IEICE TRANSACTIONS

on Fundamentals of Electronics, Communications and Computer Sciences

DOI:10.1587/transfun.2024IML0001

Publicized:2025/01/14

This advance publication article will be replaced by the finalized version after proofreading.

A PUBLICATION OF THE ENGINEERING SCIENCES SOCIETY

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LETTER *Special Section on Image Media Quality*

Self-Position Estimation of Construction Equipment using a 360-Degree Camera and UAV Marker

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SUMMARY In recent years, the construction industry has been advancing construction DX and ICT construction. These efforts assume the availability of a communication environment, which may be challenging in certain terrains, such as canyons or underground. Self-position estimation, indispensable for the autonomous operation of construction machinery, is also a critical topic. In this study, multiple airborne markers with local coordinates measured by surveying instruments were detected in images acquired by a 360-degree camera mounted on a construction machine to estimate the machine's self-position.

keywords: *Localization, 360-degree camera, UAV marker*

1. Introduction

With Japan's declining and aging population, there is a growing demand for increased productivity in all industries. In the construction industry, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) is promoting i-Construction [1], which utilizes ICT and other technologies in all construction production processes, and unmanned construction is an important theme to be realized in the construction industry, where accidents resulting in death or injury [2] are common. Currently, GNSS [3] is the main method used for location information in unmanned construction, but it is difficult to use GNSS in canyon areas because satellite signals are difficult to reach. For such points, self-position estimation in a local coordinate space that does not depend on GNSS is necessary. Methods using height information [4] and stereo surveying [5] have been considered for self-position estimation using a 360-degree camera in a local environment.

In this study, it is necessary to construct an independent environment because the point is assumed to be in a canyon area or other areas where satellite signals cannot reach. Therefore, local coordinates are assigned to markers installed at the construction point, and these markers are photographed by a 360-degree camera attached to a construction machine. The assigned coordinates and image coordinates are used for self-position estimation.

2. Localization using a 360-Degree Camera

As shown in Fig. 1, the image obtained by a 360-degree camera is a rectangular image created by expanding a spherical image into a panoramic image. In a panoramic image, pixels and angles have a linear (proportional) relationship, and the horizon is maintained by the gyro function.

To verify the relationship between the spherical image and the panorama image, coordinate lines were drawn on a flat vertical wall from the camera's perspective, and a spherical image was captured. On this wall, lines indicating constant horizontal angles relative to the camera were drawn as hyperbolas, and lines indicating constant vertical angles were drawn as vertical lines, according to Eq. (1). In the spherical image of this wall, it was observed that the lines indicating both vertical and horizontal angles were equidistant, as shown in Fig. 2. This indicates that in a spherical image, the angle change per pixel is constant. Utilizing this characteristic, the camera's position was calculated based on the relationship between the number of pixels in the celestial image and the corresponding angles.

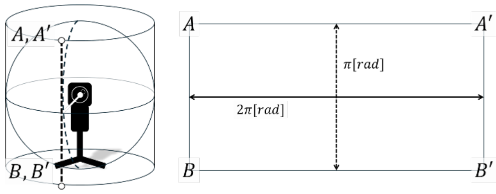
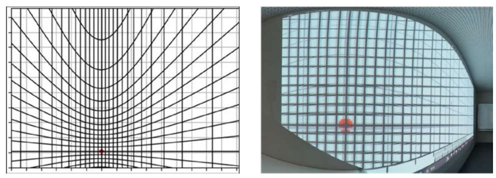


Fig. 1 Imaged figure of a right-angle cylindrical view.



(a) equirectangular curve (b) 360-degree camera shot

Fig. 2 Procedure for checking the projection method.

$$(\boldsymbol{d}\tan\boldsymbol{\varphi},\ \boldsymbol{d}\sec\boldsymbol{\varphi}\cot\boldsymbol{\theta}) \quad (1)$$

d : Distance to wall [m]

φ, θ : Longitude, Latitude [rad]

The calculation method of 360-degree camera coordinate is shown. Since the information obtained from the panoramic image is in pixels, it is converted to angles from Eq. (2) based on the relationship between camera resolution and circumference.

$$[rad] = \frac{\pi}{pic} \times [px] \quad (2)$$

pic : Vertical or horizontal pixels (3264 px)

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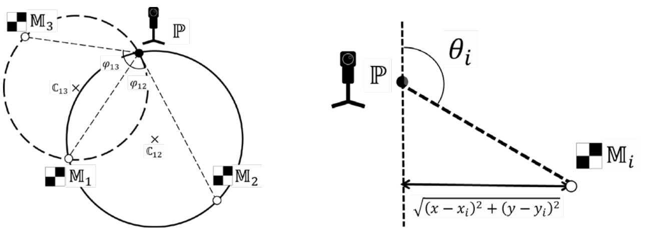
The horizontal plane is the X-Y coordinate and the vertical axis is the Z coordinate. First, since the angles obtained from the panoramic image are in the image coordinate system, a unit transformation must be performed. Since the vertical width of Fig. 3 or the image corresponds to π[rad] (the horizontal width is 2π[rad]), it can be obtained from Eq. (3). Note that the image coordinate system and the spatial coordinate system have different signs in the horizontal direction.

Next, the horizontal distance between the camera and the marker and the zenith angle of the marker are used to obtain the Z coordinate in Eq. (4). This time, since the horizontally corrected image is used, the equation is valid under horizontal conditions.



(a) X-Y coordinate (b) Z coordinate

Fig. 3 Camera position calculation method.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} Y & -X \\ X & Y \end{bmatrix}^{-1} \begin{bmatrix} -Y & X & \mathbb{C}_{12} \times \mathbb{C}_{13} \\ X & Y & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ -2 \end{bmatrix} \qquad (3)$$

Supplementary formula :

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \mathbb{C}_{12} - \mathbb{C}_{13}$$

$$\mathbb{C}_{mn} = \frac{1}{2} \begin{bmatrix} x_m + x_n & y_m - y_n \\ y_m + y_n & -x_m + x_n \end{bmatrix} \begin{bmatrix} 1 \\ cot\ \varphi_{mn} \end{bmatrix}.$$

$$z = z_i - \sqrt{(x_i - x)^2 + (y_i - y)^2} \cdot cot\theta_i \qquad (4)$$

$\mathbb{P}(x,\ y,\ z)$: 360-degree camera coordinates

$x_i,\ y_i,\ z_i$: Coordinates of marker i ($\mathbb{M}_i$)

3. Experimental Method and Result

Nine anti-aircraft markers for UAVs (markers) were set up inside the campus, and 360-degree cameras were placed inside the markers at a total of 11 locations in sequence and photographed (Fig. 4). The coordinates of the markers on the panoramic image were manually obtained to avoid false positives due to image processing, etc. The local coordinates of the point including the 360-degree camera were surveyed with a Total Station (TS). The locations of the markers and cameras are shown in Fig. 5.

At each location, any three of the nine markers are selected, and the camera's self-position is estimated using Eq. (2) and (3). There are up to 84 ways to select markers at each location, but the selection of 3 markers is limited because not all 9 markers may be in the image depending on the camera position.

(a) On-point scenery (b) Marker (c) 360-degree camera

Fig. 4 Experimental setup.

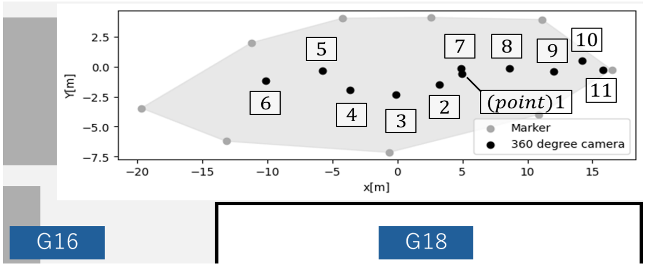


Fig. 5 Location of markers.

The camera coordinates surveyed by TS were compared with the estimated values as true values. The error calculation of the position coordinates is obtained by Eq. (5). In this experiment, the allowable error was set at 0.100 m [6] in consideration of practical use at the work point, and the "true rate" was defined as the percentage that satisfied this requirement. Table 1 shows the representative values for each location including it. Here, the number of combinations is the number of combinations of three markers obtained at each location. Overall, the average error from the true value was 0.127 m, the minimum error was 0.056 m, and the maximum error was 3.644 m. The acceptable error of 0.100 m was not met at all locations.

The maximum error was extremely large, as at site 6, and at sites 10 and 11, the number of combinations was small because the markers were in blind spots and could not be captured well.

$$\sqrt{(\mathbf{x}-\mathbf{x_t})^2 + (\mathbf{y}-\mathbf{y_t})^2 + (\mathbf{z}-\mathbf{z_t})^2} \qquad (5)$$

$(x_t,\ y_t,\ z_t)$: true value

Table 1 Representative value for the calculated results for each location.

	True rate[%]	mean error[m]	Min. error[m]	Max. error[m]	combination
point1	74.29	0.062	0.024	1.055	35
point2	71.43	0.062	0.008	0.534	56
point3	53.57	0.027	0.027	2.607	56
point4	58.93	0.070	0.009	2.999	56
point5	60.00	0.064	0.034	1.764	20
point6	**28.57**	**0.137**	0.037	**18.142**	35
point7	50.00	0.086	0.019	1.655	56
point8	40.00	**0.165**	0.019	**6.886**	35
point9	**20.00**	**0.162**	0.054	**3.389**	20
point10	**0.00**	**0.348**	0.267	0.687	**4**
point11	**0.00**	**0.216**	0.120	0.360	**4**
average	41.53	**0.127**	0.056	**3.644**	34

4. Discussion

Depending on the position of the 360-degree camera, the distance from the marker may be too far, resulting in a large error. Fig. 6 shows the results of visualizing the average error at each location as a circle. Fig. 6 shows that the closer to the center of the polygon created by the markers, the smaller the error. Therefore, it is important to place the markers in consideration of the positional relationship between the range of movement and the center of the figure.

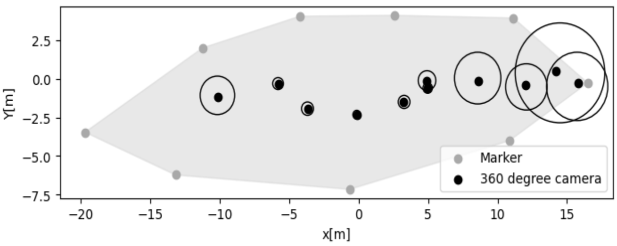
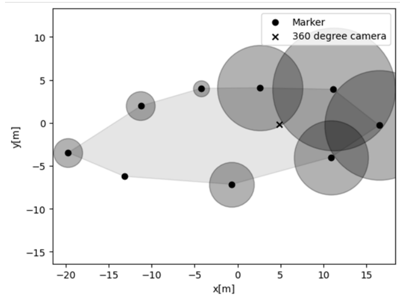
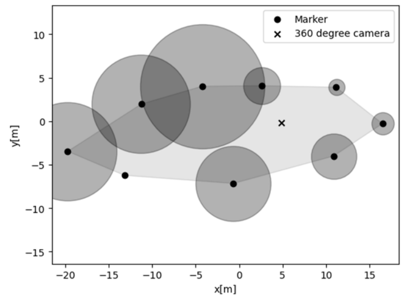


Fig. 6 Error circle.

Due to the nature of the coordinate calculation, the closer the vectors composed of the camera and marker are parallel or perpendicular, the more divergent the values will be, resulting in errors. Fig. 7 visualizes the number of "True" or "False" markers selected at location 7, where the correct response rate is 50%. From Fig. 7, when calculating coordinates more correctly, care should be taken to select markers closer to the camera and less distant ones. From these considerations, we believe that there is an optimal distance between the marker and the camera that should be selected for this self-position estimation.



(a) True answers



(b) False answers

Fig. 7 Visualization of marker selection for True and False answers at point 7.

5. Conclusion

In this study, self-position estimation was performed by detecting airworthiness markers that had been given local coordinates in advance by surveying instruments on images acquired by a 360-degree camera. The markers, which were fixed and installed at nine locations in advance, were photographed by a 360-degree camera, and self-position estimation was performed from the obtained panoramic images at 11 different locations. The experimental results showed that the average error in self-position estimation was 0.127 m, which did not meet the target acceptable error of 0.100 m. However, it was clear that the distance relationship between the marker used to calculate the position and the camera position in the case of self-position estimation affects the accuracy of the estimation.

Future issues include the derivation of the optimal relationship between markers and camera positions for self-position estimation, the construction of a marker detection model from camera images using AI, etc., and the verification of real-time self-position estimation using video images.

Acknowledgement

This work is supported by OTAKA corporation (Kurobe, Toyama, JAPAN).

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