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Accuracy Improvement of Stereo-Based Distance Measurement for Close Range Vessel Positioning

Tadashi Ogura*† , Yoshiaki Mizuchi*, Young-Bok Kim**, and Yong-Woon Choi*

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Abstract: This paper describes a distance measurement system with high accuracy that utilizes a stereo-based camera and a pan-tilt unit for automatically maintaining the positional relationship between a vessel and a target on the side of a facility at a close range. The measurement system offers an advantage in that it can measure the distance to a target while tracking it. In order to improve the ability to control the position of a vessel between it and a target while maintaining the distance especially at a close range, the accuracy of the measurement system has to be improved. The accuracy of the distance measured by our system is increased with revisions of the conclusively generated data of distance measurement. We verified the accuracy of our system from an experiment, which generated results that had an accuracy of 30 mm for distances in the range between 2-8 m.

Key Words : Distance Measurement, Stereo Camera, Template Matching, Vessel Positioning.

1. Introduction

Vessels utilized for tasks such as berthing, loading or unloading, and refueling require safe maintenance at a location that is in close proximity to target facilities. Persons engaged in these jobs are exposed to the latent risk of accidental collisions. As a solution to effectively reduce accidental collisions between the vessel and a facility, we have considered a technique that allows a vessel to maintain its positional relationship between it and the target and automatically measures the distance between them. This can be achieved by developing a distance measurement system on the vessel side and a clear target on the facility side. By measuring the distance to a target using the measurement system mounted on a vessel, we ensure that the vessel is controlled to maintain the positional relationship so that it can be constantly maintained at a certain distance. In order to achieve this, the measurement system on a vessel should satisfy the following three factors.

The first is the distance accuracy measured by the system. On the vessel, high measurement accuracy is required as the vessel is automatically controlled to maintain the positional relationship at a relatively close distance. The Global Positioning System (GPS) has been widely used to obtain the position data of a vessel in an ocean. However, it does not satisfy our conditions pertaining to

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*† Tadashi Ogura(corresponding author), Yoshiaki Mizuchi, Yong-Woon Choi: Department of Information System Science, Soka University.
E-mail : e14m5210@soka.ac.jp, Tel : +81-42-691-8197
**Young-Bok Kim: Department of Control & Mechanical Engineering, Pukyong National University.

measurement accuracy used in relatively close distances of about 5 m. A typical technique to measure the distance to a target is to use laser beams [1, 2]. While this has a high accuracy in distance measurement, it is not suitable for continuously tracking a target. The second condition is the response time given on the measurement system, which is very important to the reliability of real-time distance measurement on a vessel. A GPS-based system is generally slow in response time [3]. Furthermore, such a system is not suitable for the environment to maintain the positional relationship between a vessel and a facility at a close range. The third and final condition is to measure the distance while continually tracking a certain target. For automatically maintaining the vessel, the distance between two known points should be continuously gathered, which is achieved by tracking the target. The distance measurement system can measure the distance while tracking a given target because it adapts camera-based stereo vision. A measuring system [4] that satisfies the high response requirements and tracking of these factors has been proposed. The measuring system can measure with an accuracy of 1 m for distances of 20-100 m while tracking the target. However, the measuring system has not been discussed with measuring a distance close to target and the accuracy is not enough to satisfy the factors. Thus, it is necessary to ensure that our measurement system has improved accuracy of distance measurement for close range vessel positioning. Generally, measurement of the distance by stereo vision has a measurement error caused by physical components. To measure distance at high accuracy, the physical error should be revised. In this study, by conclusively revising generated data based on distance measurement, the accuracy of distance measurement is improved.

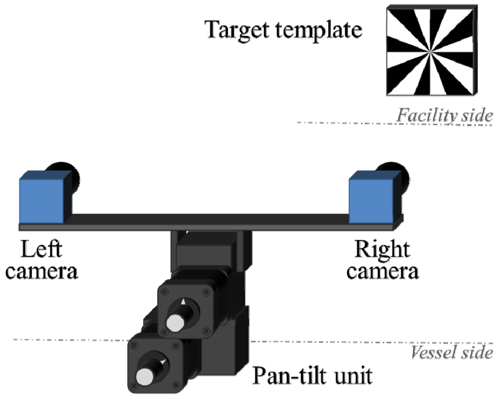


Fig. 1 Overview of the distance measurement system using a stereo camera mounted on a pan-tilt unit and a target

In this paper, we endeavor to discuss the principles of the distance measurement system that are required to maintain the positional relationship between a vessel and a target at a close range. Experimental results will also be presented.

2. Distance Measurement System

2.1 System Overview

As shown in Fig. 1, the distance measurement system is composed of two cameras on the left and right for measuring distance; cameras on a pan-tilt unit that are mounted on the vessel side, and a target on the facility side. The purpose of the left and the right cameras is to measure the distance to a given target via the stereo vision method. The target on the facility side has a radial pattern. We have adapted this pattern as it is robust in the size change of images regardless of distance. A characteristic of the radial pattern that is advantageous is that it can always obtain the center point of a template regardless of the change of variety in image size. The target of the input image of each camera is detected by template matching method, which is referred to as vector code correlation (VCC)[5-7]. VCC is a low cost calculation technique, which has been demonstrated in previous studies as being applicable to target detection even in outdoor lighting conditions[5, 6] or adverse weather [7] conditions. Thus, VCC is suitable for distance measurement applied to a vessel.

2.2 Basis of Distance Measurement

Fig. 2 shows the schematic diagram of the distance measurement system based on a set of stereo vision. This figure depicts the system shown in Fig. 1 in further detail and explains the basic concepts including the parameters necessary to obtain the distance to a target with a set of stereo vision. As shown in Fig. 2, the distance D_z from the baseline L to the target with the condition that the optical axes of the left and right cameras are in parallel is found by the following equation (1):

$$D_z = \frac{L}{\tan\theta_L - \tan\theta_R} \tag{1}$$

where L is the length of a baseline between the two cameras, and the angle between the target and the optical axis of each camera forming a stereo vision are θ_L and θ_R, respectively. Meanwhile, this set of stereo vision is mounted on a pan-tilt unit that is placed at the midpoint of the baseline, as shown in Fig. 1. Therefore, the distance measurement system can afford to make the stereo vision rotate on the pan and the tilt direction. For instance, when the stereo vision is rotated on the pan direction for tracking the target, the distance D_m from the midpoint to the target can be computed via the following equation (2):

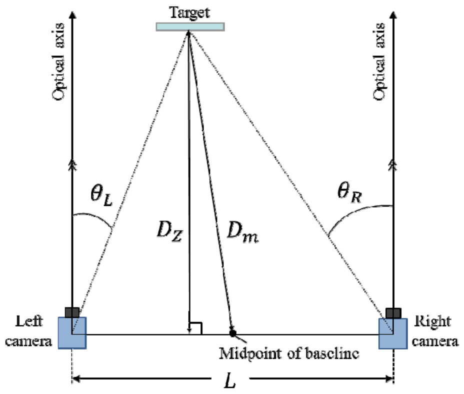


Fig. 2 Schematic of the distance measurement system based on a set of stereo cameras

$$D_m = \sqrt{\frac{1}{2}D_z(\tan^2\theta_L + \tan^2\theta_R + 2) - \frac{L^2}{4}}. \tag{2}$$

In the proceeding section (Section 2.3), we concretely explain how θ_L and θ_R used in Equations (1) and (2) are determined.

2.3 Angle between the Optical Axis and Target

Fig. 3 illustrates the schema of an input image when the target was captured by the imaging device through the lens of the left camera. As shown in Fig. 3, the target location in the input image is given as coordinates (u_t, v_t) via target detection. The target location denotes the pixel location relative to the intersection of the image plane and the optical axis of the camera. The angle θ between the optical axis and the target is calculated via the following equation (3):

$$\theta = \tan^{-1}\frac{u_t s_u}{f} \tag{3}$$

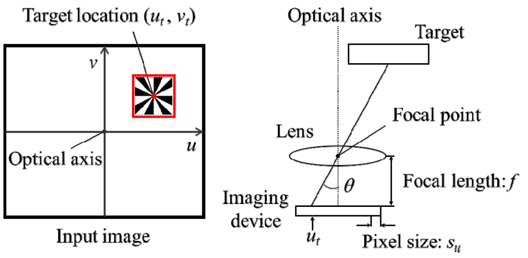


Fig. 3 Schema of an image when the left camera shown in Fig. 2 captured the target

where s_u is the pixel size in the horizontal direction and f is the physical focal length of the camera lens. These are known values from the specification of a device to be mounted on the distance measurement system. The angle in the vertical direction between the optical axis and the target can be computed in the same manner.

3. Revised Distance Data

The method of determining distance D_z is possible under the condition that the optical axes of the left and the right cameras are in parallel, as shown in Fig. 2. However, it is challenging for both optical axes to always remain in parallel. For example, as shown in Fig. 4, assume that the optical axis of the right camera is panned φ_R degrees of the left camera. The angle of θ_R from the optical axis of the right camera to the actual target is detected as solid lines. However, as the optical axes are assumed to be in parallel in software, the computed target is detected with an angle of θ_R from the ideal axis as dashed lines. Therefore, the computed target is incorrectly detected due to the angle of φ_R, and this causes distance measurement errors. Then, when values of baseline L = 300 mm and φ_R = 0.1 degrees were provided to stereo vision, the simulation result for the distance error produced is as shown in Fig. 5. As shown in this graph, we can understand that the error values increased as the actual distance to the target increased. Therefore, it is very important to revise the distance measured with stereo vision.

In the case of the physical factor as shown in Fig. 4, the distance should be revised by back calculating the factor. However, it is difficult to perfectly revise the factor and a small margin of revision causes an error that increases according to the distance in a similar manner to the graph of Fig. 5. Thus, by comparing conclusively generated distance data with correct distance data, the parameter for revising the distance is determined.

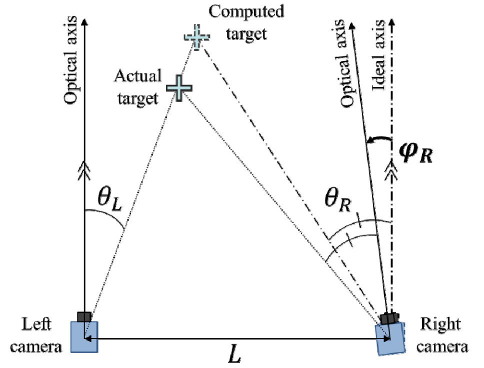


Fig. 4 Schema to demonstrate the error placing caused when the right camera is panned ϕR degrees from the ideal optical axis

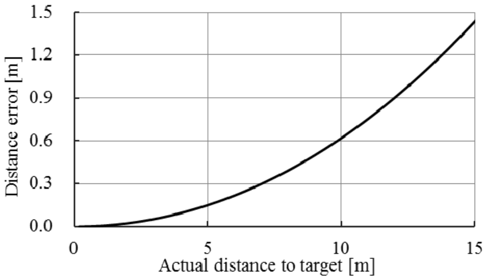


Fig. 5 Simulation result for the distance errors of the baseline L = 300 mm and ϕR = 0.1 degrees

To revise the distance measured with the distance measurement system, we require finding a means for the distance errors that can be quadrated to it. Thus, it is necessary to calculate the parameter to revise the error identical to that for producing the graph of Fig. 5. The parameters, α_0, α_1, and α_2, for the quadratic equation are determined by the following equation (4) computed using the method of least squares:

$$\begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} \sum 1 & \sum C_i & \sum {C_i}^2 \\ \sum C_i & \sum {C_i}^2 & \sum {C_i}^3 \\ \sum {C_i}^2 & \sum {C_i}^3 & \sum {C_i}^4 \end{pmatrix}^{-1} \begin{pmatrix} \sum C_i - M_i \\ \sum C_i(C_i - M_i) \\ \sum {C_i}^2(C_i - M_i) \end{pmatrix} \tag{4}$$

where C is the correct distance to a target and M is the distance measured by the system.

The quadratic equation of the parameters α_0, α_1, and α_2, which is calibrated in the same way, is also installed in our distance measurement system.

$$D = \frac{-(a_1+1) \pm \sqrt{(a_1+1)^2 - 4a_2(a_0 - M)}}{2a_2} \quad (5)$$

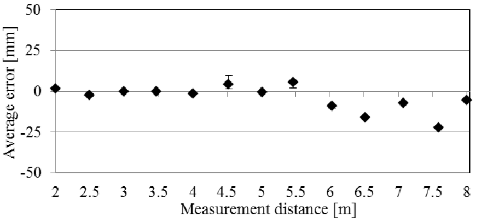
Thus, we can obtain the revised distance D by fitting a quadratic equation for the distance errors found in advance to its measured distance data via software.

4. Experiment

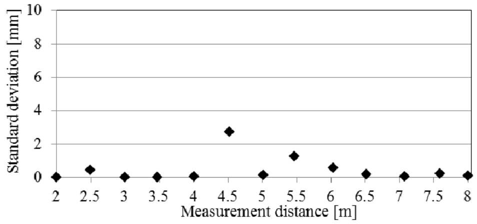
In collecting distance data required to maintain the positional relationship between a vessel and a target at a close range, the distance measurement system was tested to verify that it satisfies the aforementioned (in Section 1) three factors, namely high accuracy for the measured distance, response time, and target tracking. For example, for high accuracy on the measured distance, we have referred the distance accuracy of the sensor system to be within 100 mm for berthing [2]. To verify the distance accuracy, we measured a distance of 2-8 m to the target template shown in Fig. 1 at an interval of 0.5 m. We also investigated the average and deviation for the distance errors to use the images of 100 frames continuously at each position. The specifications of our measurement system used in this test such as the baseline length, the focal length, and pixel size are reported in Table 1.

Table 1 Specification of our system used for distance measurement

Measurement distance	2-8 m (0.5 m interval)
Baseline length	300 mm
Focal length	16 mm
Image resolution	640 × 480 pixel
Pixel size	7.5 mm
Target size	200 × 200 mm
OS	Windows 7
Memory	8 GB
CPU	Intel Core i5



(a) Average distance error



(b) Standard deviation

Fig. 6 Average and the deviation of distance errors measured with our system

Fig. 6 (a) shows the average and dynamic range of distance errors. The actual distance denoted on the horizontal axis of this graph was measured by a laser distance meter, which has a measurement accuracy within 1.0 mm. The measured distances were compared to the actual distances. As seen in this graph, the maximum distance error is the error of -22.6 mm at an actual distance of 7.5 m. This shows that our measurement system has a higher accuracy than that of the sensor system for berthing which was referred to.

Fig. 6 (b) shows the standard deviation of distance errors measured with our measurement system. As shown in this graph, the maximum standard deviation is 2.8 mm at an actual distance of 4.5 m. This denotes that the target was tracked and the distance was measured with high accuracy in the images of all captured frames. In addition, the processing time of the measurement was about

50 ms. This processing time indicates that our proposed system has a processing ability of about 20 frames per second.

From the experimental results, we can confirm that our measurement system has sufficient accuracy and processing speed to measure the distance for positioning between a vessel and a target at a close range.

5. Conclusion

We proposed a distance measurement system that is capable of highly accurate measurements and target tracking by utilizing a stereo-based camera and a pan-tilt unit for automatically maintaining the positional relationship between a vessel and a target on a facility side at a close range. In order to produce a measurement system with such capabilities, we had to improve its accuracy.

The results measured with the measurement system explain that the system has a measurement accuracy within 30 mm and a standard deviation of less than 4 mm for distances in the range of 2-8 m. Furthermore, it can measure and track the target at a speed of 20 frames per second. From these experimental results, we conclude that our measurement system can be effectively used in controlling a vessel for maintaining the positional relationship at a close range.

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