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A Method for Reconstructing Three-Dimensional Positions of Swarming Mosquitoes

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We developed a new field method for reconstructing the three-dimensional positions of swarming mosquitoes. This method overcame certain inherent difficulties accompanied by conventional stereoscopic methods and is applicable to three-dimensional measurements of other insect species. Firstly, we constructed a probabilistic model for stereoscopy; if mosquitoes and six reference points with known coordinates were photographed simultaneously from two or more perspectives, then from the positions of images of mosquitoes and the reference points on the photographs, 1) the position of each camera with respect to the reference points is estimated; 2) stereo images which correspond to an identical real mosquito are matched; and 3) the spatial positions of the mosquitoes are determined. We automated the processes 1), 2) and 3), developing computer programs based on our model. We then constructed a portable system for three-dimensional measurements of swarming mosquitoes in the field. Initial data that illustrate the application of our method to studying mosquito swarming were presented.

KEY WORDS: swarming mosquitoes; three-dimensional measurements; probabilistic model; computer program; field equipment.

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INTRODUCTION

Animal motion is usually in three dimensions; hence, three-dimensional measurements are indispensable for clarifying various aspects of insect behavior. Several methods have been developed for tracing the three-dimensional (3D) behavior of a flying insect (e.g., Dahmen and Zeil, 1984; Reiley *et al.*, 1990) and for studying grouping animals such as insect swarms (e.g., Okubo *et al.*, 1981; Shinn and Long, 1986), fish schools (e.g., Cullen *et al.*, 1965; Pitcher, 1973, 1975), and bird flocks (e.g., Gould and Hepner; 1974, Major and Dill; 1978). These methods are based on the principle of stereoscopy, in which objects are recorded simultaneously from different viewpoints and the 3D positions are estimated from a set of two-dimensional (2D) information on the multiple view of a scene.

However, 3D measurements are still difficult, particularly in measuring aggregating animals, for the following reasons. First, cameras and other apparatus must be set up in very precise positions. Second, when there are multiple images of objects in one view, one must find the image in each view that represents the corresponding, real object in space. This is known as the correspondence (or matching) problem, and it cannot be avoided when there are multiple animals in a single scene, which is the case for animal aggregations such as swarms. Matching is an extremely time-consuming and difficult process, and there are few algorithms for automatic matching.

We constructed a probabilistic model for automatic matching and reconstructing 3D positions of objects and developed computer programs based on the model. We then constructed a portable measurement system and studied mosquito swarming in the field. The precise positioning of equipment is not prerequisite in our method and the process of matching is automated with the computer programs. Because of these properties, our method gives efficiency in data processing and flexibility in experiments, in particular, making field experiments much easier. Therefore, it is applicable to 3D measurements of various kinds of insect aggregations.

In this paper, we first explain the method for matching and reconstructing the 3D positions and then describe the photographic system used in the field. We also report initial results of our field experiments; more detailed analyses of mosquito swarming will appear elsewhere.

PROBABILISTIC MODEL FOR STEREOSCOPY

Binocular System

First, we consider the binocular system, in which 3D positions of objects are reconstructed using a pair of photographs (or other image data; hereafter, we refer to photographs for convenience) taken from different directions.

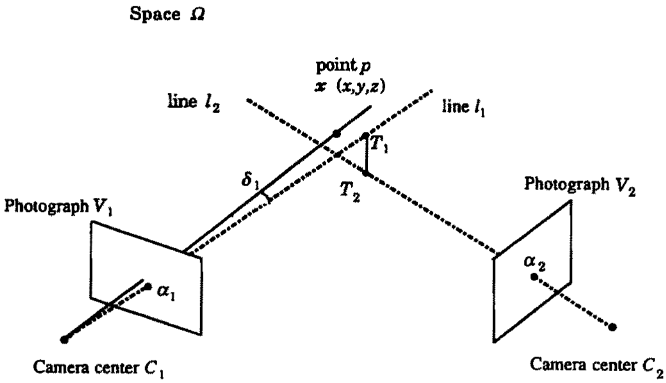

Fig. 1. Suppose that a point p in region Ω was photographed from two different directions and image α_i was obtained on photograph V_i. The line l_i connects the camera's projection center C_i and image α_i ($i = 1, 2$). Lines l_1 and l_2 should meet at point p. Due to instrumental errors, however, these lines do not cross each other but take mutually twisted positions with distance $d = T_1T_2$. δ_1 is the error angle between line l_1 and the line connecting C_1 and point p.

A photograph is regarded as a projection from 3D space onto a plane. A projection matrix can be estimated if six reference points of known coordinates are contained in a photograph (Sutherland, 1974). Suppose that we photographed mosquito p (hereafter referred to as point p) and obtained image α_i on photograph V_i, for $i = 1$ and 2, respectively (Fig. 1); based on the projection matrix and the 2D position of an image α_i on photograph V_i, we can calculate the equation of line l_i that connects the camera's projection center C_i to image α_i of point p (Fig. 1). If there is no measurement error, lines l_1 and l_2, which correspond to the same point, should meet at the true position of point p. Practically, however, we cannot eliminate measurement errors resulting from optical aberrations or quantization of space. Therefore, calculated lines l_1 and l_2 do not intersect but take mutually twisted positions with distance $d = T_1T_2$ (Fig. 1). If there are multiple images in each photograph, we will obtain many lines that do not cross each other. In such a case, we have to solve two problems: The first is matching, i.e., finding pairs of lines that correspond to an identical, real object in space; and the second is reconstructing the 3D position of an object for each pair of lines. Matching is very difficult when the objects look alike as is the case with many animal groups.

We constructed the following model to find correct pairs of lines and to reconstruct the 3D positions of objects.

To begin, we made three assumptions.

(1) The region Ω, which can be photographed simultaneously from two directions, is finite, i.e., the camera field of view is finite.

(2) The points are distributed in the region Ω with a uniform a priori probability ν.
(3) When we photograph a point p and obtain line l_i, let δ_i be the error angle between the line l_i and the line that connects the camera's projection center C_i and point p (Fig. 1). The distribution of error angles follows the two-dimensional normal distribution with standard deviation η_i. The isoprobability surface of the error density function forms a circular cone, whose vertex is the projection center C_i.

Suppose we photograph a real point p with coordinates (x, y, z). Taking into account assumptions 1–3, the probability density ρ_0 of finding lines l_i in photograph V_i $(i = 1, 2)$ is then expressed as

$$\rho_0(x, y, z) = \nu \frac{1}{2\pi\eta_1^2} \exp\left(-\frac{\delta_1^2}{2\eta_1^2}\right) \cdot \frac{1}{2\pi\eta_2^2} \exp\left(-\frac{\delta_2^2}{2\eta_2^2}\right) \tag{1}$$

Usually the distance from the projection center C_i to point p is sufficiently large and the standard deviation η_i is sufficiently small. Therefore, it is reasonable to approximate the isoprobability surface by a cylindrical surface in the neighborhood of point p as shown in Fig. 2. Because $\sin \delta_i$ is approximated by δ_i, the distance from point p to the calculated line l_i is expressed as $r_i = |T_iC_i|\ \delta_i$, with the standard deviation being $\sigma_i = |T_iC_i|\ \eta_i$, where $|T_iC_i|$ is the distance between T_i and C_i, for $i = 1$ and 2, respectively. Without loss of generality, we can assume a new coordinate system in which l_1 corresponds to the X axis and l_2 to the line parallel to the XY plane and intersecting the Z axis (Fig. 2). Omitting the constant ν, we can rewrite (1) for the new coordinate system as

$$\begin{aligned}\rho(x, y, z) &= \frac{1}{4\pi^2\sigma_1^2\sigma_2^2} \exp\left(-\frac{r_1^2}{2\sigma_1^2} - \frac{r_2^2}{2\sigma_2^2}\right) \\ &= \frac{1}{4\pi^2\sigma_1^2\sigma_2^2} \exp\left(-\frac{y^2 + z^2}{2\sigma_1^2} - \frac{(x \sin\theta - y\cos\theta)^2 + (z - d)^2}{2\sigma_2^2}\right)\end{aligned} \tag{2}$$

See Fig. 2 for notations.

We obtain the probability $H(l_1, l_2)$ that the pair of lines l_1 and l_2 corresponds to the same point p by integrating (2) over the region Ω. We can approximate it by integration in the whole space R^3 because the value of $\rho(x, y, z)$ is very small except around the vicinity of T_1 and T_2.

$$H(l_1, l_2) = \int_\Omega \rho dv \approx \int_{R^3} \rho dv = \frac{1}{\sqrt{\pi(\sigma_1^2 + \sigma_2^2)}\ |\sin\theta|} \exp\left(-\frac{d^2}{2(\sigma_1^2 + \sigma_2^2)}\right) \tag{3}$$

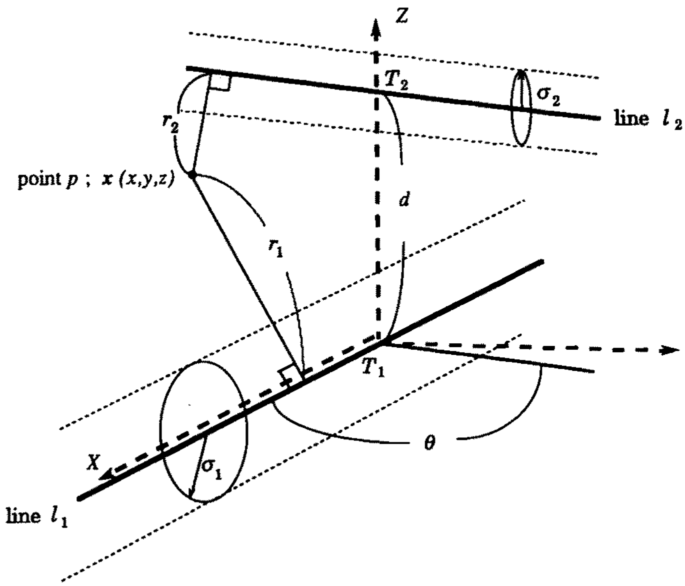

Fig. 2. Point p and lines (l_1, l_2) in the new coordinate system. Line l_1 corresponds to the X axis, and l_2 is parallel to the XY plane and intersects the Z axis. r_1 and r_2 are the distances from point p to lines l_1 and l_2. σ_1 and σ_2 are the standard deviations of the errors when we assume that the isoprobability surfaces of error are approximated by cylindrical surfaces in the neighborhood of point p. θ is the angle of line l_1 and line l_2.

Since we assumed the normal distribution, x^*, the estimate of position p also gives the maximum value of $\rho(x, y, z)$, i.e.,

$$x^* = \left(0,\ 0,\ \frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2}\, d\right) \tag{4}$$

Thus, position p is the point internally dividing the segment T_1T_2 by the ratio $\sigma_1^2 : \sigma_2^2$.

With computer programs, we determine the corresponding pairs of lines from the two photographs and estimate 3D positions of points by the following procedure.

(1) Enter the positions of the reference points on each photograph into the computer.
(2) Calculate the projection matrix P_i for photograph V_i $(i = 1, 2)$.
(3) Enter the positions of images α_{k_i} of objects on photograph V_i. Let the number of images on photograph V_i be k_i $(k_i = 1, 2, \ldots, n_i)$.

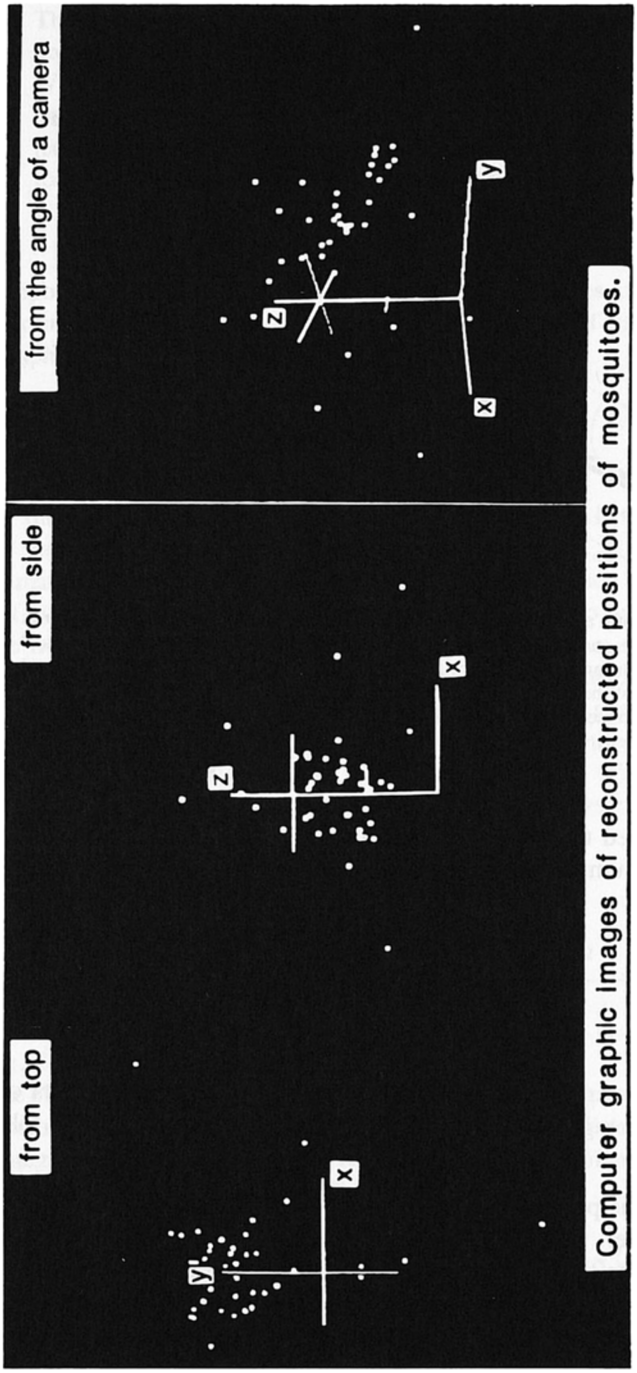

Fig. 3. Reconstructed graphic images of swarming mosquitoes and the reference unit. Left: View from the top. Middle: View from the side. Right: View from the viewpoint of a camera.

(4) Calculate the equation of line $l_{ik_i}(k_i = 1, 2, \ldots, n_i)$, which connects the camera's projection center C_i and each image α_{ki} on photograph V_i.
(5) For line l_{1k_1} in photograph V_1, calculate the probability $H(l_{1k_1}, l_{2k_2})$ that l_{1k_1} corresponds to the same point as l_{2k_2} for all the lines in photograph V_2.
(6) Let l_{2*} be the line in photograph V_2 giving the largest value of $H(l_{1k_1}, l_{2k_2})$. If the value $H(l_{1k_1}, l_{2*})$ exceeds the predetermined threshold H_{min}, then we conclude that the pair l_{1k_1} and l_{2*} corresponds to the same existing point and estimate its position by expression (4).
(7) In the case where there is not line in photograph V_2 that gives a value above H_{min}, we assume that l_{1k_1} has no corresponding line in photograph V_2. In fact, it is possible that certain points are photographed by only one camera.
(8) Repeat steps 5–7 for all l_{1k_1} $(k_1 = 1, \ldots, n_1)$.

The 3D computer graphics program allows us to view the reconstructed images of points from any direction, including the three camera angles (Fig. 3).

Trinocular System

It is possible that a pair of lines having no corresponding true point in space is close to each other or that there are two points on one line. In these cases, an incorrect pair of lines accidentally gives a high value of $H(l_{1k_1}, l_{2k_2})$ resulting in false matching. The third camera is then used to decrease this kind of matching error in the following manner. First, for photographs V_1 and V_2, pairs of lines (l_{1k_1}, l_{2*}) that exceed H_{min} are determined. Then it is determined whether there is a line l_{3k_3} in the third photograph V_3 that corresponds to the pair of lines (l_{1k_1}, l_{2*}) obtained from photograph V_1 and V_2; that is, whether there is a line l_{3k_3} that passes in the vicinity of the point estimated by lines (l_{1k_1}, l_{2*}). If there is no line that corresponds to the lines (l_{1k_1}, l_{2*}) in photograph V_3, this pair is considered to be false.

Our model can be extended to multiocular systems. The rigorous mathematical reduction of the model, which includes extension to multiocular systems and theoretical considerations concerning matching errors, is given elsewhere (Okabe and Ikawa, 1994).

Precision in Estimation and Errors in Matching

We examined the precision in estimation of our method by taking photographs of the points with known spacial coordinates. To this end, we constructed a 1.2 × 1.2 × 1.2-m frame with steel rods. Between the rods, we stretched threads with 18 small plastic beads attached. The errors of the positions of these beads were within 3 mm. We photographed the frame and beads from three

Table I. Precision of Estimation of the Three-Dimensional Positions of Points

Measurement axis	Mean absolute error (mm)	Standard deviation of error (mm)	No. observation
X	3.11	4.14	54
Y	4.38	5.20	54
Z	1.90	2.98	54

directions simultaneously; this procedure was repeated three times from different camera positions. Then the positions of beads in each photograph were entered into a computer using a digitizing tablet. Also entered were the six vertices of the frame as the reference points. We then estimated the three-dimensional positions of the beads. Table I lists the mean absolute errors with standard deviations for X, Y, and Z axes. We regarded these errors as permissible for 3D measurement of mosquito swarming because, as described later, the mutual distance of mosquitoes in a swarm ranges from ~4 to ~193 cm.

The maximum number of points that we can match correctly depends on the resolution of the image entering device and the distribution of images on a photograph. Currently, the resolution of image entering devices ranges from ~1/200 (TV camera output NTSC signal) to ~1/700 (photograph + digitizer or image scanner). Correspondingly, the number of points that can be matched within an error probability of 0.01 ranges from ~2 to ~7 for the binocular system and from ~35 to ~130 for the trinocular system, providing the distribution of the images in each photograph is uniform (Okabe and Ikawa, 1994).

MEASUREMENT OF THE MOSQUITO SWARMS

For three-dimensional measurements, it is essential to visualize mosquitoes swarming in the dark. We illuminated swarms with a camera's flashlight so that their images were shown as shining points on photographs (Fig. 4). Momentary illumination by a flashlight seemed not to affect the swarming behavior. If mosquitoes were exposed to continuous light, on the other hand, they flew away from the swarming site.

The field apparatus consisted of three motor-driven 35-mm cameras (Nikon F3) with a zoom lens (28–80 mm), a lighting unit (Nikon SB6), a portable reference unit, and a 1.2 × 1.2-m black cloth. The black cloth was used as an artificial marker to attract male mosquitoes. The three cameras were positioned on the vertices of a regular triangle, at the center of which were placed the reference unit and the black cloth (Fig. 5). The distance between the reference unit and each camera was ~3.5 m. The cameras were attached to low tripods and were faced slant upward so that their field of view could cover the region

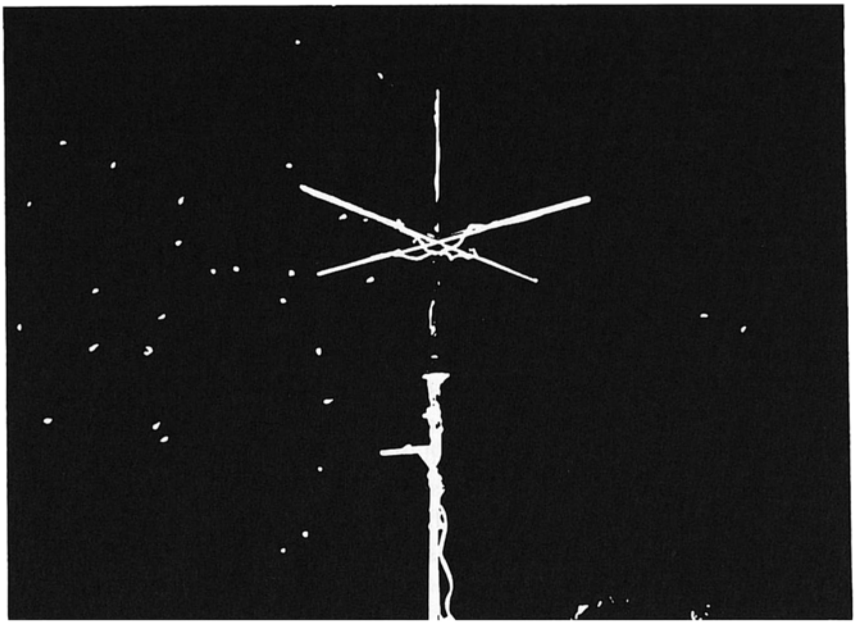

Fig. 4. A photograph of swarming mosquitoes. The cross-shaped bar is the reference unit.

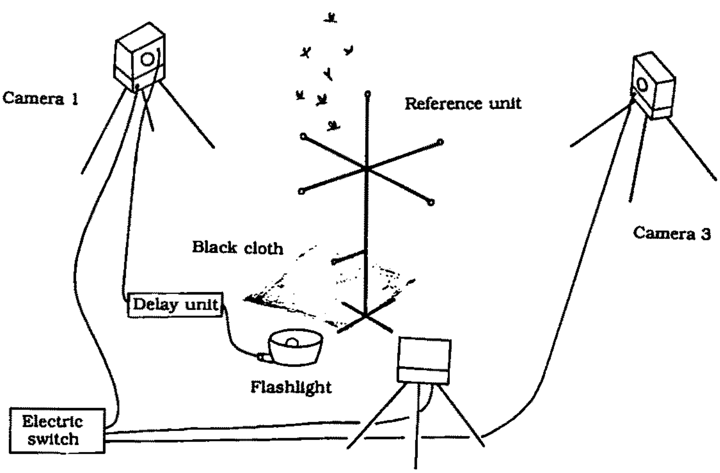

Fig. 5. The configuration of the measuring system: three cameras, a reference unit, a flashlight, and a black cloth spread close to the reference unit as a swarm marker. The six tips of the reference unit are the reference points. The camera shutters are released simultaneously by an electric signal. A delay unit regulates the firing of the flashlight so as to illuminate all the cameras simultaneously.

Table II. Height and Mutual Distance of Swarming Mosquitoes

Sample	Number of individuals	Height of mosquitoes (cm)			Mutual distance of mosquitoes (cm)		
		Average	Maximum	Minimum	Average	Maximum	Minimum
1	10	108.0	146.4	68.1	100.4	192.7	25.2
2	5	143.6	193.9	96.7	79.2	106.5	55.2
3	9	88.0	134.0	75.1	62.5	135.5	7.8
4	10	118.2	159.1	82.6	58.1	107.2	17.8
5	6	143.7	193.7	96.7	80.1	107.2	55.5
6	8	106.9	183.1	75.0	83.0	165.6	3.8

from the ground to more than 3 m above. Each camera covered more than 3 × 3 × 3 m of space above the cloth. The camera shutters were released simultaneously by an electronic signal. The flashlight was put in a small pit on the ground near the cloth to illuminate the swarming mosquitoes. The firing of the flashlight was regulated through a small electric circuit so as to illuminate all the cameras simultaneously. The cameras were loaded with high-sensitivity films (ASA 3200). Photographs were enlarged to 20 × 25 cm to decrease the input error.

We photographed swarming *Culex tritraeniorhyncus* in Saitama, Japan, and estimated the 3D positions of mosquitoes. Example data of six shots of mosquito swarming are given in Table II. The maximum heights of mosquitoes from the swarm marker ranged from 134.0 to 193.7 cm, and the maximum mutual distances ranged from 106.5 to 192.7 cm.

By stroboscopy, we also photographed trajectories of swarming *Culex pipiens pallens*, in Tokyo. Each trajectory was very short due to the limitation of flashlight power. We traced nine paths. The speed of mosquitoes in each path ranged from 24.3 to 156.26 cm/s, with an average of 80.8 cm/s.

DISCUSSION

Our method has the following advantages in constructing the measuring system, carrying out experiments, and estimating 3D positions.

(1) All the equipment required for measurements is commercially available at rather low prices.
(2) The whole measurement system is lightweight and compact. It can be easily assembled and disassembled in the field.
(3) Precise positioning of cameras and the reference unit is not necessary; this enables us to conduct various types of field experiments.
(4) Once the positions of objects and reference points on a photograph are entered into a computer, almost all the procedures are automated. Most important, matching by the computer program saves time and effort.

(5) The matching by our method is very reliable, because the probability that a pair of stereo images corresponds to the real objects is calculated for all the possible pairs and the pairs with low values of probability are eliminated.
(6) The time for calculation is very short even on a personal computer.
(7) The reconstructed images of mosquitoes can be viewed from any direction.

Because of these properties, our method is applicable to 3D measurement for many kinds of animals in both the laboratory and the field.

To trace the movement of swarming mosquitoes, it would be more convenient to use a TV camera–VTR system. However, we used a photographic system because (1) presently it gives much higher resolution than a TV camera system, and (2) a TV camera system requires expensive equipment such as noctovideos and infrared-sensitive cameras with illuminators, which were used by Gibson (1985) and Riley *et al.* (1990). The trinocular system is preferable to the binocular system for 3D measurement with TV cameras judging from the number of possible correct matches [~ 2 and ~ 35 in the binocular and the trinocular system, respectively (Okabe and Ikawa, 1994)]. The movements of a number of insects can be traced correctly from frame to frame, using the direction of the movements as the cue, because each individual will not change its direction greatly in several successive frames. With three TV cameras, 30×3 frames will need to be processed to trace only 1 s of animal movements. In a TV camera system, therefore, it is desirable that both measuring positions of images on frames and entering 2D information into a computer are automated with the use of an image processor.

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