A study on visual tracking of the underwater mobile robot for nuclear reactor vessel inspection

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Abstract: This paper describes visual tracking procedure of the underwater mobile robot for nuclear reactor vessel inspection, which is required to find the foreign objects such as loose parts. The yellowish underwater robot body tends to present a big contrast to boron solute cold water of nuclear reactor vessel, tinged with indigo by Cerenkov effect. In this paper, we have found and tracked the positions of underwater mobile robot using the two color information, yellow and indigo. The center coordinates extraction procedures are as follows. The first step is to segment the underwater robot body to cold water with indigo background. From the RGB color components of the entire monitoring image taken with the color CCD camera, we have selected the red color component. In the selected red image, we extracted the positions of the underwater mobile robot using the following process sequences; binarization, labelling, and centroid extraction techniques. In the experiment carried out at the Youngkwang unit 5 nuclear reactor vessel, we have tracked the center positions of the underwater robot submerged near the cold leg and the hot leg way, which is fathomed to 10m deep in depth.

Keywords: visual tracking, nuclear reactor vessel, underwater robot, Cerenkov effect

1. INTRODUCTION

The two reactor types PWR and PHWR are normally operated in Korea. A PWR is an acronym derived from the word Pressurized Water Reactor. And PHWR, called CANDU also, is acronym of Pressurized Heavy Water Reactor. The PWR uses boron-solute water as a moderator and CANDU reactor uses heavy water (Deuterium) as one. In the case of PWR reactor, the presence of loose (i.e., disengaged and/or drifting) parts in the primary coolant system can be indicative of degraded reactor safety resulting from failure or weakening of a safety-related component. A loose part, whether it be from a failed or weakened component or from an item inadvertently left in the primary coolant system during construction, refueling, or maintenance, can contribute to component damage and material wear by frequent impacting with other parts in the system. A loose part increases the potential for control rod jamming and for accumulation of increased levels of radioactive crud in the primary coolant system. At the Korea Atomic Energy Research Institute we are developing the underwater mobile robot for loose part detection and removal in the nuclear reactor vessel [1]. The primary purpose of the loose part detection using the underwater mobile robot is the detection of loose metallic parts, bolts, nuts and washers, in the primary system. In the overhaul period, these loose parts detection and removal can provide the time required to avoid or mitigate safety-related damage to, or malfunction of, primary system components. In general, underwater robot vehicle for maritime exploration have the body, which is colored with yellow or red. The yellowish or red body of underwater vehicle helps the operator finding the vehicle's position easily on the sea colored with indigo. We dyed the underwater mobile robot body with yellow color, because the yellow is in contrast to blue color of the boron solute water in nuclear reactor vessel. As the nuclear reactor goes on increasing in operation time, the boron solute cold water in the primary system have the more and more bluish color by the Cerenkov effect. The Cerenkov effect is defined as the emission of radiation in the visible and ultraviolet spectrum arising when a charged particle crosses a medium with a velocity greater than that of light in the same medium. In this paper, the visual tracking procedure of the underwater mobile robot is described.

The yellowish underwater robot body tends to present a big contrast to boron solute cold water of nuclear reactor vessel, colored with indigo by Cerenkov effect. We have found and tracked the positions of underwater mobile robot using the two color information, yellow and indigo. The center coordinates extraction procedures are as follows. The first step is to segment the underwater robot body to cold water with indigo background. From the RGB color components of the entire monitoring image taken with the color CCD camera, we have selected the red color component. In the selected red image, we extracted the positions of the underwater mobile robot using the following process sequences; binarization, labelling, and centroid extraction techniques. In the experiment carried out at the Youngkwang unit 5 nuclear reactor vessel, we have tracked the center positions of the underwater robot submerged near the cold leg and the hot leg way, which is fathomed to 10m deep in depth

2. UNDERWATER MOBILE ROBOT

At the Korea Atomic Energy Research Institute we are developing a mobile underwater robot for nuclear reactor vessel inspection. Figure 1, 2 show the appearances of the robot system and controller.

Fig. 1. Photo of the mobile underwater robot

Fig.2. Robot Controller

For short or long term monitoring of nuclear reactor vessel, the mobile underwater robot is easy to remotely control, small, and lightweight. It is portable and video is produced in NTSC formats. The underwater mobile robot are equipped with laser pointers, cameras and fathoming tool, which can be used to visually inspect the submerged infrastructure of reactor vessel and CSB(Core Support Barrel), measure the cracks, and store large quantities of data(still image and video streams). The underwater robot vehicle, which is connected to an umbilical, can reach depths of up to 30m. The detailed technical specifications of the robot system are shown in Table 1.

Table 1 Specifications of underwater robot

Items	Specifications
Dimension	26” X 14” X 12” [LWH]
Weight	31 pounds
Effective Weight	7 pounds
Effective Submerging Depth	150 ft
Maximum Submerging Depth	200 ft
Operating Temperature	32~104 F
Video	NTSC
Thruster	12 pounds
CCD Sensor	1/4” Interline, 768 X 494
Lens	18 X 1, Motorized Zoom (4.1 ~ 73.8mm)
Laser Pointers	680nm, 3mW LD

3. POSITIONING OF UNDERWATER ROBOT

As the nuclear reactor goes on increasing in operation time, the boron solute cold water in the reactor vessel have the more and more bluish color by the cerenkov effect. Figure 3 shows the underwater robot, moving to the CSB outside wall, for visual inspection. As in the shown in figure 3, we can discriminate the yellowish mobile robot vehicle from the reactor vessel filled with indigo colored water. In figure 3, the right-sided circular structure is CSB(core support barrel).

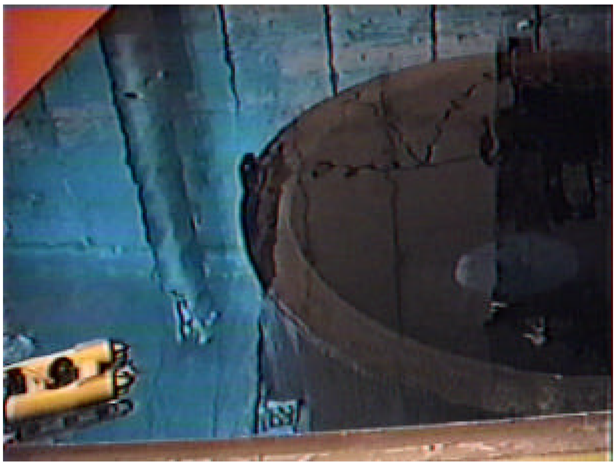


Fig.3. Underwater robot moving to the CSB outside wall

The red object, in the left-top view in the figure 3, is crane for install, removal of nuclear pellets bundle. A color value in figure 4 is a long integer that packs the red, green, and blue components, where each component can range from 0 to 255. Figure 4 shows RGB components and gray component, extracted from figure 3.

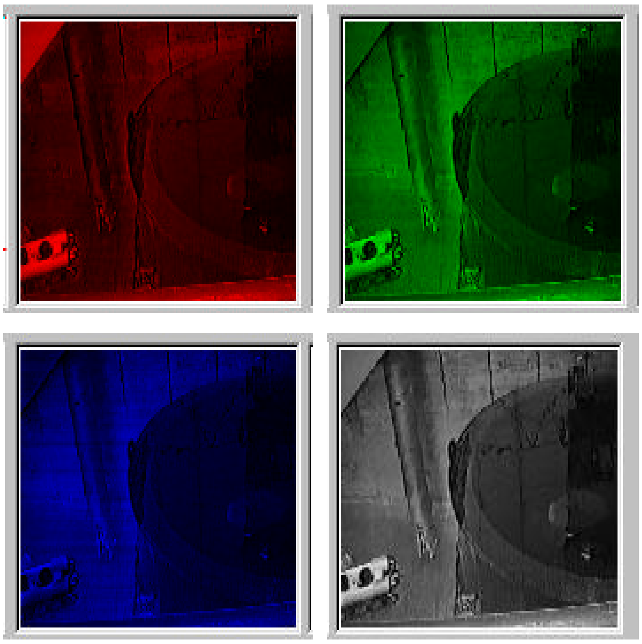


Fig.4. RGB and Gray component extraction

As shown in figure 4, the left-top view image represent red component. And right-top of the figure 4 shows green component. In the red and green component image of the figure 4, we can discriminate robot vehicle from reactor vessel easily. In the bottom-left bluish image of the figure 4, we can hardly find the position of the robot from the reactor vessel filled with boron solute water, dominant indigo color. So, we analyzed the red, green, blue, and grey level profiles at the same position of the figure 4. Figure 5 and 6 depicts the gray level profiles of horizontal and vertical directions. From the x-axis profile, shown in figure 5, we can estimate the red component have the most salient signal-to-noise ratio characteristics compared to the other color components. In the robot p ositioned coordinates (1~64), the gray level is more than 192. And in the other coordinates(65-316), the gray level is 64 and below.

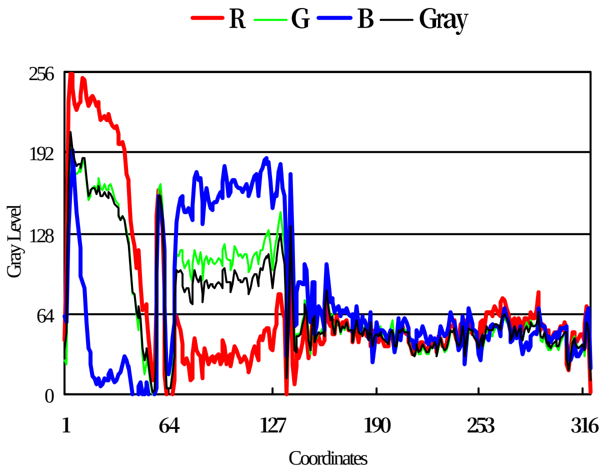


Fig.5. Gray level profile of RGB and Gray component

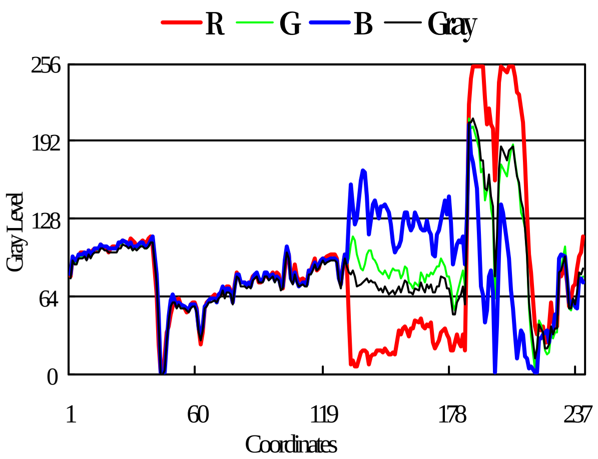


Fig.6. Gray level profile in vertical direction

From the horizontal and vertical profiles of gray component as shown in figure 5 and 6, gray level of robot vehicle positioned coordinates (1-64, 180-215) ranges in between 128 and 192. In the reactor vessel area, represented with dominant bluish color (65-130, 126-184), the gray level of that region ranges in between 64 and 128. From the x-axis and y-axis profiles, shown in figure 5 and 6, it is shown that the gray component have the inferior signal-to-noise characteristics compared to the red component. From these facts, we can conclude that using the red component from color camera is more efficient tracking method than processing the black and white image from the monochrome CCD camera.

4. EXPERIMENT AND RESULTS

Figure 7 shows the image of underwater mobile robot moving and submerging ahead to CSB outside wall in the reactor vessel of Youngkwang unit 5 nuclear power plant. The mobile robot images, shown in figure 3 and 7, were acquired with a SONY DCR-P5 digital camcorder, which consists of 1/4" CCD sensor and 10X motorized zoom lens.

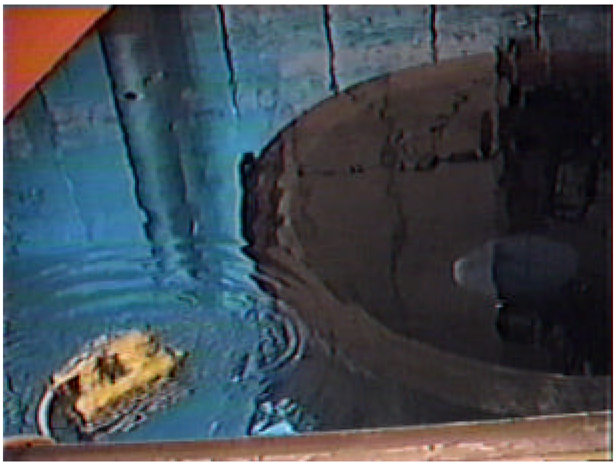


Fig.7. Underwater robot submerging ahead to CSB

The underwater robot is positioned as follows.

1) Acquire color image from SONY DCR-P5 camcorder and extract the red component form the color image.
2) Threshold the image to produce a binary image. The threshold value was set by analysis of intensity histograms, profiles, and projection method. From the results of the figure 5 and 6, we set the threshold value to 128. (see figure 8) As shown in the utmost left image of figure 8, igure 8, we can clearly segment the

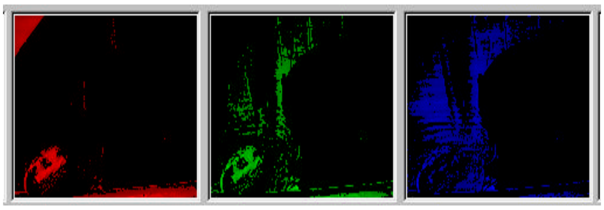


Fig.8. RGB component image after threshold

3) Carry out connectivity analysis via labeling operation. From the characteristics of each label, which include region-of-interest coordinates, size, and center coordinates, we extract the position of the underwater mobile robot by size filter. The center coordinates of the ROI is the center of mass of figure of the same shape with constant mass per unit area [2].
4) The position and ROI(region-of-interest) coordinates of the robot are the starting coordinates of the next image frames.

In the left image of the figure 8, it is known that the red component have the most superior signal-to-noise ratio compared to the other components. We know that, in the vicinity of the robot vehicle, there are not noises in red component image. Figure 9 shows the processing sequence. The software platform is based on Windows 2000 operating system and consists of custom native libraries, Matrox MIL-LITE 7.1 for image capture, digitizing, memory transfer, and display. Code was written in MSVC6.0 programming language.

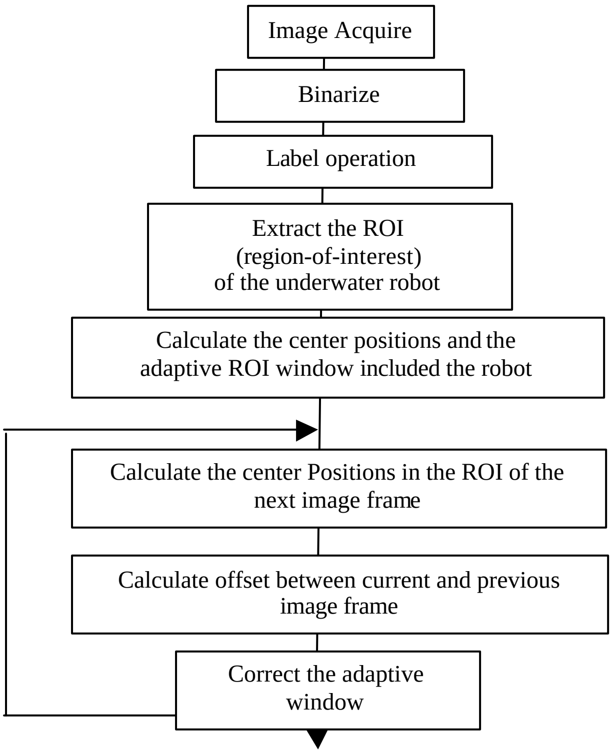


Fig. 9. Image processing sequence to position the robot

In the figure 10 and 11, the results of the center position extractions of the underwater mobile robot moving and submerging ahead to CSB for visual inspection. In the figure 10, the white rectangle represents the adaptive ROI window and cross-hair shows the center positions of the robot.

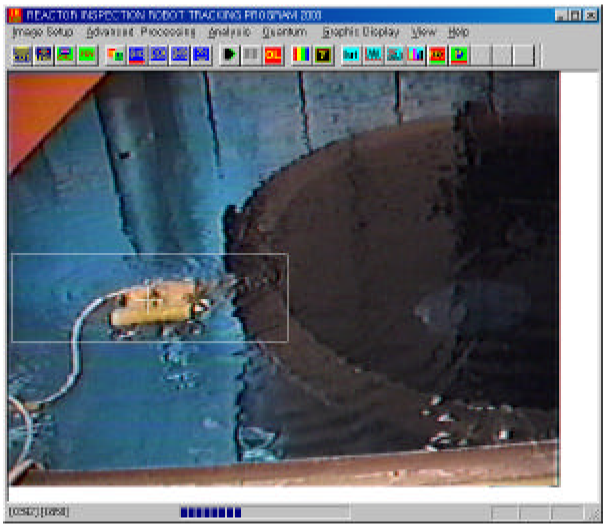


Fig.10. Adaptive ROI window

In case of flickering noise and digitization (analog-to-digital conversion) error, it is possible to lose the positions of the robot in a moment. As shown in figure 12, due to the light source temporally installed in the bottom of the reactor vessel, the target position diverges from the ROI window included robot vehicle (see figure 12-c, and 12-d). When the position of the robot vehicle fluctuates between the previous and the current image frame, we adaptively adjusted the ROI window. Adding the ROI windows of the previous frame to the current frame, and then setting up the ROI window of the next image frame, we can control the target position's divergence (see figure 12-e).

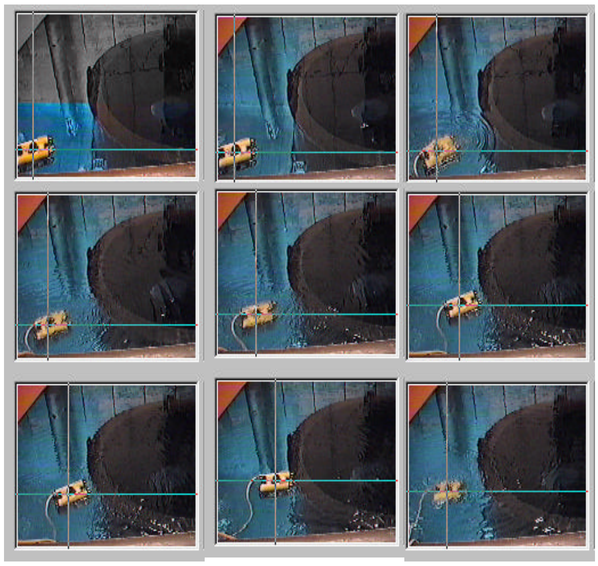
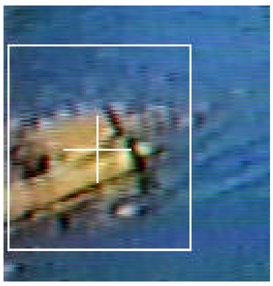


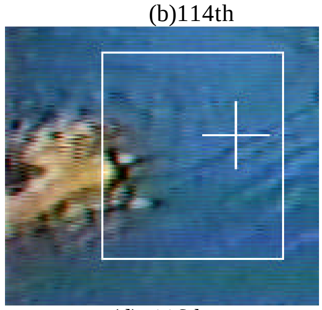
Fig.11.The robot tracking sequence frames



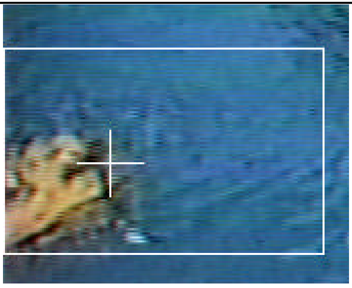
(a) 113th

(b)114th

(c) 115th



(d) 116th



(e)117th

Fig12. The tracking problems due to flickering noise.

Figure 13 shows the tracking results.

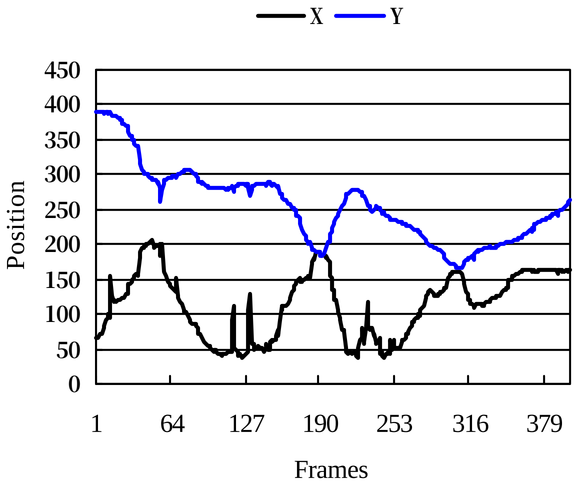


Fig.13. Trajectory of the mobile robot moved.

As shown in the figure 13, the spikes of the lower graph represent the flickering noise or capture error. From the view of the this figure, in spite of the above flickering noises, applying the variable ROI window, it is shown that we can robustly track the positions of the underwater robot, moving and submerging ahead to the CSB wall for visual inspection.

5. CONCLUSIONS AND FUTURE WORK

The tracking procedure of the underwater mobile robot moving and submerging ahead to nuclear reactor vessel for visual inspection, which is required to find the foreign objects such as loose parts, is described. The yellowish underwater robot body tends to present a big contrast to boron solute cold water of nuclear reactor vessel, tinged with indigo by cerenkov effect. In this paper, we have found and tracked the positions of underwater mobile robot using the two color information, yellow and indigo. From the horizontal and vertical profiles analysis of the color image, the blue, green, and the gray component have the inferior signal-to-noise characteristics compared to the red component.

The center coordinates extraction procedures are as follows. The first step is to segment the underwater robot body to cold water with indigo background. From the RGB color components of the entire monitoring image taken with the color CCD camera, we have selected the red color component. In the selected red image, we extracted the positions of the underwater mobile robot using the following process sequences; binarization, labelling, and centroid extraction techniques. In the experiment carried out at the Youngkwang unit 5 nuclear reactor vessel, we have tracked the center positions of the underwater robot submerged near the cold leg and the hot leg way, which is fathomed to 10m deep in depth When the position of the robot vehicle fluctuates between the previous and the current image frame due to the flickering noise and light source, installed temporally in the bottom of the reactor vessel, we adaptively adjusted the ROI window. Adding the ROI windows of the previous frame to the current frame, and then setting up the ROI window of the next image frame, we can robustly track the positions of the underwater robot and control the target position's divergence. From these facts, we can conclude that using the red component from color camera is more efficient tracking method than processing the black and white image from the monochrome CCD camera.

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