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Implementation of an Underwater ROV for Detecting Foreign Objects in Water

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Abstract

An underwater remotely operated vehicle (ROV) has been implemented. It can inspect foreign substances through a CCD camera while the ROV is running in water. The maximum thrust of the ROV's running thruster is 139.3 N, allowing the ROV to move forward and backward at a running speed of 1.03 m/s underwater. The structural strength of the guard frame was analyzed when the ROV collided with a wall while traveling at a speed of 1.03 m/s underwater, and found to be safe. The maximum running speed of the ROV is 1.08 m/s and the working speed is 0.2 m/s in a 5.8-m deep-water wave pool, which satisfies the target performance. As the ROV traveled underwater at a speed of 0.2 m/s, the inspection camera was able to read characters that were 3 mm in width at a depth of 1.5 m, which meant it could sufficiently identify foreign objects in the water

Index Terms: 3D printing, Computer vision, Structural strength analysis, Underwater ROV

I. INTRODUCTION

The in-containment refueling water-storage tank (IRWST) of a nuclear power plant is a huge tree storage tank arranged in an annular shape around the nuclear reactor. The system tree inside the IRWST is used as a nuclear-fuel reloading tree when the situation is normal. In the case of an accident, it is used as an emergency core coolant; thus, improving the supply reliability is a very important factor. In addition, the IRWST has a structure in which four strainers are arranged vertically symmetrically at approximately 25° and 65° to block the inflow of foreign substances into the system.

In Korea, automated robots from foreign countries are used for inspecting and maintaining steam generators and nuclear reactors during operation. A representative development example of Korea's nuclear power plant robot is the *KAERO-m* series.

In the United States, the *SM* manipulator for inspection was developed. It has been continuously developed from *SM4* to *SM25*. *ROSA-III* is a versatile robot capable of inspection and maintenance. Packbot's *iRobot* and Honeywell's *T-Hawk* robot, developed for military use in the United States, were used during the accident at the Fukushima, Japan, nuclear power plant to acquire images inside and outside the nuclear power plant.

In France, the French Electric Power Corporation (EDF), the AREVA multinational corporation, and the Atomic Energy Agency (CEA) have been continuously developing nuclear-related robots and automation technologies. However, because nuclear-power use is avoided, technological developments have not been occurred recently.

Park and Lho [1, 2] developed a system for inspecting the nuclear fuel-storage tanks of nuclear power plants for foreign substances and a system for maintaining the steam-generating pipes of nuclear power plants using robots. Cho [3] developed a remote-vision inspection system in a nuclear reactor using underwater robots. Yun [4] studied the thrust of underwater robots. Choi [5] introduced a thruster-control and

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signal-processing system for the HEMIRE, deep-sea unmanned underwater vehicle. Choi and Jeong [6] developed a vision inspection remotely operated vehicle (ROV) in the upper and lower heads of nuclear power plants. Kim and Jeong [7] developed the control system of a mobile robot that inspects the inside of pipes.

The filter of a nuclear power plant has a closed structure, so a visual inspection is impossible from the outside. It is extremely necessary to develop an underwater ROV that can inspect the filter inside a tank, which may be contaminated with radioactivity and the presence of foreign substances. Therefore, we shall develop an underwater ROV suitable for inspections.

II. ROV DEVELOPMENT AND PERFORMANCE TEST

A. ROV Structure Design

The proposed ROV system for foreign-matter inspection is largely composed of the ROV mechanism and the control panel. As shown in Fig. 1, the ROV mechanism unit has a controller and a driving unit inside, and is composed of a body and a guard frame to mitigate collisions. It has thrusters for vertical and horizontal movement. It is equipped with an inspection camera to check foreign substances in the filter, a front camera that can look forward, and an omni-camera that can look at itself. It also has a depth sensor to measure the depth.

B. ROV Thruster-Part Design

As shown in Fig. 2, the ROV has four vertical thrusters that can move it up and down, and four horizontal thrusters that can rotate and move it horizontally.

As shown in Fig. 3, the four horizontal thrusters mounted on the ROV can move it horizontally toward the east, west, south, and north directions.

The design target values for the thruster part of the ROV are as follows.

- ROV weight in air: W_R = 27.8 kg$_f$
- ROV size: 680-mm width, 680-mm length, 1,115-mm height
- Horizontal thruster thrust: F_{th} = 3.55 kg$_f$ × 4
- Vertical thruster thrust: F_{tv} = 3.0 kg$_f$ × 4
- Working depth of ROV: 5 m
- Working speed of ROV: 0.2 m/s
- Maximum travel speed of ROV: 1.03 m/s (2 knots)

The buoyant force (F_b) applied to the ROV in water is calculated as shown in (1).

$$F_b = \gamma V_R. \tag{1}$$

Where γ is the specific weight of water and V_R is the volume of the ROV. After calculating the ROV volume by 3D modeling, $V_R = 0.0213\ \text{m}^3$; hence, the buoyancy, $F_b = (1{,}000\ \text{kg}_f/\text{m}^3)\ (0.0213\ \text{m}^3) = 21.3\ \text{kg}_f$.

This is acceptable for the thrust required for the ROV to descend into the water at a working speed of 0.2 m/s. When

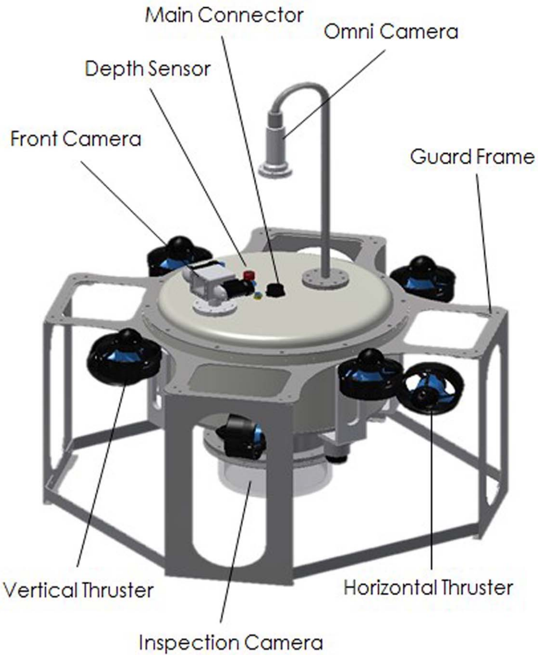


Fig. 1. Concept of the ROV to be developed.

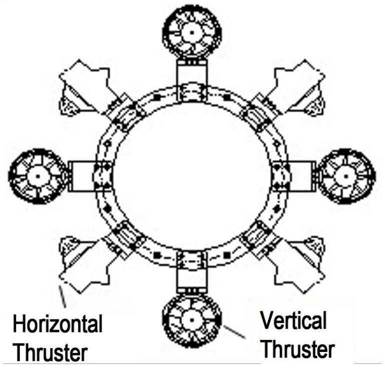


Fig. 2. Arrangement of vertical and horizontal thrusters.

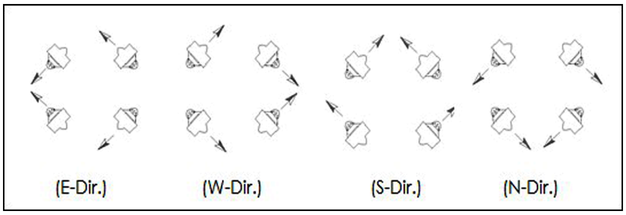


Fig. 3. Four horizontal thrusters driving in the E, W, S, and N directions.

the ROV rises, the thrust force F_{tv} (12.0 kg_f = 117.7 N) is greater than the resistance force W_R - F_b = (27.8 - 21.3) * 9.82 = 63.8 N, so it can rise.

When the ROV moves horizontally in water at a constant working speed, the resistance force, F_r, is derived as (2) [4].

$$F_r = \rho A v^2, \tag{2}$$

Where ρ is the density of water, A is the cross-sectional area of the ROV on which the water acts, and v is the working speed of the ROV.

Assuming that the ROV is cylindrical, the cross-sectional area, A = 0.12 m^2, of the front surface of the ROV is where the water resistance acts. Therefore, the resistive force acting on the ROV, F_r = (1,000 kg/m^3) (0.12 m^2) $(0.2 \text{ m/s})^2$ = 4.8 N.

Therefore, the maximum thrust, F_{th} = 139.3 N, of the horizontal thruster is much greater than the resistance, F_r = 4.8 N, at the working speed in the horizontal direction (0.2 m/s); hence, the ROV can easily move forward or backward at the working speed. In addition, the resistance force at the maximum speed in the horizontal direction (1.03 m/s) is calculated as follows: F_r = (1,000 kg/m^3) (0.12 m^2) $(1.03 \text{ m/s})^2$ = 127.3 N.

Therefore, when the ROV is running at the maximum speed, the horizontal thrust force of F_{th} =139.3 N is greater than the resistive force of F_r =127.3 N; hence, it can travel forward and backward at the maximum speed. However, considering the potential reduction in thruster efficiency, owing to frequent use in the future, it is necessary to increase the thrust capacity of the horizontal thruster.

C. CCD Camera-Part Design

Table 1 lists the main specifications of the inspection cameras used. As shown in Fig. 4, the field of view (FOV) for capturing an image was enlarged by installing a camera at the bottom of the ROV.

D. Structural Strength and Deformation Analysis

As shown in Fig. 5, the developed product was 3D modeled for a structural-strength analysis and the development-prototype production was verified using CATIA software.

Table 1. CCD camera specifications

Item	Value
Lens	4.3-129 mm
Shutter time	1/66,500-2 s
Pan angle	360°
Tilt angle	180°
Zoom	30 times
Resolution	1,920 × 1,080 pixels
Memory	512 MB RAM, 256 MB Flash

When the ROV experiences a collision while traveling at a speed of 1.03 m/s, the ROV's own weight acts on one side of the guard frame. A structural analysis was performed using the *ANSYS* simulation software. As shown in Fig. 6 and Fig. 7, the maximum stress generated by the collision in the analysis is 22.8 MPa, and the maximum amount of deformation is 1.18 mm. The yield tensile strength of the SUS304 material of the guide frame is 250 MPa, which is sufficient for safety, in terms of the structural strength.

E. Prototype Design and Production

Using a 3D printer (*Replicator Z18,* MakerBot), the 3D modeling data were input (Fig. 5). The prototype of the development product was reduced to 20% of the actual size, and is shown in Fig. 8. No problems were found in the design structure or verification.

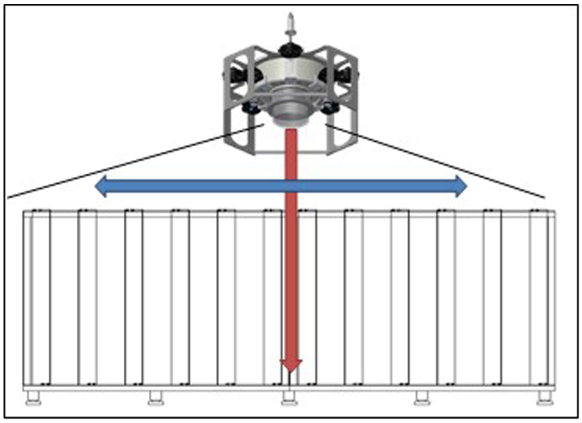


Fig. 4. Capturing view of the inspection camera.

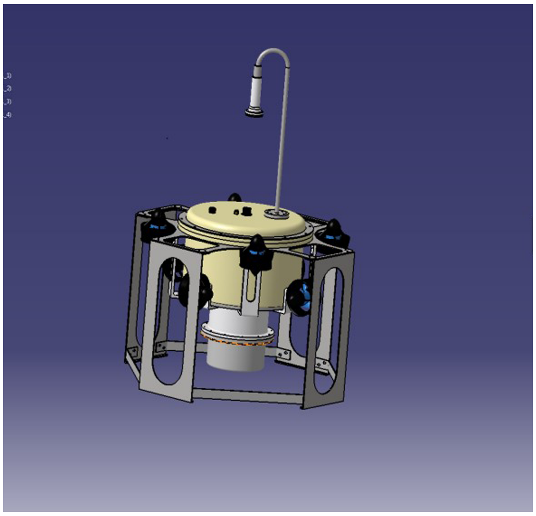


Fig. 5. 3D model of the ROV mechanics.

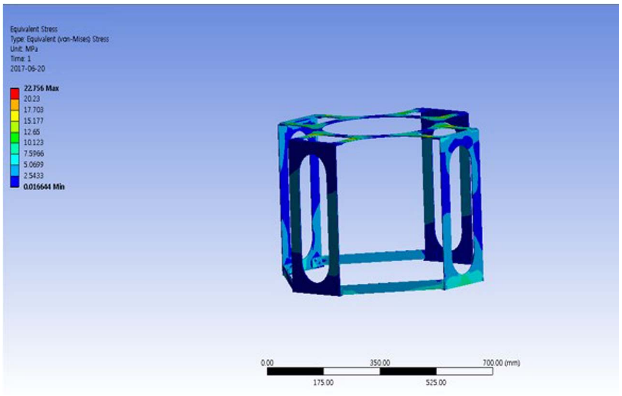


Fig. 6. Stress analysis of the guard frame.

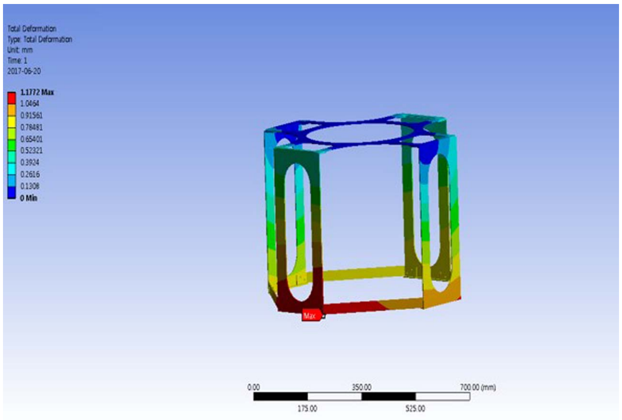


Fig. 7. Deformation analysis of the guard frame.

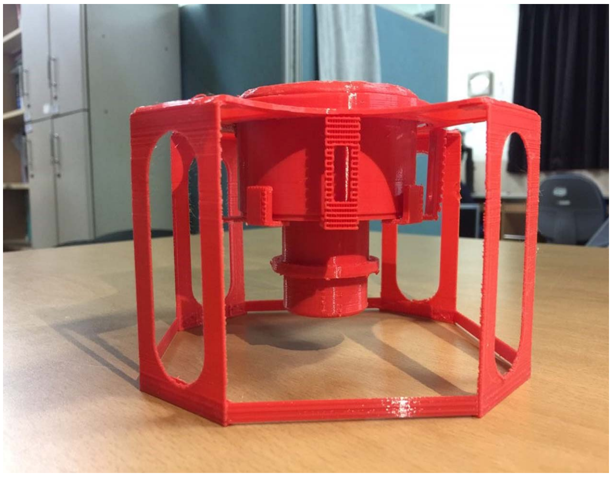


Fig. 8. Prototype ROV manufactured by 3D printer.

The prototype ROV was 3D printed, as shown in Fig. 9. Its structural strength and deformation were subsequently analyzed and verified.

Fig. 9. Overview of the developed ROV mechanics.

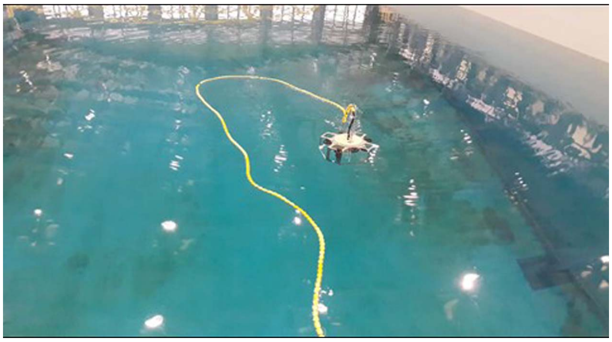
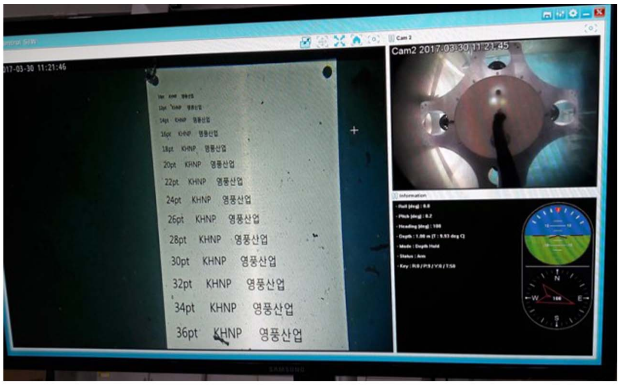


Fig. 10. Performance test of developed ROV in water.

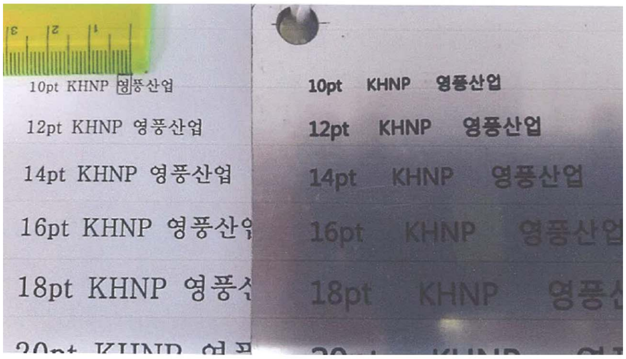
F. Performance Test

As shown in Fig. 10, a performance test was conducted to observe the maximum moving speed of the ROV at a depth of 5.8 m in a 50-m long, 20-m wide, and 10-m deep water wave pool at room temperature (20 ºC) and 60% humidity. The maximum moving speed of the ROV was measured as 1.08 m/s, and the target performance was satisfied.

Fig. 11 shows the image acquired by the inspection camera above a 1.5-m depth, while the ROV moves at an average feed rate of 0.2 m/sec in a 1.5 m × 5 m × 4 m filter tank to



(a) Image captured by inspection camera



(b) Result of captured images

Fig. 11. Images captured by inspection camera and results [8].

inspect foreign substances in the filter. Because it can decode characters of 3 mm width and height, the foreign matter in the filter could be sufficiently detected.

III. CONCLUSIONS

The results of implementing an underwater ROV for checking foreign substances in a nuclear-plant filter are summarized as follows.

1) The maximum thrust up and down of the ROV was 117.7 N. The ROV could descend at a speed of 0.2 m/s into the water, and it could rise because the resistance force was greater than 63.8 N, even when ascending.

2) The maximum thrust of the ROV's horizontal thruster is 139.3 N. This is much greater than the 4.8-N resistance for moving forward and backward at a speed of 0.2 m/s underwater. It is slightly larger than the maximum resistance, 127.3 N, so it can move forward and backward underwater at a running speed of 1.03 m/s.

3) A structural strength analysis of the guard frame, when the ROV was running at a speed of 1.03 m/s, indicated that the maximum stress was 22.8 MPa and the maximum deformation amount was 1.18 mm, confirming that it was safe during collisions.

4) The maximum running speed of the ROV was 1.08 m/s and the working speed was 0.2 m/s in a 5.8-m deep-water wave pool, which satisfies the target performance.

5) When the underwater ROV was running at a speed of 0.2 m/s in water, the detection camera was able to decode characters of 3 mm in width and height below 1.5 m, which meant it was able to sufficiently observe foreign objects in the filter, and satisfies the target performance.

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