A novel virtual four-ocular stereo vision system based on single camera for measuring insect motion parameters

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A novel virtual four-ocular stereo measurement system based on single high speed camera is proposed for measuring double beating wings of a high speed flapping insect. The principle of virtual monocular system consisting of a few planar mirrors and a single high speed camera is introduced. The stereo vision measurement principle based on optic triangulation is explained. The wing kinematics parameters are measured. Results show that this virtual stereo system not only decreases system cost extremely but also is effective to insect motion measurement.

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The development of micro-air vehicle (MAV) research in the field of aeronautics promotes the study of insect flight mechanism, as a result that measuring insect motion parameters becomes hotter in bionic study recent year. Compared with contact technique, non-contact techniques especially optics technique have been proved most successfully in measuring insect motion parameters. Optics methods make use of two dimensional (2D) information of sequence images gathered by high speed camera to resort three dimensional (3D) shapes, according to the difference of 3D reconstruction, these methods can be divided into symmetry method, plane method, stripe method, comb fringe projection method, and so on.

Both symmetry method and plane method are based on the kinematics symmetry assumption of near and far wings. Symmetry method makes use of corresponding points of outline in different wings to resort the wing contour, while plane method makes use of geometric analysis to reconstruct 3D spatial coordinates. But the two wings are not symmetry strictly in the course of beating motion actually, so both of above methods are sensitive to asymmetry. With strip method, a simulative wing model outline generated by a computer is divided into a number of chordwise strips, measurement is fulfilled by adjusting stripes in turn until each stripe matched well with leading and tailing edges of the wing[1,2]. Comb fringe projection method makes use of structure information brought by comb fringes projected on the wings to reconstruct 3D by optics triangulation, then the wing shape is obtained by interpolating and curve fitting[3]. Although the accuracy of comb fringe projection method is the best of the all mentioned above, the fringe recognition is complex and it would invalidate when the wing is parallel to comb fringes.

In a word, optics methods mentioned above can only be applied to measure low speed flapping insects and only the motion parameters of single wing are measured. Stereo vision technique which makes use of optics triangulation is adopted in industry inspection widely because of its high precision and large quantity information. Although stereo vision technique has advantage mentioned above, multiple high speed cameras are needed for measuring insect motion parameters, which would increase the cost of measurement system. In this paper, we propose a novel virtual monocular measurement system in which only single high speed camera is used to measure double wings motion parameters.

By using two or more mirrored surfaces, a stereo view can be captured by single camera, just as the same as being imaged by two cameras from different directions. Both curved and planar mirrors can be used. Normally curved mirrors have been primarily used to capture a wide field of view, instead the virtual stereo systems are more compact and simple by using of planar mirrors[4]. Figure 1(a) gives out the principle of a virtual stereo system by using planar mirrors. The object is projected to the left and the right mirrors, and these two images are reflected to the corresponding planes of the outer mirror simultaneously, which just can be captured by the camera Oc. It is just like that two cameras are located in the virtual optical centers and the two virtual optical centers are positioned at points Cl and Cr respectively. A stereo pair of images is formed as the left and right halves in a single image. Figure 1(b) shows the principle of four virtual views, for which the two-plane reflection mirror is replaced by a four-plane reflection mirror, meanwhile four planar mirrors are located at the symmetry position of primary two mirrors, then reflections of the scene object on the four-plane mirror projected by four symmetry

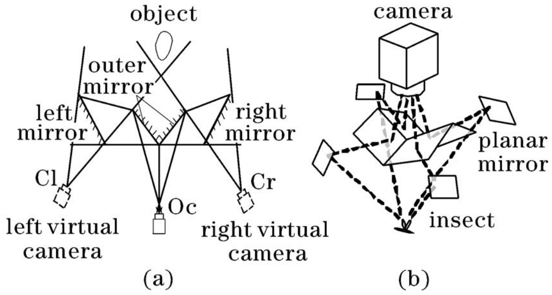

Fig. 1. Virtual monocular configurations with one camera. (a) Virtual binocular, (b) virtual four ocular.

light paths are captured by the camera. Each image is formed as the quarter in a single image by four virtual cameras positioned at four different viewpoints.

The scene point can be measured by stereo vision system effectively only when it is located at the overlap field of view of the cameras. So occlusion problem should be solved firstly in stereo system. Because of the high speed flapping and large flapping amplitude along with the torsion deformation in the course of alternate changing from upstroke to downstroke in beating period, the binocular stereo system cannot gather all motion information of double wings. If the two cameras are posed from left to right relative to the insect wings in turn variation of flapping angle and relative position between the wings and the body will arouse occlusions; if the two cameras are posed in front of and behind the wings separately, the occlusion mentioned above is solved but we cannot avoid the occlusion aroused by torsion deformation as a result that double wings motion information cannot be gathered in all sequence images within a beating period. If we want to obtain the entire outline information of the double wings, multiple camera views must be used. Considering that the high speed cameras are expensive, we design a virtual four-ocular system in which single high speed camera is used to decrease system cost. Multiple reflections of an insect were captured by this system, then the motion measurement of the insect can be fulfilled by the occlusion-free images.

Figure 2 shows the configuration of the virtual four-ocular stereo system. The system is composed of a CMOS high speed camera (2), a combined four-plane mirror (1), four plane mirrors (3), four lamps (4), and a computer. The camera with a speed up to 10000 frames per second is used to gather motion images and a Nikon camera lens whose focus length is 55 mm is used to image within close distance. The combined four-planar mirror is just below the camera, the four planar mirrors distribute around the combined planar mirror symmetrically, each of which corresponds to a plane of the combined mirror, these planar mirrors are used to form four reflections that can be captured by the high speed camera. Four lamps of each with power of 1000 W are applied to ensure enough luminance. Four pieces of white backcloth corresponding to each lamp are used to form homogeneous back illumination so as to ensure sequence images clearly.

When an object in space is viewed from two different places by two cameras separated by small distance, space

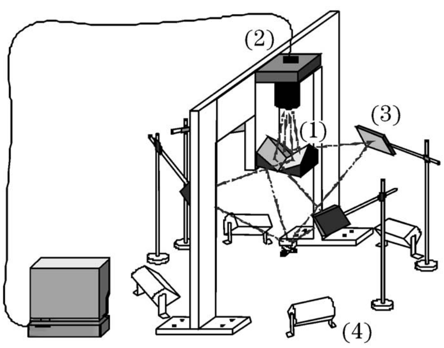

Fig. 2. Configuration of virtual four-ocular stereo system.

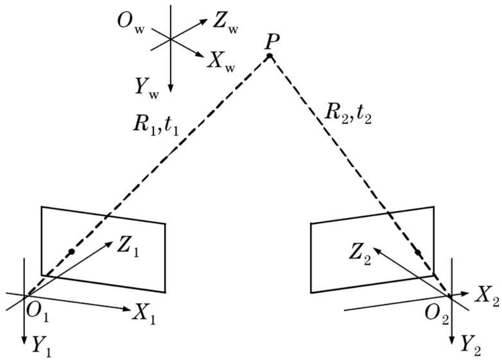

Fig. 3. Determine the spatial coordinates of an object from stereo vision method.

depth of the object can be determined by optical triangulation. As shown in Fig. 3, P is an arbitrary point in space, the world coordinate system is denoted by $O_wX_wY_wZ_w$. The homogeneity coordinate of point P in world coordinate system is denoted by (X_w, Y_w, Z_w, 1). The camera coordinate systems of the left and the right cameras are denoted by $O_1X_1Y_1Z_1$ and $O_2X_2Y_2Z_2$ respectively. Homogeneity coordinates of the point P in each camera coordinate system are denoted by (X_{c1}, Y_{c1}, Z_{c1}, 1) and (X_{c2}, Y_{c2}, Z_{c2}, 1). The $p1$ and $p2$ are image points of the point P in the left and the right images, the homogeneity pixel coordinates of $p1$ and $p2$ are denoted by (u_1, v_1, 1) and (u_2, v_2, 1), respectively. The rotation matrices and translation matrices between the camera coordinates and the world coordinate are described by ($R1$, $t1$) and ($R2$, $t2$), where $R1$, $R2$ are 3×3 orthogonal matrices, $t1$, $t2$ are 3×1 column vectors, normally these matrices are called external matrices. Matrices a_1, a_2 express the intrinsic parameter matrices of the left and the right cameras respectively. Then the relationships between the camera coordinates and the world coordinate are denoted by

$$\begin{vmatrix} X_{c1} \\ Y_{c1} \\ Z_{c1} \\ 1 \end{vmatrix} = \begin{vmatrix} R_1, & t_1 \end{vmatrix} \begin{vmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{vmatrix}, \tag{1}$$

and

$$\begin{vmatrix} X_{c2} \\ Y_{c2} \\ Z_{c2} \\ 1 \end{vmatrix} = \begin{vmatrix} R_2, & t_2 \end{vmatrix} \begin{vmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{vmatrix}, \tag{2}$$

the relationships between the pixel coordinates and the camera coordinates are described by

$$z_{c1} \begin{vmatrix} u_1 \\ v_1 \\ 1 \end{vmatrix} = a_1 \begin{vmatrix} X_{c1} \\ Y_{c1} \\ Z_{c1} \end{vmatrix}, \tag{3}$$

and

$$z_{c2} \begin{vmatrix} u_2 \\ v_2 \\ 1 \end{vmatrix} = a_2 \begin{vmatrix} X_{c2} \\ Y_{c2} \\ Z_{c2} \end{vmatrix}. \tag{4}$$

If camera intrinsic parameter matrices are known, furthermore the relationships between pixel coordinates and world coordinate are expressed by

$$z_{c1}\begin{vmatrix} u_1 \\ v_1 \\ 1 \end{vmatrix} = a_1 \,|\, R_1, \quad t_1 \,|\begin{vmatrix} X_\mathrm{w} \\ Y_\mathrm{w} \\ Z_\mathrm{w} \\ 1 \end{vmatrix}, \tag{5}$$

and

$$z_{c2}\begin{vmatrix} u_2 \\ v_2 \\ 1 \end{vmatrix} = a_2 \,|\, R_2, \quad t_2 \,|\begin{vmatrix} X_\mathrm{w} \\ Y_\mathrm{w} \\ Z_\mathrm{w} \\ 1 \end{vmatrix}, \tag{6}$$

where $a = \begin{vmatrix} f/\mathrm{d}x & 0 & u_0 \\ 0 & f/\mathrm{d}y & v_0 \\ 0 & 0 & 1 \end{vmatrix}$, f is the effective focal length, u_0 and v_0 are row and column numbers of the optical center, dx and dy are physical distances of a pixel in X and Y directions respectively. So if intrinsic parameter matrix and external matrix of each camera are known, the spatial coordinate of the point P can be determined by two correspondence image points via Eqs. (5) and (6)[5].

In general, if we want to obtain high precision, the distortion aroused by optical lens must be considered. Radial lens distortion is generally enough to amend the lens distortion in machine vision inspection. The system is calibrated to obtain the intrinsic and external parameters mentioned above by moving plane target whose pattern is like checker alternating with white and black squares. The resolution of image is decreased because of four images being projected on one image, so the measuring accuracy is mainly limited by the pixel number of the image. Using the moving plane method can obtain better calibration accuracy that compensates low image resolution. The calibration result had a standard deviation of 0.03 mm.

Accurate description of wing beating motion of insect such as the flapping angle, the torsional angle and the lag angle is fundamental to the analysis of aerodynamics. Only the insect flight mechanism explained with double wing motion parameters is comprehensive because the insect flying is fulfilled by double wings. By using the virtual four-ocular stereo system, the above-mentioned double wings motion parameters of a honeybee are measured. A honeybee was attached and placed in the measurement region, then the high speed camera was switched on when the honeybee was beating. Film speed of the camera was 2000 frames per second, the exposal time was set to 1/6000 second so as to avoid motion blur, the image resolution was 512 × 256 pixels. Figure 4 shows the representative captured image of the honeybee wings.

Figure 5 gives some necessary definitions of the motion parameters for describing the wing motion. The plane P in which the wings vibrate relative to the honeybee body is called the stroke plane, it is defined by the wing base and the wing tip at its lowest and highest points within a beating period. The body plane Q is so defined that pass through the left wing base, the right wing base and the midpoint of the line linking left antenna and right antenna. The line that joins the wing base and tip is defined as longitudinal chord. The flapping angle φ is defined as the angle between the projection of longitudinal chord on the stroke plane and the cross line of body

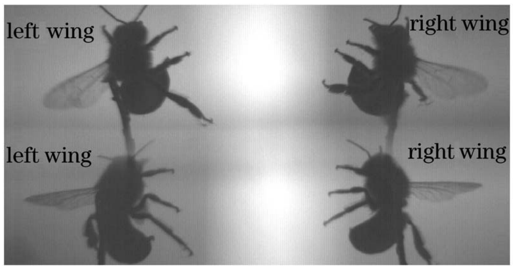

Fig. 4. Honeybee wings captured by virtual system.

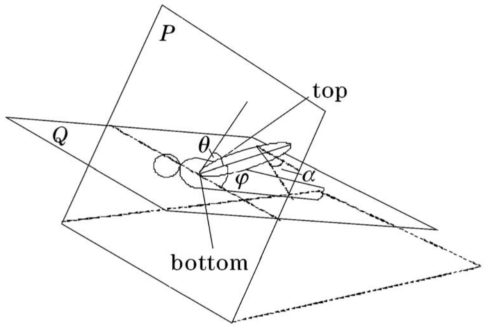

Fig. 5. Motion parameters of a honeybee wings.

plane and stroke plane. The lag angle α describes the angle between the flapping plane and the longitudinal chord. The attack angle θ describes the angle between the line which joins intersections of the perpendicular plane of the longitudinal chord with the leading edge and tailing edge of the wing and the flapping plane[6]. Because only spatial coordinates of discrete point in the tailing edge can be obtained, we calculate the attack angle by using interpolation method. All parameters except body plane are defined corresponding to left wing and right wing respectively. It is noted that during the beating motion, the forewing and hindwing of a honeybee are in the same plane, the wings move as a single wing.

We measured the flapping angle φ, attack angle θ, lag angle α and wing tip path of a honeybee during one beating period. Figures 6(a) and (b) show the variation of wings flapping angle and lag angle with time during one beating period. The beating frequency of the honeybee was about 125 Hz. In this case, beating motion of double wings was smooth and similar to sinusoidal motion, but the amplitudes of flapping angle about the two wings are different. The amplitude of the left wing was about 120°, however the amplitude of the right wing was about 90°. This means that the two wings are not kinematics symmetry in the course of beating motion. The lag angle of both the left wing and the right wing was small, which can validate that the wings moved in a fixed contrail and did not deviate far from the stroke plane in the course of beating motion. Figures 6(c) and (d) show the attack angle of the two wings at three sections of the span-wise where r/R equals to 25%, 50%, and 75%, where r denotes the distance between the wing base and the measured section and R is the length of longitudinal chord. It can be seen that the attack angle became larger when the section was close to the wing base while the attack angle became smaller when the section was far from the

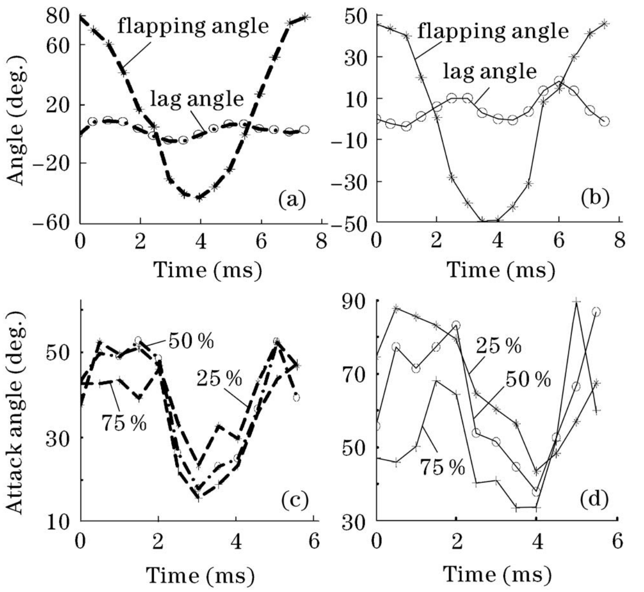

Fig. 6. Measurement results. Flapping angle ϕ and lag angle α of left wing (a) and right wing (b), attack angle θ of left wing (c) and right wing (d) at sections of $r/R = 25\%$, 50%, and 75%.

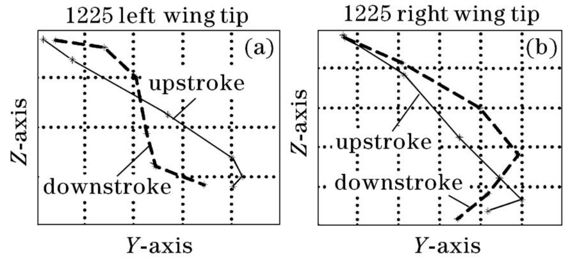

Fig. 7. Side view of the wing tip for the left and right wings.

wing base. This case can be explained from physiology[7]. The leading edge of the wing is regarded as a spar and posses great resistance to bending but is compliant in torsion. Aerodynamic forces produced during the wing stroke will result in torsion, the flapping force extends from the base to the tip because beating motion is controlled by the muscles close to the wing base, so the torsion deformation close to the wing base must be larger than that far from the wing base. Furthermore during downstroke the attack angle decreases, in contrast the attack angle increases in the period of upstroke, the resistance to be overcome is the largest when the wing flapped to the top of body. It can be said that the more resistance the wing needs to overcome, the lager the torsion is.

Figure 7 illustrates the wing tip path in a beating period. It is the projection of the wing tip in the plane passing through the midpoint of the line linking two wing bases and perpendicular to the body plane. The wing tip path of downstroke is in dashed line while the upstroke in solid line. The paths of both left wing and right wing are like 8-shape loop with a cross over, and the paths of the two half stroke are nearly symmetrical. This wing tip path validates that the wing does not deviate far from the stroke plane in the course of beating motion also.

We have proposed a virtual four-ocular stereo system based on one high speed camera and applied this system to measure the double wings motion parameters of the moving insect. Results show that this measurement system has the following advantages. 1) Motion parameters of double wings with larger variation of flapping and torsion can be measured effectively and simultaneously with the system. 2) The system cost is cheap because of only one high speed camera used, which avoids synchronism of multiple high speed cameras.

Compared with common stereo vision system, this system is complex because an elaborately designed optical reflection system is added and the difficulties of system adjustment increase meanwhile, but its complexity can be ignored by the advantages mentioned above. The measurement results show the effectiveness and high accuracy of this virtual stereo measurement system in biomechanical research. With loss of generality, this virtual measuring system can be not only used to measure insect motion parameters but also applied to other moving object within small view field.

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