Improving the accuracy of a fisheye stereo camera with a disparity offset map

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***Abstract*—This paper deals with improving the accuracy of a fisheye stereo camera by correcting images using a disparity offset map, which is a map of disparity errors that are calculated from the disparity of the feature points obtained from an object with a known distance. By correcting the disparity errors and aligning the images, errors, such as those due to the insufficient calibration of the camera parameters, are reduced. A disparity offset map is constructed, and the accuracy of the distance measurement of a fisheye stereo camera using the disparity offset map is evaluated by experiments.**

***Index Terms*—fisheye camera, stereo camera, equirectangular image, disparity offset map**

I. Introduction

In recent years, cameras and range sensors for driver support are often used. Some examples of these aids include stereo cameras, LIDAR, and sonar. In this paper, we focus on the fisheye stereo camera. The fisheye camera has a wide-angle view of about 180 degrees. By constructing a fisheye stereo camera using two fisheye cameras, it is possible to measure a wide-angle range image. There have been several studies on fisheye stereo cameras. Abraham et al. [1] simplified stereo matching by rectifying the images of the fisheye stereo camera. However, the reconstruction of environment is not dense. Moreau et al. [2] discussed the epipolar constraint of a fisheye image for an equisolid angle projection model and achieved reconstruction of environment using a stereo camera. However, the method has large computational costs. Hane et al. [3] achieved real-time three-dimensional measurement by using the plane-sweeping method. In some studies, a fisheye stereo camera was applied to a UAV [4] and to vehicles [5]–[7]. In these studies, fisheye images were usually transformed to perspective images to simplify the corresponding point search of stereo images. With this, the peripheral regions of an image are severely stretched. Consequently, it becomes difficult to carry out stereo matching in the peripheral regions, and the distance detection range becomes narrower than when images are used that have not been deformed by a fisheye camera. To solve these problems, Ohashi et al. [8], [9] proposed a fisheye stereo camera that uses equirectangular images. Equirectangular images can convert fisheye images into those in which the vertical axis and the horizontal axis of the rectangular coordinate system are the elevation angle and the azimuth angle, respectively. An equirectangular image simplifies the corresponding point search without severely stretching the peripheral region. However, there is a problem, in that the precision of distance measuring is insufficient due to the large distortion as compared to perspective images, errors of external parameters, and the like. As reported in this paper, accuracy is improved by using a disparity offset map that corrects an image using the disparity of a target at a known distance. The experiment shows the effectiveness of the proposed method.

II. Fisheye stereo camera

A. Fisheye Camera Model [10]

Projection systems of a fisheye lens include an equidistant projection, an orthogonal projection, a stereographic projection, and an equisolid angle projection. However, since the actual fisheye camera has errors, such as deviation of the optical axis, it does not follow these ideal projection models exactly. In this paper, intrinsic parameters are calculated by using the camera model proposed by Scaramuzza et al. [10], and the influence of individual differences of the camera is corrected.

B. Equirectangular Image

As shown in Fig. 1(a)(b), when perspective projection is applied to a fisheye image, the center region of the image is smaller, and the peripheral regions of the image are stretched. Since image quality in the reduced center region and the stretched peripheral regions is bad, it is difficult to obtain corresponding points in these regions by stereo matching. Therefore, to remove the distortion of the fisheye image and decrease the stretching of the image caused by projection, an equirectangular image in Fig. 1(b) is used [8], [9]. Since an equirectangular image can transform the fisheye image into orthogonal and equidistant coordinates, represented by elevation angle λ and azimuth angle ϕ, respectively, which have low distortion, and keep the form of the image, the images with equirectangular image can be easily searched for stereo correspondence. A conceptual diagram for converting a fisheye image to an equirectangular image is shown in Fig. 2.

III. Disparity Offset Map

A. Disparity Error for Feature Points with Known Distances

Feature points are extracted from a target with a known distance on equirectangular image, and disparity errors of

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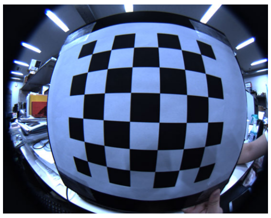
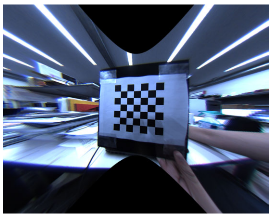
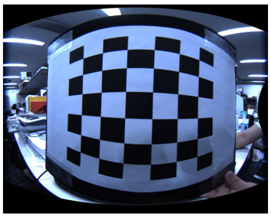


(a) Fisheye image



(b) Perspective image



(c) Equirectangular image

Fig. 1. Transformed images from a fisheye image

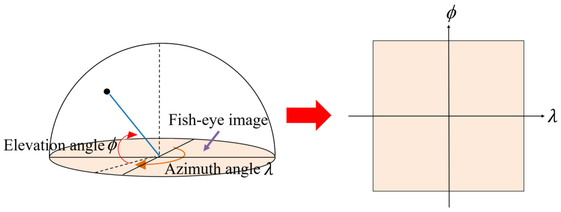


Fig. 2. Conversion from fisheye image to an equirectangular image

each point are obtained. Disparities are obtained for horizontal direction x and vertical direction y. An object far away at a known distance is chosen as the target. The building surrounded by a red rectangle in Fig. 3 is an example. Feature points are extracted, and matching is performed using the AKAZE [11] feature. Furthermore, it is difficult to have distant objects over the entire image. Therefore, by moving the posture of the camera, images of distant objects are taken at various positions in the image, and they are extracted so that feature points can be obtained for the entire image. The points where Euclidean distances of feature points of the left and right images are large are eliminated as outliers.

Fig. 3. Target with a known distance on an equirectangular image

B. Disparity Offset Map

A map is created in which the disparity errors for all pixels are obtained from the disparity errors of the feature points. This map is called a disparity offset map. The feature points around each pixel are used, and the weighted average is calculated by weighting w_k according to the distance d_k between the pixel and the point. The disparity errors e_i and e_j of pixel (i, j) are determined from the disparity errors e_{uk} and e_{vk} of feature points (u_k, v_k) by the following equations.

$$e_i = \frac{\sum_{k=1}^{n} w_k \cdot e_{uk}}{\sum_{k=1}^{n} w_k} \quad (1)$$

$$e_j = \frac{\sum_{k=1}^{n} w_k \cdot e_{vk}}{\sum_{k=1}^{n} w_k} \quad (2)$$

$$w_k = \frac{1}{2\pi\sigma^2} \exp\left\{-\frac{d_k^2}{2\sigma^2}\right\} \quad (3)$$

$$d_k = \sqrt{(u_k - i)^2 + (v_k - j)^2} \quad (4)$$

Equation (3) follows a two-dimensional Gaussian distribution, and σ represents the standard deviation. The surrounding feature points for determining the disparity error of the pixel are limited from the pixel to a point at a Euclidean distance equal to or less than a threshold value. n is the number of feature points within this threshold. If the surrounding points do not exist within the threshold value, the disparity errors of that pixel are assumed to be indefinite.

C. Image Correction by Disparity Offset Map

The image is corrected based on the disparity errors of the pixel of the disparity offset map. In this paper, correction is made to the left image. The pixels (n, m) obtained by correcting the disparity errors from the pixels (i, j) can be expressed by (5) and (6), respectively.

$$n = i - e_i \quad (5)$$

$$m = j - e_j \quad (6)$$

IV. EXPERIMENT

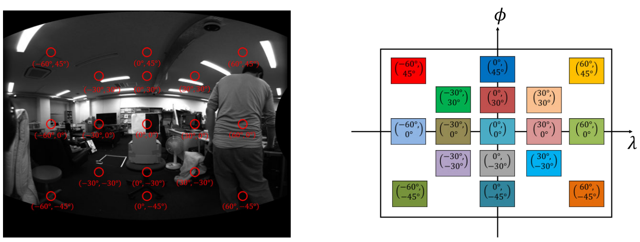
A. Experimental Conditions

We conducted an experiment to evaluate the accuracy of the proposed method ' s distance measurement. Fig. 4 shows the constructed fisheye stereo camera. The CMOS cameras are the Point Grey Research Flea3, and the fisheye lenses are the SPACE TV1634M. The number of pixels is 1328 × 1048 pixels, the baseline length is 52 mm, the measurement range in the horizontal direction is 165 °, and the vertical direction is 132 °. Since the camera searches for corresponding points to the right during stereo matching, the measurement range in the horizontal direction is narrower than the horizontal angle of the camera ' s view. Intrinsic parameters of the fisheye camera were estimated by utilizing the OcamCalib Toolbox [10] in MATLAB. The template size is 7 × 7, and the disparity search range is 48 pixels. Figure 5 shows a diagram in which the experimental environment and measurement points are shown by color. Measurement distances were set to 1 m and 5 m, and the measurement target was set as the border between black and white paper. For the distance measurement result, the measurement values of 5 points in total for each point of interest and two points above and below were taken as one measurement, and five measurements were performed, and the mean and the standard deviation were obtained from totally 25 points. The feature points were extracted for buildings with the distance of about 300 m surrounded by a red rectangle in Fig. 3, and points with a Euclidean distance of 10 pixels or less were used. The number of images taken was 230, and 23,239 feature points were extracted. The threshold value for disparity offset map creation was set with the following conditions.

(Cond.1) Euclidean distance $= 50$ pixel, $\sigma = 25$ pixel.

(Cond.2) Euclidean distance $= 100$ pixel, $\sigma = 50$ pixel.

Fig. 4. Fisheye stereo camera



(a) Experimental environment (b) Measurement points

Fig. 5. Experimental environment and measurement points

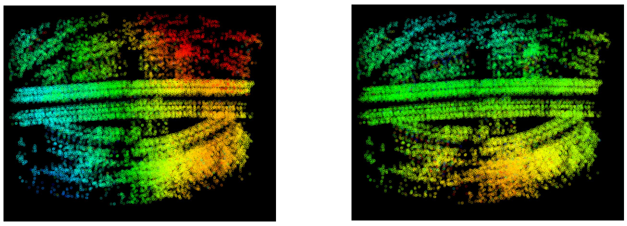
B. Experiment Results

The disparity errors of the feature points are shown in Fig. 6, and the offset maps obtained from Fig. 6 are shown in Fig. 7 and Fig. 8 for condition 1 and 2 respectively. Figures 9-11 show the effects of map correction in range images, error of measured distances, and their standard deviations. In Fig. 6-8, the colors of blue to red correspond to -5.0 to 5.0 pixels. Points with disparity less than -5.0 pixel and more than 5.0 pixel were set to blue and red respectively, and the part where there are no points in the periphery and the disparity error cannot be obtained is black. In Fig. 9, the colors of red to blue correspond to 0.0 to 10 m and more. The colors of the bar graph of Fig. 10 and Fig. 11 correspond to the measurement points of Fig. 5(b).

From Fig. 10 and Fig. 11, errors are reduced by making corrections. The error decreased to a maximum of about 0.16 m at the distance of 1 m and a maximum of about 1.0 m at the distance of 5 m. It is considered that the reason for the improvement of the error is larger in the result of 5 m than 1 m is that an offset map is obtained for the distant object. In addition, it is considered that the large error is in a part where the feature points are sparse in Fig. 6 and in the part where the disparity error of the feature point is highly biased. In addition, the distance accuracy is mostly the same in conditions 1 and 2 of the disparity offset map

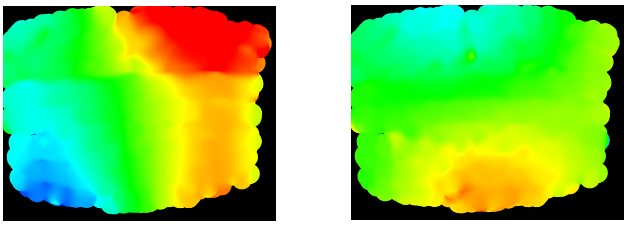
V. CONCLUSIONS

In this paper, we showed that the distance accuracy of the fisheye stereo camera using the equirectangular image can be improved by performing image correction using a disparity offset map. In future works, we will aim to further improve accuracy by improving the method of selecting feature points used for disparity errors and using a disparity offset map to verify changing to a closer target.



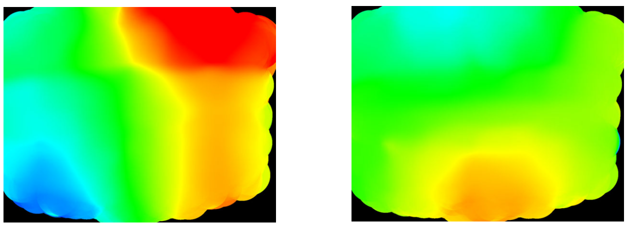
(a) x direction (b) y direction

Fig. 6. Disparity errors of feature points



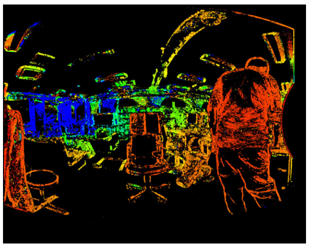
(a) x direction (b) y direction

Fig. 7. Disparity offset map (Cond.1)

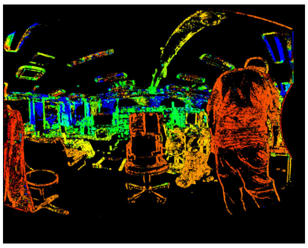


(a) x direction (b) y direction

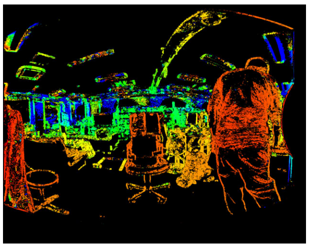
Fig. 8. Disparity offset map (Cond.2)



(a) Without correction

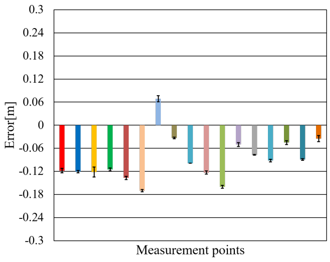


(b) With correction (Cond.1)

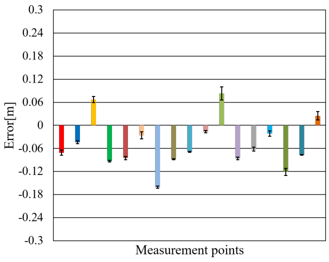


(c) With correction (Cond.2)

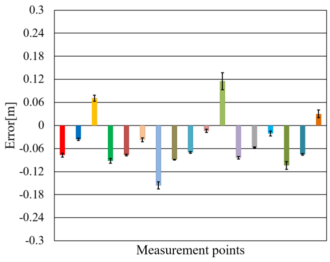
Fig. 9. Range images



(a) Without correction

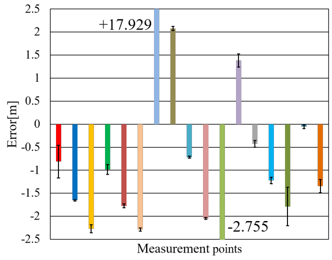


(b)With correction (Cond.1)

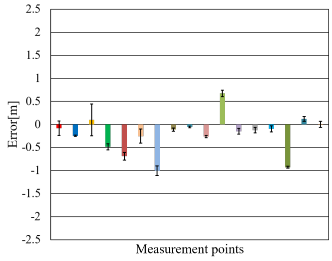


(c)With correction (Cond.2)

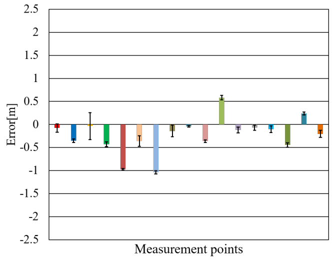
Fig. 10. Distance measurement error and standard deviation for 1 m



(a) Without correction



(b) With correction (Cond.1)



(c) With correction (Cond.2)

Fig. 11. Distance measurement error and standard deviation for 5 m

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