each thruster appropriately. Fig. 14 (a) shows the arrangement of the three horizontal thrusters, and Fig. 14(b) shows the definition of the force and moment. First, rise-and-fall operation is assumed to be independent of other operations. Therefore, in order to generate a thrust Fz, the control function generates half of Fz using two thrusters for rise and fall in Fig. 14 (b). Then, the thrusts $F_1$, $F_2$, and $F_3$ computed by formula (3) are distributed to the three thrusters, and horizontal movement and revolution operation are realized.

In formula (3), $F_x$ is thrust for moving in the direction of back and front, $F_y$ is the thrust for moving in the right-and-left direction, and $M$ is the moment generated along the circumference of the axis which makes perpendicular facing down positive. Hovering operation is done by correcting the change from the initial position and the initial attitude angle using the above procedure.
Thruster 3

\[
\begin{bmatrix}
F_1 \\
F_2 \\
F_3
\end{bmatrix} =
\begin{bmatrix}
0 \\
\frac{1}{\sqrt{3}} \\
-\frac{1}{\sqrt{5}}
\end{bmatrix}
F_x +
\begin{bmatrix}
\frac{2}{3} \\
-\frac{1}{3}
\end{bmatrix} F_y +
\begin{bmatrix}
\frac{1}{3r} \\
\frac{1}{3r}
\end{bmatrix} M \wedge \Lambda \ (3)
\]

(a) Arrangement of horizontal thruster

(b) Definition of force and moment

Fig. 14 Outline of control function

Hovering control

Movement by stream

Fig. 15 Outline of evaluation test for hovering control function

When the hovering control function was used, of the movement of the support ROV is between 0.03m to less than 0.1m which is the target. When control was stopped, the support ROV moves over a wide range. According to the above result, we confirmed that this function is effective.

CONCLUSION

We developed the prototype tandem underwater vehicle system which can be used for inspections in narrow spaces of a nuclear power plant reactor vessel. This system consists of the inspection ROV which carries out inspections by going into the narrow spaces, and the support ROV which supports the movement of the inspection ROV. The following items were confirmed in a performance test. First, the support ROV was able to move in three dimensions, while the inspection ROV was stored in the support ROV. The inspection ROV could be released from the support ROV, and the latter could hover over the area where the inspection ROV was working. Furthermore, the support ROV could release and retract a cable that was connected to the inspection ROV and the cable carried signals from the inspection ROV cameras and sensors. The hovering control function of the support ROV used self-
position and attitude angle detection. The self-position was computed by the optical cutting method and the picture correlating method, and the attitude angle was computed through a Karman filter for the signals of three kinds of sensors. From the performance evaluation, we confirmed that the self-position could be detected within 0.05m and the attitude angle could be detected with an error of less than 5 degrees. Moreover, in the condition of a flow velocity of 0.1 m/s, the hovering control function was able to keep the support ROV hovering within the movement limit of 0.03m. We confirmed that the tandem underwater vehicle system operated effectively and inspections could be carried out in narrow spaces. Next, we will carry out an evaluation in an actual reactor environment.

REFERENCE