Development of Composite Markers for High-Precision Industrial 3D Inspection Systems

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This study focuses on the development of markers for high-precision industrial 3D inspection systems that employ camera-based imaging. Previous marker optimizations have demonstrated effectiveness in two-dimensional detection. However, in a three-dimensional inspection context, traditional markers fail to maintain a consistent intensity distribution across varying photographic angles. To overcome this challenge, we propose a novel methodology: the calculation and quantification of deviations between the fitted center and the actual center of markers at different angles.

By determining their plane positions at the detection center from two distinct angles, each marker's three-dimensional detection position is reconstructed. This restoration further allows for accurate positioning and measurement of the detected object in three-dimensional space, enhancing the detection system's accuracy and efficiency. By reestablishing the triangular posture, each marker's detection position is brought closer to its actual position, enabling the calculation of the composite marker's central position based on the triangle's positional relationship.

This study employs a simulation method to compare the detection result deviations between single markers and compound markers. The findings indicate that this methodology effectively optimizes the issue of inconsistent light intensity distribution at different shooting angles. This solution offers an accurate and reliable 3D positioning strategy for the continued development of industrial 3D detection systems.

1. Introduction

In the field of visual navigation and three-dimensional spatial motion detection, high-precision motion detection for mechanical arms has always been a pivotal area of research. Currently, the prevalent vision-based motion detection methods often struggle to achieve subpixel-level precision, undoubtedly limiting their broad application.[1] Therefore, in this study, a novel motion detection method was proposed, which employs model fitting to attain subpixel-level accuracy in motion detection.

During the development of two-dimensional motion detection methods, markers made of plastic balls connected by optical fibers generally met the research requirements.[2] However, when our perspective expands to three-dimensional spatial motion detection, the situation changes significantly. During the three-dimensional motion detection, the joint detection by multiple cameras becomes indispensable. Still, this necessity raises a new challenge. The optical fiber connected plastic ball markers show inconsistent light intensity distribution at different angles, leading to a deviation between the detection center and the actual center. This deviation can cause an undeniable impact on multi-camera joint detection, posing a severe threat to the accuracy of detection.

After analyzing the angle between the marker's normal and the camera shooting angle, and according to the experimentally measured relationship between this angle and the deviation, this study compensates for the positional deviation of the markers. The high-precision positional information that corresponds to the markers.

2. Developed composite marker and experimental setup

To address the problem of deviation between the detection center and the actual center, a new design of marker was developed in this study as shown in Figure 1. By setting up composite markers with high

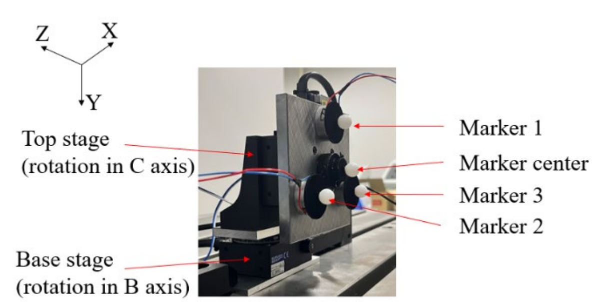

Fig. 1 Design of marker

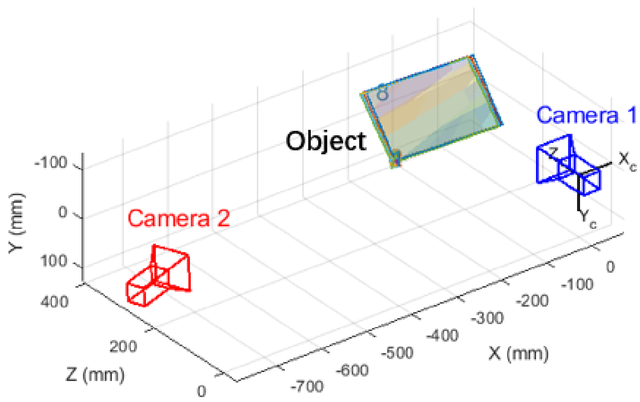

Fig. 2 Illustrates the relationship between the camera positions

Table 1 Experimental Parameters

Camera resolution	800×600 pixel
Sampling frequency	250 fps
Marker diameter	12 mm

positional accuracy, and conducting individual detection for each marker, the posture between the markers based on the camera is reconstructed.

The research utilized an experimental setup featuring a central plastic sphere with an LED light as a marker. A magnet was affixed to the marker's base to control and adjust the position relationship between the marker and the device. The marker's center and the rotation stage's rotational axis's deviation were contained within 5μm, as ensured by a Dial gauge. Three additional markers were installed in a triangular arrangement around the Marker center, with a positional offset of 40mm and a deviation limited within 10 μm. This setup allowed observations from various perspectives. Notably, all markers were self-made, which ensured control over their dimensions and shapes.

Figure 2 presents the positions of cameras used in the study. In the measurement of the error map, only Camera 1 was utilized. For the three-dimensional reconstruction in Chapter 4, Camera 2 was introduced. The setup's methodology involved rotating the markers using the rotation stage and identifying the markers' position via a camera. Deviations between the detected position and the actual physical center of the markers were noted. This data became part of the compensation algorithm and a reference for optimizing the setup.

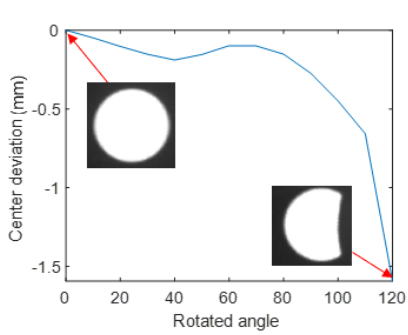

Fig. 3 Relationship between deviation and shooting angle, and performance of intensity distribution

3. Measurement of error map

3.1 Measurement Method

In the experiment for measuring the error map, the Marker center was rotated using the rotation stage. During this process, an investigation was conducted to identify the deviations between the actual physical center of the Marker center and its detected location by the camera. Because the Marker center is manually aligned on the rotation center of the stages within 5 μm deviation, the nominal positional change of the marker is assumed to be zero. The marker was rotated in increments of 10 degrees using the rotation stage, covering a range of 0 to 120 degrees.

3. 2 Measurement Results

The deviations observed during the rotation across the specified range were recorded. Figure 3 represented the deviation between the actual and detected positions of the marker as it was rotated by the rotation stage. At the same time, the image of the marker is shown. When the rotation angle reaches 120 degrees, it can be found that the base of the marker obscures the marker, which directly leads to a sharp change in the deviation of the center of the marker. These data points served as a primary source for the construction of the error map. In later stages of analysis and error compensation, the collected data were employed by incorporating interpolation methods to estimate the deviations at the unmeasured positions.

4. Compensation of position identification error

4. 1 Method

In an attempt to compensate for the position identification error, a unique method was employed. This method centered around the use of an algorithm that factored in the positional offsets of the markers. The Marker center was rotated in 5-degree increments, first by manipulating the rotation stage at the base to achieve a 45-degree rotation, then the rotation stage at the top for another 45-degree rotation. This process created a theoretical trajectory that resembled an eighth of an arc (more accurately, nine points at 5-degree intervals on a circle). The angular position of the markers was then calculated based on the triangular configuration and was used for compensating the detected position.

4.2 Experiment

In the experimental phase, the second camera was installed as illustrated in Figure 2. A chessboard pattern was employed to capture a substantial number of paired images. This strategy facilitated the calibration process, enabling the acquisition of distortion parameters for the rectification of image distortion and intrinsic parameters for 3D reconstruction. Moreover, it allowed for the computation of the extrinsic parameters, namely, the translation matrix and rotation matrix, which define the spatial relationship between the two cameras.

The central marker was rotated in 5-degree increments using the rotation stage. Initially, the base rotation stage, operating on the B axis, was meticulously manipulated to attain a rotation of 45 degrees.

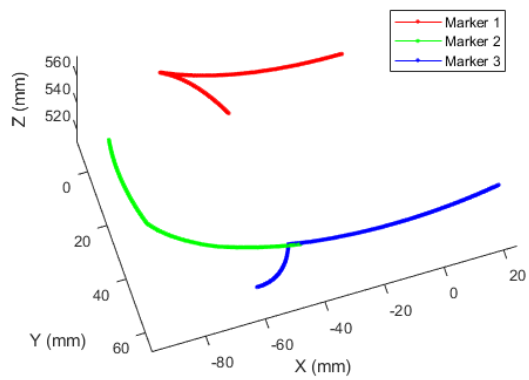

Fig. 4 Three-dimensional trajectories of Marker 1, Marker 2 and Marker 3

Subsequently, the top rotation stage, functioning on the C axis, was maneuvered to achieve an additional 45-degree rotation. This process yielded a theoretical trajectory for the central marker that resembled an eighth of a circle.

The three-dimensional coordinates of the three individual markers constituting the compound marker were calculated, as shown in Figure 4. The posture of the triangle made by each independent marker within the compound marker was computed frame by frame. This computation enabled the generation of a compensatory value from the angle between the normal and the camera, with the value being interpolated from the previously recorded experimental data. The distance was interpolated based on the experimentally measured deviation und er these angular conditions.

Using the rectified binocular position information, triangulation was used to obtain the position information of the marker after compensation. The comparison results before and after the implementation of the compensation method are displayed in Figure 5. The motion of the single marker was set to be the same as that of the compound marker. This allowed for the examination of the motion trajectory of the single marker before and after compensation. The deviation between the detected trajectory and the fitted circle was magnified through the least squares method, showcasing the differences between the two trajectories.

5. Conclusion

In conclusion, our study presented the advancement of composite markers aimed at enhancing precision in industrial 3D inspection systems. The investigation grappled with the issue of inconsistencies between the detected center and the actual center of markers, a problem that arises due to varying light intensity distribution at different angles. To evaluate the proposed method's efficacy, we conducted a simulation that, despite its simplifying assumptions like overlooking camera field diffusion and distortion, still demonstrated the potential of our approach.

While expectations were set high, the experimental results manifested a moderate yet notable 35% enhancement in performance after considering the deviation and implementing appropriate compensation measures. However, this improvement fell short of the

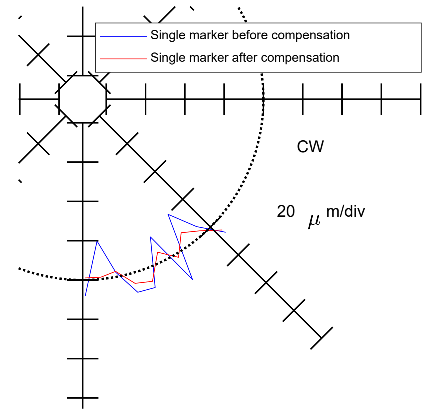

Fig. 5 Comparison results before and after applying the compensation method

anticipated levels. This discrepancy could potentially be ascribed to several complex influencing factors. For example, alterations in the marker's position within the camera's field of view, combined with the marker's self-rotation during the motion, could result in a complex distribution of deviations. Moreover, variations among the markers or asymmetry of the marker around its own axis of rotation could also contribute significantly to this observed disparity.

These findings indicate that while our method holds promise, a persistent discrepancy remains between the actual center of the marker's motion trajectory and its corresponding position within the visually-based coordinate system. Future research efforts should be directed towards refining the marker and the model fitting process. Doing so would further minimize these discrepancies, ultimately augmenting the accuracy of motion detection in a three-dimensional space.

REFERENCES

1. Besl, P. J. and McKay, N. D., "Method for registration of 3-D shapes." In Sensor fusion IV: control paradigms and data structures., Vol. 1611, pp. 586-606, 1992
2. Huang, H., Kono, D. and Toyoura, M., "Vision-based vibration measurement of machine tool." Journal of Advanced Mechanical Design, Systems, and Manufacturing., Vol. 16, No. 1, pp. JAMDSM0014-JAMDSM0014, 2022