Three-Dimensional Visual Measurement for MAV Aerodynamic Shape Based on Stroboscopic Imaging Technique

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Abstract: Current researches have obtained massive experimental results and analyses, however, they mainly use the high-speed image equipment to record object movement. This paper introduced a new three-dimensional visual measuring technique for flexible aerodynamic shape, which is based on stroboscopic imaging detection technique. By using this technique, continuous image data of micro air vehicle (MAV) aerodynamic shape during its movement were obtained in the situation in which there was no high-speed image equipment. In the experiment, features that describe surface texture information were extracted by using scale invariant feature transform (SIFT). Through matching, those points which are the same as the extracted SIFT features at different locations in stroboscopic image were searched. In order to improve the accuracy of tracking, RANSAC algorithm was applied to eliminating incorrect pairs. As a result, the corresponding relationship among extracted points at different locations in one picture was established and the morphological change value, then motion trace of feature points extracted from aerodynamic shape during movement could be calculated. The whole experiment framework was based on binocular vision measurement principle to obtain sufficient visibility and enough accuracy for tracking.

Keywords: aerodynamic shape; binocular vision measurement; stroboscopic imaging technique; scale invariant feature transform

基于频闪成像技术的MAV气动外形三维视觉测试

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摘　要：在目前的实验条件下虽已掌握了大量的气动外形测试数据和分析结果，但这些实验都是基于高速影像设备来完成物体运动记录的．为此，提出了一种基于频闪成像探测技术的柔性气动外形三维视觉检测方法，基于此方法，能够在不具备高速影像设备的条件下获取微小型飞行器(MAV)柔性气动外形的连续图像数据，使用尺度不变特征转换(SIFT)方法提取出描述表面纹理特性的特征点，在频闪图像中的各个不同位置依次进行搜索、匹配，找出特征点的同名点．为了提高跟踪精度，使用了RANSAC方法对误匹配对进行消除．实验结果表明，该方法不仅能实现柔性外形的形态学变化检测，而且能建立一幅频闪图像中不同位置上提取出的特征点之间的关系，从而计算出气动外形上特征点的运动轨迹．整个实验框架是基于双目立体视觉测量原理来满足检测与跟踪的高精度及可视性的．

关键词：气动外形；双目视觉测量；频闪成像技术；尺度不变特征转换

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In recent years, micro air vehicle (MAV) plays an important role in the field of military and civilian. But due to MAV's own structural features such as small scale, light weight, low speed and quick response, external disturbances become more pronounced. So anti-disturbance mechanism is now one of the research focuses both at home and abroad. Moreover, aerodynamic detection for MAV is the key technology to solve such anti-disturbance issues and make it more adaptable to complicated environment.

As an aircraft testing equipment, wind tunnel is usually utilized in the experiment to produce special flow, simulate real flight environment and access a variety of experimental data. Current experiments involve the three following main detection methods for aerodynamic characteristics. The first one is based on simulation and numerical calculation, which is widely carried out in research institutions at home and abroad such as CAAA and University of Michigan[1-2]. Through this method, aerodynamics and torque can be calculated with high accuracy. However, because it is an ideal model, experimental results are not able to solve problems occurring in practical flight. The second method uses a variety of force sensors to measure deformations or acting forces in the experimental model. Beihang University and Nanjing University of Aeronautics and Astronautics have obtained lots of experimental data in this way[3-4]. These parameters are useful for researching the characteristics of MAV aerodynamics affected by planform or morphological structure. However, due to its contact measurement mode, experiment equipment itself has interference effect on results. As a non-contact measurement, the third method is mainly based on visual detection principle to realize high precision and high speed. Common visual methods are the application of high-speed camera[5], binocular vision system[6] and particle image velocimetry technique[7], all of which usually have advantages over the previous two detection methods.

The visual detection method mainly relies on high-speed image equipment to record dynamic parameters, so its applications are limited by experimental conditions. This paper proposes a new visual measurement approach to record MAV aerodynamic shape change, which is based on stroboscopic imaging technique. Using this technique, continuous image data of MAV aerodynamic shape during movement can be obtained. Through the analysis of feature points extracted from aerodynamic shape, morphological change value and motion trace of MAV shape are finally calculated.

The rest of the paper is organized as follows. Section 1 describes compositions of this experiment system, especially binocular vision system. Section 2 introduces our proposed method that uses scale invariant feature transform (SIFT) features to detect and track moving object based on stroboscopic imaging technique. Section 3 reports experimental results for motion trace. Section 4 concludes the paper.

1 Compositions of experimental system

1.1 Construction of system

It is known that, wind tunnel is an important approach to analyzing MAV aerodynamic characteristics. In this paper, the testing environment is a shading enclosed space, in which some devices such as stroboscopic light and cameras are installed to achieve detection function. Experimental framework is shown in Fig. 1.

The stroboscopic light is used for obtaining continuous image data of the flexible aerodynamic shape during object movement. According to the position and motion speed of the object, light direction and flash frequency of stroboscopic light are adjusted correspondingly. So without high-speed image equipment, continuous movement of high-speed object can be recorded as dozens of overlapping images in one picture.

Since the principle of method we adopt relies on local feature extraction, the tested object used in the experiment should have some texture information on its surface. In addition, an airway device fixed on the framework is used to produce special external disturbance.

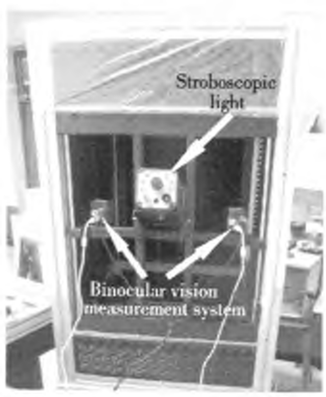

Fig. 1 Experimental framework

1.2 Binocular vision

On the framework, the position and pose of two cameras can be adjusted to change their baseline lengths and angles between baseline and optical axis. The binocular vision system here is mainly used to obtain sufficient visibility and enough accuracy for detecting, tracking and reconstructing. Compared with structured light measurement, binocular vision method depends more on object structure and surface texture. In this experiment, due to dozens of overlapping images in one picture, binocular vision method was able to avoid the confusion of modulated structured light in the image and establish the corresponding relationship among different locations.

The model of binocular vision is shown in Fig. 2, and the coordinate of any point in the left camera coordinate system (x_l, y_l, z_l) can be calculated by Eq. (1)

$$\begin{cases} x_l = z_l X_l / f_l \\ y_l = z_l Y_l / f_l \\ z_l = \dfrac{f_l(f_r t_1 - X_r t_3)}{X_r(r_7 X_l + r_8 Y_l + r_9 f_l) - f_r(r_1 X_l + r_2 Y_l + r_3 f_l)} \end{cases} \tag{1}$$

where (X_l Y_l) and (X_r Y_r) are the left and right camera image coordinates of spatial point respectively; f_l and f_r are the focal length of two cameras; r_1—r_9 are the parameters in rotation matrix $\boldsymbol{R}$; and t_1—t_3 are the parameters in translation matrix $\boldsymbol{T}$[8]. Since the midpoint of baseline is defined as the origin of the world coordinate system, the transition matrix between left camera coordinate system and world coordinate system is calculated by Eq. (2).

$$\begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} x_l \\ y_l \\ z_l \end{bmatrix} + \begin{bmatrix} B/2 \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

where (X_w Y_w Z_w) is the coordinate of any point in world coordinate system.

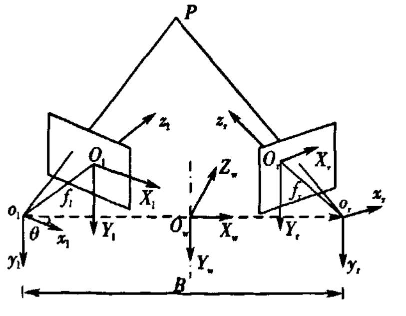

Fig. 2 Structural model of binocular vision measurement system

So if the focal length of two cameras, any point's two image coordinates, $\boldsymbol{R}$ and $\boldsymbol{T}$ are known, three-dimensional information of that point can be calculated easily. Given that parameter selection immediately influences binocular vision measurement system precision[9] and parameter values are partially constrained by testing environment, in the experiment system, 8 mm was selected as the focal length of two cameras, 410 mm was selected as the baseline length and two cameras were placed symmetrically with $\theta = 23°$.

2 Proposed method in this paper

2.1 SIFT feature extraction

Since the stroboscopic imaging technique is utilized to record the space motion and surface deformation of the object, some changes in illumination and image rotation will occur. Furthermore, scale space of images also change during object motion. Compared with other feature extraction methods such as SUSAN, Harris and Harris-Laplace, SIFT feature points are more adaptable to image scaling, rotation, noise, and partial changes in local deformation and illumination[10-11].

Firstly, the input image $I(x, y)$ is convoluted with a variable-scale Gaussian, $G(x, y, \sigma)$, to calculate the scale space of this image $L(x, y, \sigma)$:

$$L(x,y,\sigma) = G(x,y,\sigma) * I(x,y) \tag{3}$$

This scale space function is regarded as the only possible scale space kernel. Then scale space extrema is calculated as stable keypoint in the different-of-Gaussian image, which is produced by subtracting two adjacent scales.

$$D(x,y,\sigma) = (G(x,y,k\sigma) - G(x,y,\sigma)) * I(x,y) = L(x,y,k\sigma) - L(x,y,\sigma) \tag{4}$$

Secondly, some unreliable keypoints are removed by giving a threshold to confine the evaluation for each candidate and, correspondingly, the location and orientation of these feature points are detected by using related formulas. At last, a unique descriptor for each feature point is created to describe it and its surroundings by computing the gradient magnitude and orientation of the sample point and building a histogram of eight directions.

2.2 Matching

One of the major goals of matching is to search the points which are the same as any extracted SIFT feature at different locations in stroboscopic image. The corresponding coordinate relationship among extracted points at different locations is established.

In general matching process, one point and its nearest neighbor with minimum Euclidean distance in the database are defined as a matched pair. Due to ambiguous features or features that arise from background clutter, many matches are incorrect. Thus a more effective method for comparing the distance of the closest neighbor with that of the second-closest neighbor is adopted. Initial matches are shown in Fig. 3.

Fig. 3 Initial matches among different locations

2.3 RANSAC

The full name of RANSAC is random sample consensus. It is an algorithm used to fit mathematical model, estimate and optimize the parameters of a mathematical model from a set of data. In addition, RANSAC is also used to remove outliers and reserve correct points. In the algorithm, the input parameters are t, k and d. t is a threshold value of error tolerance for determination when a datum fits a model and d is the number of close data values required to assert that a model fits well to data. Both values need to be determined from specific requirement related to the application and the data set, possibly based on experimental evaluation. Another parameter k is the number of iterations performed by the algorithm, which can be determined theoretically[12]. Usually, k is calculated as follows:

$$k=\frac{\log(1-p)}{\log(1-w^n)} \tag{5}$$

where p is the probability that the RANSAC algorithm selects only inliers from the input data set when it chooses n points from which the model parameters are estimated; w is the probability of choosing an inlier each time a single point is selected; here n is the minimum number of data required to fit the model.

In this paper, in order to improve the accuracy of feature point matching, discard outliers and obtain an accurate affine transformation model, RANSAC algorithm was used. Based on several experimental calculations and analytical comparison, those parameters were selected as $n=4$, $p=0.99$, $w=0.5$ and $t=6$, respectively. For getting a correct and high precision model, the number of close data values d was generally required to be large enough.

The corresponding relationships after removing incorrect pairs are shown in Fig. 4. Results show that RANSAC algorithm could constantly correct parameters and remove outliers in the process of solving affine model. As a result, parameter error was reduced and tracking accuracy was improved correspondingly.

Fig. 4 Correctly matched pairs after using RANSAC

3 Experimental results

3.1 Camera calibration results

The objective of camera calibration is to determine intrinsic parameters and extrinsic parameters of vision system. In many cases, the performance of measurement strongly depends on the accuracy of camera calibration. Here, the experiment used Zhang's calibration[13] to calibrate 2D planar pattern. Using two identical CCD cameras with 1 280 × 1 024 pixels, 15 images of a planar checkerboard are obtained from different directions respectively, as shown in Fig. 5 and Fig. 6. Based on Camera Calibration Toolbox from Matlab, intrinsic parameters of two cameras and extrinsic parameters are calculated. The previous one is shown in Tab. 1, where (u_0 v_0) is the coordinates of the principal point in camera image coordinate system, and the extrinsic parameters are

$$
\boldsymbol{R}=\begin{bmatrix} 0.6812 & 0.0045 & 0.7321 \\ -0.0016 & 1 & -0.0047 \\ -0.7321 & 0.0020 & 0.6812 \end{bmatrix}
$$

$$
\boldsymbol{T}=\begin{bmatrix} -345.0187 \\ 5.3631 \\ 149.3381 \end{bmatrix}
$$

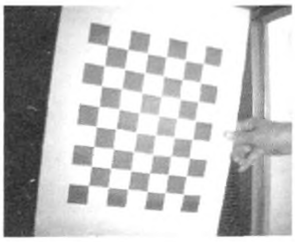

Fig. 5　Left image of a planar checkerboard

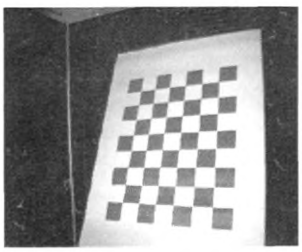

Fig. 6　Right image of a planar checkerboard

Tab. 1　Calibration results of camera intrinsic parameters

Camera	f/mm	u_0	v_0
Left	8.185	613.9	528.9
Right	8.167	663.0	546.1

3.2　Three-dimensional coordinate and surface fitting

Based on calibration parameters, the coordinate of any spatial point P can be calculated by Eqs. (1) and (2). Here, in order to analyze the valuable data, interest regions shown in Fig. 7 are selected arbitrarily at different locations in the left and right images respectively. The method proposed in Section 2 is used and three-dimensional information of feature points extracted from these regions is calculated, as shown in Fig. 8. After collecting the relationships among extracted points at different locations and corresponding spatial coordinates, free surface at each location is fitted and reconstructed, as shown in Fig. 9. These fitting surfaces are sufficient to represent the flexible shape under external disturbance. Finally, the morphological change value and motion trace of aerodynamic shape can be calculated.

Fig. 7　Interest regions selected at different locations

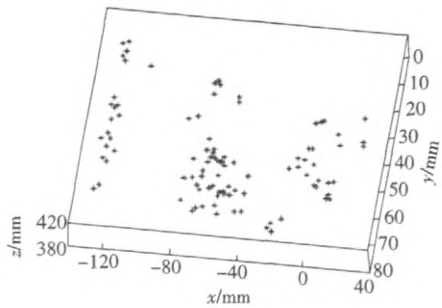

Fig. 8　Three-dimensional coordinates of corresponding feature points

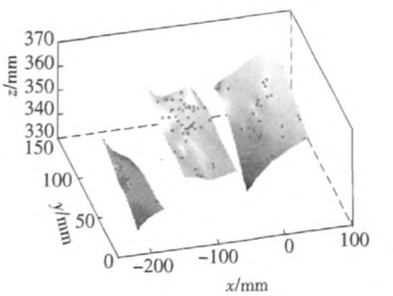

Fig. 9　Free surface at each location fitted from extracted feature points

4　Conclusions

Experimental results show that the proposed method within our system for detecting and tracking aerodynamic shape has successful and practical applications. In the situation in which there is no high-speed image equipment, this method is used to calculate the coordinates of feature points at different locations in stroboscopic image, to establish the corresponding relationships among these points and finally to obtain the morphological change value and motion trace of MAV shape. In the next research work, the following issues should be focused on as well. This method will be extended to flexible aerodynamic shape testing. At the present stage, only three-dimensional detection on object with rigid aerodynamic shape is researched. Next the measurement approach and optimization algorithm will be improved and finally three-dimensional detecting and tracking for deformable shape will be realized. The related theories will be derived. External disturbances such as airflow velocity, pressure and temperature will be combined with location and spatial interrelation of object to deduce interaction relationship between them.

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