High-precision pose measurement method in wind tunnels based on laser-aided vision technology

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Abstract The measurement of position and attitude parameters for the isolated target from a high-speed aircraft is a great challenge in the field of wind tunnel simulation technology. In this paper, firstly, an image acquisition method for small high-speed targets with multi-dimensional movement in wind tunnel environment is proposed based on laser-aided vision technology. Combining with the trajectory simulation of the isolated model, the reasonably distributed laser stripes and self-luminous markers are utilized to capture clear images of the object. Then, after image processing, feature extraction, stereo correspondence and reconstruction, three-dimensional information of laser stripes and self-luminous markers are calculated. Besides, a pose solution method based on projected laser stripes and self-luminous markers is proposed. Finally, simulation experiments on measuring the position and attitude of high-speed rolling targets are conducted, as well as accuracy verification experiments. Experimental results indicate that the proposed method is feasible and efficient for measuring the pose parameters of rolling targets in wind tunnels.

1. Introduction

The pose measurement for models in wind tunnel experiments is widely required during the design and manufacture process of aircraft. Recently, characteristics of targets in the wind tunnel such as smaller volume, high-speed self-rotating motion, etc., have become a great challenge for pose measurement.

Much work has been done on the pose measurement for wind tunnel models. NASA Langley Research Center (LaRC) designed a standard package consisting of an accelerometer and several vibration isolation pads to measure the pitch attitude of wind tunnel models, and the accuracy of less than 0.01° could be obtained under smooth wind tunnel operating conditions. However, for rolling small targets, the measurement device proposed by LaRC was difficult to be installed inside the tested model. Besides, the roll and yaw attitudes could not be calculated. Optotrak™ developed a wind
tunnel pose measurement device utilizing linear CCD cameras and infrared cooperating markers. Although the device was quite accurate and stable, the infrared cooperating markers were relatively big and a powerful light source was necessary, which caused the inability of measuring small models. NASA LaRC also developed a pose measurement system based on binocular vision for wind tunnel models. The model images were captured continuously using two CCD cameras synchronously through the observing window. After measuring the 3D centroid coordinates of retro-reflection markers, the pose parameters of the wind tunnel model could be calculated. However, because the light was easily reflected to cameras by the thick glass of the observation window, the image quality was difficult to guarantee by using retro-reflection markers. In addition, the luminance and the space brightness uniformity of the images could be reduced in high-speed shooting conditions. Chen et al. have proposed a pose measurement method for models in the wind tunnel based on stereo vision. The cooperating targets with two bi-directional laser beams are placed between two screen walls, then the 3D coordinates of the bi-directional laser beam markers are obtained utilizing the stereo vision measurement technology, and the pose parameter of the model is then calculated through the rotating and translation matrixes. This method has improved the measurement precision by scaling the variation of the target. Fan et al. proposed an attitude angle and position tracking system for indoor carrier based on integrated navigation fusion strategy of integrated navigation fusion strategy (INS)/ultra wide band (UWB). They used feedback correction method to integrate the two subsystems, INS and UWB. Then, optimal comprehensive and filtering strategy based on fuzzy adaptive Kalman filtering (FAKF) is introduced to realize the data fusion of two subsystems. Though, the position and attitude angle parameters of the mobile carrier can be obtained in real time. However, when it comes to small rolling high-speed targets in the wind tunnel, UWB technology can hardly be applied in the complex measuring environment. Royal aircraft manufacturing company designed a combined pose measurement system (MAM). By using measurement system, they were able to measure four pose parameters of a model in the wind tunnel simultaneously, that is the pitch angle, roll angle, yaw angle and geometry offset of the model’s geometric center. Three orthorhombic servo accelerometers were utilized to measure the pitch angle and roll angle of the target. In addition, the yaw angle and horizontal offset of the model’s geometric center can be measured by photoelectric sensors. Results show that the measurement error of the yaw angle is less than 0.5°. However, the measurement accuracy is large which cannot satisfy the measurement requirements in the wind tunnel. Besides, there is not enough room for mounting accelerometers inside the model, thus this method is not suitable for small targets used in this paper. Crites from McDonnell Douglas aircraft manufacturing company developed a polarized laser goniometer to use the angle of attack of targets in the wind tunnel. They used two photoelectric detectors to detect transmitted intensity of two polaroid, respectively. Then the angle of attack can be calculated by Malus Law according to the relationship between the angle of attack and transmitted intensity. Though the incident light intensity fluctuation would not lead to instability of measurement results, the interference of lighting source cannot be avoided. Moreover, the method can only be used to measure the angle of attack of the model and the measuring range is relatively narrowed. Thus, it cannot meet the calculation requirements of pose measurement of models in this paper. Cheng et al. developed a position and attitude vision measurement system for drop test slender models in wind tunnel conditions. Unlike traditional binocular measurement methods, the system is based upon image matching technique between the 3D-digital model projection image and the image captured by cameras. This system presents a creative and effective thinking of pose measurement for wind tunnel models. Sun et al. presented a binocular vision measurement technique to measure models’ angle of attack in a wind tunnel and the results are of high precision. Liu et al. presented a high-precision pose measurement method for auxiliary fuel tank models in the wind tunnel based on self-luminous units. This method is capable of achieving brighter image features and higher signal to noise ratio of the images. However, it is hard to install self-luminous units in small-sized objects because of their large volume.

Many scholars and research institutions have made outstanding contributions to pose measurement for wind tunnel models. However, in wind tunnel environments with a large field of view, the pose measurement technology for small models with high-speed rolling movement is far from perfect. Thus, a stereoscopic vision pose measurement method based on structured light for high-speed rolling wind tunnel models is proposed in this paper, solving the problem of pose measuring for high-speed wind tunnel models in the complex environment. Firstly, to achieve objects’ pose measurement in complex wind tunnels, a high-speed binocular vision measurement system has been built. Afterwards, based on the predicted spatial trajectory of the model, lasers are properly distributed onto the model surface, and images of the model are captured by two high-speed cameras. Then, the sub-pixel center line of the model feature corners and 3D coordinates of the feature points can be obtained after the laser stripe is extracted and matched. Eventually, the pose parameters can be obtained through coordinate transformation.

2. High-speed image acquisition method

2.1. High-speed image acquisition method based on laser line structured light

Difficulties of the position and attitude measurement for small high-speed isolates in the complicated wind tunnel environment are as follows: (a) The high-speed and high-precision image acquisition is difficult to realize due to some factors, such as the complex wind tunnel environment with small and dark experimental space, high surface reflectance of the model and observation windows with strong reflection; (b) The marker tracking in the process of position and attitude measurement is difficult to achieve due to the fact that the small-model has a high separation speed with rolling movement in a short separation time.

Currently, there are two main image acquisition methods for wind tunnel targets. One of them is the method based on reflective markers with retro-reflection material and LED source surrounding the lenses. However, in wind tunnels with thick observation windows, most of the light would be reflected back by the window. Another way to acquire image is using infrared self-illumination markers. However, large
markers are difficult to be attached onto small targets. Due to the high image acquisition speed and the dark measurement environment, it is difficult to guarantee the high brightness and a higher signal-to-noise ratio of images. Therefore, a fast image acquisition method based on laser and self-luminous markers applied to the wind tunnel environment is proposed. With this method, no extra light source and surface treatment are needed. Besides, reflection problem with respect to observation window can also be solved.

Schematic diagram of the image acquiring method is shown in Fig. 1. Firstly, subminiature self-luminous markers are arranged onto the empennage of aircraft model. Then, the line laser is projected onto the movement space of the target reasonably according to the predicted trajectory of the isolates and images are captured by utilizing the ultrahigh-speed cameras. This method guarantees not only high signal-to-noise ratio of images, but also the aerodynamic shape of the model. As shown in Fig. 2, image captured by the high-speed cameras has higher signal-to-noise ratio and brightness, which forms a foundation for later image processing.

2.2. Self-luminous markers’ layout

During the rolling movement of the target, hidden phenomenon of markers occurs. Specifically, some visible markers at present would disappear next time, and some vanished markers would reappear as time goes on. As a result, pose information is difficult to be obtained. To solve the problem, a laser-aided method is proposed in this paper. Combined with structured light on the surface of the target, self-luminous makers distributing along the circumferential direction of the empennage are selected to calculate pose parameters, as shown in Fig. 3.

In this paper, multiple vertical distribution laser stripes are adopted to achieve real-time scalability of the object in the whole moving space. In order to obtain the proper laser stripe arrangement, ADAMS is used to simulate the trajectory of the target, as shown in Fig. 4. Simulation results show that as the target moves away from the ejection mechanism, its pitch angle increases, resulting in shorter projected length in the horizontal direction. In this paper, at least two laser stripes are required to achieve the pose measurement of the target. In that case, the idea that laser stripes are equally spaced in the vertical direction does not work, for there would be less structured light projected on the target surface as the target moves to the right. Therefore, the laser arrangement is decided by the following steps: (a) A reference plane is firstly defined where the target mainly moves and the laser stripes will be projected on; (b) Then a strip of laser stripe is projected onto the reference plane vertically and the space between the $i$ th laser stripe and the $(i+1)$ th one is calculated by:

$$D_{(i,i+1)} = N L \cos \alpha \cos \beta$$

where $D_{(i,i+1)}$ indicates the space between the $i$ th laser stripe and the $(i+1)$ th one; $\alpha$ and $\beta$ are the target’s pitch and yaw angles which are obtained from the simulative results; $N$ is the safety factor, and $L$ the total length of the target. The second laser stripe is projected onto the object plane according to the calculated space from the first one. (c) Repeat Step (b) until...
laser stripes are projected onto the whole field of view, as shown in Fig. 2.

3. Surface 3D information acquisition of high-speed rolling target

In this paper, laser line strips from laser transmitter are projected on the target surface and markers attached on the empennage of the model are implemented as feature information. Then, after the procedure of image processing, feature extraction and 3D reconstruction of the feature information, position and attitude parameters can be calculated.

3.1. Calibration method for vision system

Effective method for high-precision camera calibration is of importance in the application of computer vision, as shown in Fig. 5.

In this study, imaging model with distortion coefficients is used to solve the serious distortion problem caused by wide angle lenses. The equation can be written as:

\[
Z_{c} = \begin{bmatrix}
    u + \delta_x \\
    v + \delta_y \\
    1
\end{bmatrix} = \begin{bmatrix}
    C_x & 0 & \mu_x \\
    0 & C_y & \mu_y \\
    0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
    X_w \\
    Y_w \\
    Z_w
\end{bmatrix} = M \cdot M_{c}
\]

where \((u, v)\) represents the real point caused by image distortion, \((\delta_x, \delta_y)\) the aberration introduced to the imaging model, \((C_x, C_y)\) equivalent focal length, \((\mu_x, \mu_y)\) the coordinate of the principal point, \((X_w, Y_w, Z_w)\) the 3D coordinate of one point in the world coordinate, \(Z\) the scale factor, and rotation matrix \(R\) and translation matrix \(T\) are the extrinsic parameters.

Wide-angle lenses are used in our measurement system, so that magnification near the optical axis of the image is higher than that on the image border. In this case, the image distortion (mainly referred to the barrel distortion) of a certain point becomes more severe as it is more distant from the optical axis. To obtain more accurate camera parameters without image distortion, the small-sized calibration target in the center of the 2D calibration target was utilized to initially estimate the parameters of the cameras based on the ideal imaging model. The mapping matrix is firstly calculated using the maximum likelihood estimation method. Then, initial values of the intrinsic and extrinsic parameters can be calculated using at least three images. Given the influence of image distortion, the aberration model is introduced to our camera imaging model to compensate the intrinsic and extrinsic parameters of the cameras. In the end the intrinsic and extrinsic parameters of the cameras as well as the distortion parameters are optimized by the Levenberg–Marquard (LM) method. Firstly the left and right cameras are calibrated using the above-mentioned method, respectively. Then the overall parameters of two cameras are optimized by minimizing the optimization objective function \(F(x)\), which is the constraint between corners reconstructed and the actual one. To improve the measurement accuracy, distance between corners in pose calibration plate should be taken as the restraint. Since the coordinates of each corner in world coordinate system are known, suppose the coordinates of corner reconstructed by binocular vision system are equal to the actual coordinates. Therefore the formula can be expressed as:

\[
F(x) = \sum_{i=1}^{N} \left[ (X_a - X_i)^2 + (Y_a - Y_i)^2 + (Z_a - Z_i)^2 \right]
\]

where \((X_a, Y_a, Z_a)\) represent the actual coordinates of each corner, \((X_i, Y_i, Z_i)\) represent the coordinates of corner obtained by reconstruction. When the function value tends to be zero, namely reconstruction coordinates are approximately equal to the actual coordinates and the function gets the optimization. Thus the function is optimized using trust region algorithm and then global optimum solution of the intrinsic and extrinsic parameters of each camera can be obtained. The calibration targets are shown in Fig. 6.

3.2. Image pre-processing

Due to the existence of aircraft model, hatch door, wind tunnel inner wall and other disturbances in the field of view, irregular distortion in the projection of the laser stripes may occur, resulting in a more complex measuring background. However, background maintains static basically during the measuring process. Thus, in this paper, background subtraction by computing the difference between the current frame image pixels and the background image pixels is utilized to process the sequential images. Then, the equation can be expressed as:

\[
D_b(x, y) = f_b(x, y) - f_{bk}(x, y) \geq m
\]

where \(f_b(x, y)\) is the current image, \(f_{bk}(x, y)\) the background image, \(D_b(x, y)\) the frame difference and \(m\) predefined threshold. Then, through comparing the gray difference between the two images, the position of the moving object can be calculated, as shown in Fig. 7.

3.3. Image features extraction

High-precision extraction of feature line and feature point is the basic and most important step for the solution of pose parameters. In this paper, Sterger algorithm, a sub-pixel laser stripe center detection method based on Hessian matrix of image gray level, is employed due to its high precision and strong versatility. Hessian matrix for any point on the gray image can be written as:
is the (virtual) image of the optical center of the second camera in the image observed by the first camera. Similarly, the point \( p_r \) lies on the line \( l_r \) (epipolar line) associated with the point \( p_l \), and it passes through the point \( e_r \) (the epipole) where the baseline joining the optical centers \( O_\alpha \) and \( O_\beta \) intersects \( \Pi_l \) (image plane). The epipole \( e_r \) is the (virtual) image of the optical center \( O_\alpha \) of the first camera in the image observed by the second camera. Similarly, the point \( p_l \) lies on the epipolar line \( l_\beta \) associated with the point \( p_r \), and this line passes through the intersection \( e_\beta \) of the baseline with the plane \( \Pi_l \). The epipolar constraint implies that the relationship between \( p_l \) and \( p_r \) can be given by:

\[
p_l^T E p_r = 0
\]

where \( E \) is called essential matrix, and \( p_l \) and \( p_r \) describe the corresponding points on the left and right images, respectively. Meanwhile, since both image points \( p_l \) and \( p_r \) are on the two corresponding laser stripes to be registered by ordering constraint, the matching relationship can be ascertained through the epipolar geometry.
intersection between the two lines. Finally, the matching and reconstruction of laser stripes based on epipolar constraint and structure light can be obtained. The 3D reconstruction result is shown in Fig. 9.

4. Position and attitude solution

4.1. Axis fitting of target

Since errors relate to 3D information of laser stripes reconstructed by cameras exist, to fit the axis with high precision, points on the laser stripes are selected as many as possible. The object to be tested in wind tunnel environment is composed of warhead, missile body and projectile wing. Among the three different structures, the shape of missile body is cylinder, so the theoretic distance between all the 3D points on the light stripes and axis should be radius \( r \) of the cylinder. The equation for determining fitted axis based on three-dimensional data points can be given by:

\[
\min \sqrt{\sum \frac{1}{p^n} (d(p_i) - r)^2}
\]

s.t. \[ d(p_i) = \sqrt{(y - y_0)^2 + (z - z_0)^2 + (x - x_0)^2} \]

where \( P(x_i, y_i, z_i) \) stands for one point on the fitted axis, \( A(n, p, q) \) the direction vector of axis and \( d(p_i) \) the distance between point \( P_i(x_i, y_i, z_i) \) on the laser stripe and the fitted axis. Then, the axis can be solved stably using the LM optimized algorithm.

4.2. Pose solution

The position of the centroid can be obtained according to the known distance with respect to markers on the projectile wing and its position on the fitted axis. To establish the coordinate system, the centroid \( O \) is selected as the origin of the model-coordinate system after deciding the axis fitting and the centroid position, and the axis of the model is established as the \( X \)-axis. Another line through original point \( O \) is set up as the \( Y \)-axis which is parallel to vertical line created by the feature points and the axis. Moreover, \( Z \)-axis is established according to the right-handed system. Then, based on the aforementioned principles, the initial model-coordinate system (IMCS) and the current model-coordinate system (CMCS) are established respectively, as shown in Fig. 10. Finally, pose parameters of target can be obtained through calculating the rotation and translation matrix between the two coordinate systems.

The relationship between the point \( P = [x, y, z]^T \) in initial model-coordinate system and the corresponding \( \bar{P} = [x', y', z']^T \) in the current model-coordinate system can be written as:

\[
\begin{bmatrix}
  x' \\
  y' \\
  z'
\end{bmatrix} = \begin{bmatrix} x - x_0 \\
  y - y_0 \\
  z - z_0 \end{bmatrix} \text{ where } (x_0, y_0, z_0) \text{ depicts the centroid position of target in the world coordinate system, } R_{pt} \text{ is the coordinate-transformation matrix.}
\]

And

\[
R \begin{bmatrix} x \\ y \\ z \end{bmatrix} + T = \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}
\]

where \( T \) depicts the translational transfer matrix between the initial model-coordinate system and the current model-coordinate system. Consequently, \(-\theta_z, -\theta_x, -\theta_y\) are the yaw
angle, roll angle, and pitch angle of the target in world coordinate system, then according to the coordinates of three chosen points, the position and attitude parameters can be computed.

5. Experimental analysis

In this chapter, dropping experiment based on simulation test system in laboratory is conducted to verify the viability of the pose measurement system. Moreover, the calibration of the measurement system is completed by using high-precision calibration device. Experimental process will be presented in the following sections.

5.1. Measurement system

A pose measurement system applied to the enclosed wind tunnel environment based on structured light is developed in this paper. As shown in Fig. 11, the binocular vision measurement system contains two high-speed cameras (FASTCAM SA-X), two wide-angle lens (Nikon17-35), several lasers, a vibration isolated table, one computer and two sets of high-precision electrical control platforms. By distributing several lasers reasonably, the effective capture of the moving target within a larger field of view can be guaranteed. Electronic control platform is utilized to ensure the position stability of high-speed cameras, as well as the remote control of target. During pose measurement experiments, there is obvious vibration in the wind tunnel, which directly influences the accuracy of the measurement system. Thus, the vibration isolated table is used to reduce the ambient vibration. During the tests, all measuring devices are fixed on the vibration isolated table, thereby effectively reducing the measurement uncertainty caused by ambient vibration.

5.2. Simulation experimental equipment for wind tunnels

As shown in Fig. 12, experimental facilities consist of pose measurement system based on binocular vision, ejection mechanism and controlling system. In the test with measurement field of 1 m x 1 m, ejection mechanism and controlling system are utilized to eject the target out of the tank with a particular velocity, angular velocity and angle. Besides, line lasers are utilized to project structured light onto the movement space of the target reasonably according to the predicted trajectory of the isolates. Then the vision measurement system is triggered to measure pose information of the target synchronously and the actual pose measurement result of rolling target is verified.

5.3. Experimental data in simulated environment of wind tunnel

Since the experiments were conducted in the laboratory environment simulating the wind tunnel conditions, the supersonic airflow in the wind tunnel would not be simulated in the laboratory. So we can only simulate the ejection conditions of the measured object, setting the initial angular velocity and speed. The target will perform a freely falling body motion if not considering the air resistance. Then the measurement system is triggered to measure the pose information of the target.
The simulation target position results are shown in Fig. 13, in which X, Y, Z represent the displacement of the target along X, Y, Z direction, respectively. The simulation target attitude results are shown in Fig. 14. The target is ejected out of the tank with its initial velocity and angular velocity of 5.4 m/s and 184 rad/s respectively and the vision measurement system is triggered to measure pose information of the target synchronously.

The result of the position measurement is shown in Fig. 15. The result of the attitude measurement is shown in Fig. 16. The diagram indicates that the result is stable and precise enough to meet the wind tunnel requirements. It can be seen that the experimental trajectory coincides with the simulative results, indicating the system’s feasibility of pose measurements for moving objects.

5.4. Measurement accuracy verification

The calibration diagram of measurement system is shown in Fig. 17. The accuracy of the measurement system is evaluated through the high precision calibration of electronic platform. The displacement measurement deviations in each group are depicted in Fig. 18. The angle measurement deviations in each group are shown in Fig. 19.

As shown in Figs. 18 and 19, the mean square error of displacement measurement in X direction is 0.16 mm, while in Y direction it is 0.18 mm, and in Z direction it is 0.20 mm. The main errors are mainly from errors of light strip extraction and camera calibration. The mean square error of pitching angle precision is 0.12° and the yaw angle precision is 0.14°. The highprecision solution of measurement system for pitching angle and yaw angle results from high-precision of axis fitting. The roll angle precision is 0.80°, which mainly due to the smaller diameter of the object to be tested. In conclusion, the experimental results indicate that the proposed method can exhibit high accuracy for the position and attitude measurement of high-speed rolling target in the wind tunnel.

When a new experiment needs to be conducted, the cameras need to be reinstalled; there are some installation errors between the two cameras, the cameras and lenses as well. This may cause some changes in both the intrinsic and extrinsic parameters of the cameras. In this paper, we reduce the installation error by recalibrating the binocular vision system after each installation.
6. Conclusions

(1) In this paper, a pose measurement method based on laser structured light and binocular vision is proposed to realize the rapid and high precision pose measurement of the small rolling high-speed target in the dark narrow wind tunnel environment. By using laser structured light and miniature self-illumination unit in combination, the high signal-to-noise ratio image acquisition is implemented, and effects of the wind tunnel observation window on image quality is avoided.

(2) Moreover, a pose solution method based on structured light and circular markers is proposed to overcome the matching and recognition problem of markers caused by the “hidden phenomenon”. Then, the six pose parameters could be obtained according to the 3D information of markers.

(3) The pose measurement system based on structured light is established to finish the wind tunnel simulation experiment. The results indicate that the proposed measurement method and system can achieve the rapid pose measurement of the target, and the measurement precision satisfies the experiment requirement. Our further research will focus on the improvement of the measurement system, including the measurement speed, precision and its practical application in wind tunnel.

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References


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