A monocular vision system based on cooperative targets detection for aircraft pose measurement

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Abstract. In this paper, a monocular vision measurement system based on cooperative targets detection is proposed, which can capture the three-dimensional information of objects by recognizing the checkerboard target and calculating of the feature points. The aircraft pose measurement is an important problem for aircraft’s monitoring and control. Monocular vision system has a good performance in the range of meter. This paper proposes an algorithm based on coplanar rectangular feature to determine the unique solution of distance and angle. A continuous frame detection method is presented to solve the problem of corners’ transition caused by symmetry of the targets. Besides, a displacement table test system based on three-dimensional precision and measurement system human-computer interaction software has been built. Experiment result shows that it has a precision of 2mm in the range of 300mm to 1000mm, which can meet the requirement of the position measurement in the aircraft cabin.

1. Introduction
The aircraft pose measurement system is an important subject of aircraft monitoring and control. Rich information can be obtained by visual measurement methods, which has a good performance in short distance. Targets detection in visual measurement can be divided into cooperative targets and non-cooperative targets. When measuring based on a cooperative target, a target made with a specific size and shape is used, together with a single camera to require pictures of it. The key problem of monocular vision measurement is target detection and pose solution [5, 7, 8]. Target detection is to detect the feature points for the later calculation. In the aspect of target detection, this paper uses the checkerboard as the target to detect the four corners of the boundary, which transforms the problem into similar P4P problem with four points as the characteristic point[2]. In terms of pose solution, a four-point fixed method based on spatial fixation is adopted.

In order to verify the measurement range and precision of the whole measurement system, a stepper motor is used to test the distance and angle of X, Y and Z in three directions. The reliability and measurement of the algorithm accuracy is verified as well at the same time. The human-computer interaction interface based on MFC (Microsoft Foundation Classes) is developed, and the location information can be observed in real time and the intuitive real-time dynamic curve is displayed. Experiment shows that the chessboard target has more features and is easy to extract the feature reliability, and the extracted feature pixel is sub-pixel level, which can meet the requirement of high precision calculation within 300mm ~ 1000mm.
2. System Design

2.1. Hardware System Design
The system consists of simulated aircraft, a specific target, the lens, the camera, the light source, the computer and the installation of fixed parts. The camera uses an industrial camera model whose image size required is 1286×962 and pixel size is 3.2μm×3.2μm. The interface is GigE (Gigabit Ethernet). The camera is selected as the computer H0514-MP2 with the focal length of 5mm. Light source is the natural light; I3 processor is chosen for the computer. The hardware system can be used in the determination of the spacecraft’s own position. A series of chessboard targets can be set up in the cabin to determine the location of its own aircraft. Hardware build platform is shown in Figure 1.

![Figure 1. Hardware build platform](image)

2.2. Software System Design
A block diagram of the software system is shown in Figure 2. In this paper, MFC operating interface is designed in the environment of Windows7 operating environment and Visual Studio2010. As shown in Figure 3, the window for the collection of video images is on the right side and the real-time operating curve is on the left side. The bottom of the interface is the accurate data output value and the results are displayed in the corresponding dialog box. All of these can give an intuitive response to the location of the system’s dynamic information. The operation interface is shown in Figure 3.

2.3. Implement Error Analysis
The reason for the error may be that as follows: 1. the accuracy of the target design error that cannot fully meet the size and shape of the system; 2. Estimate the error when extracting the coordinates of the feature points; 3. the error of the displacement table’s movement.

2.3.1. Position Error Estimation. According to the error propagation theory, the horizontal measurement error caused by the pixel extraction error $\delta_x$ and the focal length error $\delta_f$ is as follows:
Likewise, the position error on the $Y_C$ axis is:

$$\delta_{y_i} = \sqrt{(\frac{\partial Y}{\partial x_i})^2 \delta_x^2 + (\frac{\partial Y}{\partial y_i})^2 \delta_y^2} = \frac{L}{f} \sqrt{\delta_x^2 + \frac{y_i^2}{f^2} \delta_y^2}$$

The propagation error on the $Z_C$ axis is:

$$\delta_{z_i} = \frac{L}{f} \sqrt{\frac{L^2}{R^2} \delta_x^2 + \delta_y^2}$$

Where $L$ represents the objects distance.

2.3.2. Angle Error Estimate. Taking the roll angle as an example, the roll angle error estimate is as follows:
\[ \delta \phi = \sqrt{\left(\frac{\partial \phi}{\partial x_u}\right)^2 \delta^2 x_u + \left(\frac{\partial \phi}{\partial f}\right)^2 \delta^2ail} = \sqrt{\frac{L^2}{D^2 f^2 - x_u^2 L^2} \delta^2 x_u + \frac{x_u^2 L^2}{D^2 f^2 (D^2 f^2 - x_u^2 L^2)} \delta^2 f} \]  \quad (4)

3. Measurement Principle

(1) Known that all control points \( P_0, P_1, P_2, P_3 \) are on the plane target \( \mathcal{P} \), the corresponding points on the image plane are \( q_0, q_1, q_2, q_3 \). \( P_0P_1P_2P_3 \) are rectangular, where \( P_0P_1 \perp P_0P_3, P_1P_2 /\!/ P_0P_1, |P_0P_1|=d_1, |P_1P_2|=d_2 \);  

(2) Spatial coordinates of \( P_0, P_1, P_2, P_3 \) in the target coordinate system are known, and the pixel coordinates of \( q_0, q_1, q_2, q_3 \) are known as well;  

(3) The internal parameter matrix \( A = \begin{bmatrix} \alpha_x & \gamma & u_0 \\ 0 & \alpha_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \) of the camera imaging model is known. Find the geometric transformation between the target coordinate system and the camera coordinate system.

4. Experiments

4.1. Camera Calibration

Camera calibration is the basis for studying visual measurement system. In this paper, Matlab2010a is used to verify the validity of the camera calibration method based on 2D planar target [1, 13]. A custom-made chessboard plate with an edge length of 20mm is used as the 2D planar target. 20 images are taken for each orientation of the target plane. Each image’s size is 1286 * 962. The calibration results of the camera parameters are shown in Table 1.

| Parameter | Value  |
|-----------|--------|
| \( \alpha_x \) | 1338.84 |
| \( \alpha_y \) | 1345.02 |
| \( \gamma \) | 0 |
| \( u_0 \) | 618.15 |
| \( v_0 \) | 475.73 |
| \( k_1 \) | -0.1116 |
| \( k_2 \) | 0.1242 |

4.2. Experimental Platform and Measurement Method

In order to verify the accuracy of the pose measurement method, a pose calculation platform is constructed. The test target is fixed on a 6-DOF rotary displacement table and the camera is fixed on the other side of the horizontal displacement table. Move the horizontal displacement table, the value of this position is the true value of this position. Operate of the displacement table to move a certain distance or rotation of an angle, which can be treat as the true value of pose changes. The distance test is performed by the horizontal displacement table. The angle test is accomplished by rotating the displacement table to rotate the target. Calculate the result of the posture output after moving or rotating, and compare the difference between the two calculated values with the displacement table or the rotation true value to obtain the measurement accuracy of the pose measurement system.
4.3. Experimental Process

According to the above-mentioned distance accuracy measurement method, the Z-direction distance test result is collated and the line chart is drawn as shown in Fig. 5; the Z-direction angle test result is collated and plotted as shown in Fig. 6.

![Figure 5.Z-direction distance test line chart (mm) Figure 6. Z-direction angle test line graph (°)](image)

According to the experimental method above, five representative test pictures are selected, respectively, to obtain the distance and angle measurements and the true value of the comparison, the distance shown in Table 2, the angle comparison shown in Table 3:

| Table 2. Target position relative to the camera data (mm) |
|--------------------------------------------------------|
| **Image** | **Actual Value** | **Measured Value** | **Piston Error** |
|-----------|-----------------|------------------|-----------------|
|           | Xₐ | Yₐ | Zₐ | Xₐ | Yₐ | Zₐ | Xₐ | Yₐ | Zₐ |
| 1         | 10  | 10  | 200 | 11.8 | 9.2 | 201.2 | 1.8 | -0.8 | 1.2 |
| 2         | 50  | 50  | 300 | 50.4 | 51.3 | 300.8 | 0.4 | 1.3 | 0.8 |
| 3         | 80  | 80  | 350 | 78.4 | 81.2 | 350.3 | -1.6 | 1.2 | 0.3 |
| 4         | 120 | 120 | 400 | 121.2 | 120.8 | 400.2 | 1.2 | 0.8 | 0.2 |
| 5         | 150 | 150 | 500 | 150.1 | 151.6 | 501.1 | 0.1 | 1.6 | 1.1 |

| Table 3. Position and orientation data of target relative to camera (°) |
|------------------------------------------------------------------|
| **Image** | **True Value** | **Measured Value** | **Gesture Value** |
|-----------|----------------|------------------|-----------------|
|           | ø | ϕ | ψ | ø | ϕ | ψ | ø | ϕ | ψ |
| 1         | 1  | 10 | 10 | 1.3 | 9.5 | 9.1 | 0.3 | -0.5 | -0.9 |
| 2         | 65 | 15 | 15 | 65.5 | 16.8 | 16.1 | 0.5 | 1.8 | 1.1 |
| 3         | 80 | 25 | 25 | 80.1 | 25.7 | 25.6 | 0.1 | 0.7 | 0.6 |
| 4         | 90 | 50 | 50 | 90.5 | 50.3 | 50.8 | 0.5 | 0.3 | 0.8 |
| 5         | 120| 60 | 60 | 119.8 | 60.9 | 61.4 | -0.2 | 0.9 | 1.4 |

5. Conclusions

In this paper, the error of this specific monocular vision measurement system target can reach less than 2mm in the range of 300mm~1000mm for distance positioning; the error of positioning of the angle, Z-axis direction can reach the error of less than 0.5 ° accuracy. The error of X, Y direction can reach the accuracy of less than 2 ° accuracy. All of the precision can meet the requirements of an application scenario. In this paper, the distance and attitude test have been carried out in the experiment and reached the desired index results; this system has been able to achieve real-time measurement of the target now. In practical application, the chessboard can be installed in the vehicle environment, and image information can be also available to capture at any time to determine its location.
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7. References
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