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# Note: High-speed optical tracking of a flying insect

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We developed a video recording system with the capability of tracking moving objects and used it to track the flight of an insect. The system consists of two galvano mirrors, which redirect the light coming from the object in two orthogonal directions toward a high-speed camera to capture the image. An additional high-speed camera, which views the same object through a beam splitter placed between one of the galvano mirrors and the observation camera, detects the position of the object. The mirror angle is controlled to maintain the position of the object at the center of the view, allowing the object to be tracked. In order to validate this system, images of a live fly in flight were recorded along a flight path that was much longer than the field of view of the stationary camera. A high-resolution video image of a rapidly moving live fly was successfully captured. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3694569]

Image capturing of rapidly moving objects is required in various fields of science and engineering. The flight mechanism of insects has been clarified by analyzing video images of live individuals flying at various speeds.[1,2] In a similar fashion, the motion of the ball in various sporting events has been captured with a video camera to analyze the kinematics and aerodynamics.[3] And automated video cameras are used on the production lines in manufacturing industries to inspect the rapidly moving products.[4]

While imaging of such objects is often performed by a fixed video camera system, improvement of the spatial dynamic range, i.e., the ratio of the spatial resolution to the field of view, can be achieved if the image frame is automatically translated, allowing the object to be tracked along the path of its motion. To exploit this principle at the microlevel, Oku *et al.*[5] developed a microscope system capable of tracking moving microorganisms. The position of the object in the image was computed in real time and was fed back to the motorized translation stage of the microscope. Consequently, the object could be captured in a fixed location in the field of view. While their system was designed only for objects under a microscope, an optical tracking video camera called a cine-sextant[6,7] has been used to capture images of launched missiles or airplanes in takeoff or landing. The camera of the cine-sextant is mounted on a servo-motor-driven two-axis rotation stage, and thus can be pointed at the sky in any direction. The necessary angular acceleration of the camera for imaging an object is estimated to be $\ddot{\theta} = a/l$, where $a$ is the linear acceleration of the object and $l$ is the working distance of the camera to the object. For a missile having $a = 100$ m/s$^2$ with $l = 1000$ m, the angular acceleration is $\ddot{\theta} = 0.1$ rad/s$^2$, which is within a typical allowable limit of angular acceleration of a cine-sextant[7] ($\sim$3 rad/s$^2$). However, in the case of a live fly for which $a = 30$ m/s$^2$ (Ref. 8) and $l = 1$ m, $\ddot{\theta} = 30$ rad/s$^2$ is required, which is one order greater than for the above-mentioned cine-sextant.

In order to capture the video image of a rapidly moving insect, we developed an optical tracking system consisting of feedback-controlled galvano mirrors in front of the objective lens of a fixed video camera. Since the galvano mirror has a much smaller inertial moment than the servomotor-driven camera, it is expected that a faster response time will be needed to track the insect. To demonstrate the ability of the system, a live fly in flight was captured in video images.

Figure 1 shows a schematic design of the system we developed. The light coming from the object is reflected on a series of two fixed mirrors and two galvanometers (M3ST; GSI Lumonics) with flat mirrors (Mirror 1, 22 × 40 mm$^2$; Mirror 2, 42 × 60 mm$^2$) and reaches a cubic beam splitter. The reflected light from the cubic beam splitter penetrates a CCD camera (TM-6740CL, JAI/Pulnix; Nikkor f = 50 mm F1.2, Nikon) intended for detecting the position of the object relative to the field of view. The transmitted light though the cubic beam splitter is imaged on another camera (FASTCAM-1024PCI, Photron; Nikkor ED f = 180 mm F2.8, Nikon) intended for observing the object at higher resolution. The axes of the two galvano mirrors are arranged to be orthogonal to each other, so that the line of sight from the camera can be directed into both horizontal and vertical directions within the $\pm 30^\circ$ range allowed by the galvano mirror. The video signal from the camera for position detection was transferred to a personal computer (PC) via a frame-grabber board (APC-3310CL; Aval Data). The frame rate of this camera was set to $f_c = 3205$ fps and the effective number of pixels was 56 × 40. The angle of the galvano mirror was controlled by a PC through a digital-to-analog (DA) converter board (PEX-304216, 16-bit; Interface) and servo driver (MiniSAX; GSI Lumonics) designed for the galvanometers.

The following operation was performed to track the object imaged on the cameras. The image taken by the camera for position detection was thresholded by a predefined value, and the center of mass of the thresholded region was computed. The displacement vector of the center of mass of the region relative to the center of the image was calculated. Each component of the vector was scaled by a predefined factor and was added to the value of the voltage for the position

 

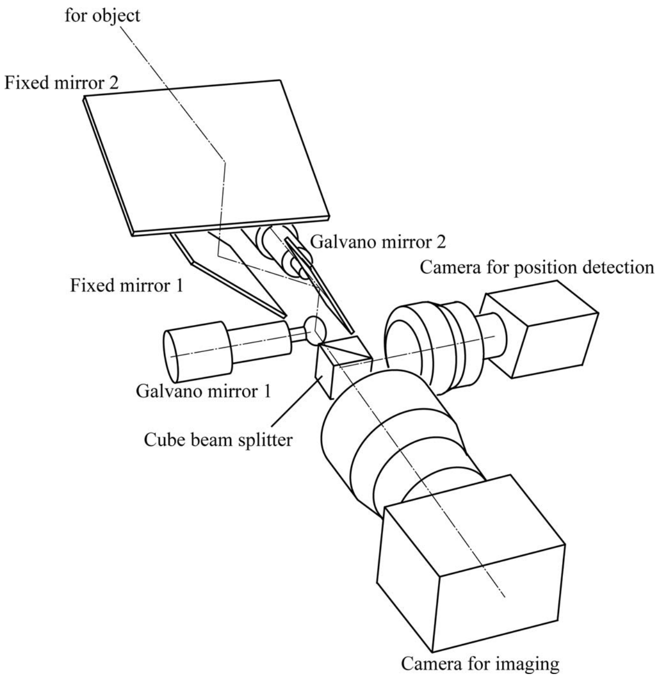


FIG. 1. Arrangement of optical devices.

command input of the servo driver to update the mirror angle. This process was performed within each frame period $\Delta t = 1/f_c (= 1/3205\ \text{s})$ and repeated to track the object.

The exposure time of the camera was set to be identical to $\Delta t$. Since the object travels a finite distance during the exposure period, its image would be blurred under continuous illumination like that used in this study. Therefore, the location of the mass center of the blurred image of the object is expected to be identical to the location of the object at the middle of the exposure time ($=\Delta t/2$ after the beginning of the exposure). After this exposure period, the image was transferred to the memory of the PC, which takes another $\Delta t$, and then image processing was performed in another time period $\Delta t$. Then the mirror moves, reaching a new position within another $\Delta t$, at which point the whole cycle completes. Thus, the total time required to direct the mirror to the object at the new position is $3.5\Delta t$ (=1.09 ms).

In addition to this duration, the time response of the servo to the stepwise change of the input signal has to be added to specify the actual delay time of the current system. The smaller mirror (Mirror 1) travels over an optical angle of 30°, i.e., twice the mechanical angle, within 5 ms, while the larger mirror (Mirror 2) requires as much as 8 ms. This response time was found to be almost proportional to the height of signal step. The small step response is typically 0.8 ms for Mirror 1 and less than 3 ms for Mirror 2.

The devised system was used to take video images of a live fly in flight. Several tens of false stable flies (*Muscina stabulans*, 7 mm in body length; Sumika Technoservice Co.) were released in a plexiglas chamber having dimensions of $730 \times 730 \times 130\ \text{mm}^3$ installed in front of the present system and were illuminated from the front by a metal halide lamp (HVC-SL, 150W, 12500 lm; Photron). A white plastic board was placed behind the backside of the chamber to provide contrast. The distance from the chamber to the head of the camera was ~800 mm. The field of view of the observation camera was $\sim 100 \times 100\ \text{mm}^2$. Although the flies were allowed to fly freely in the chamber, most of them stayed at the chamber base, with only a few flying intermittently. In

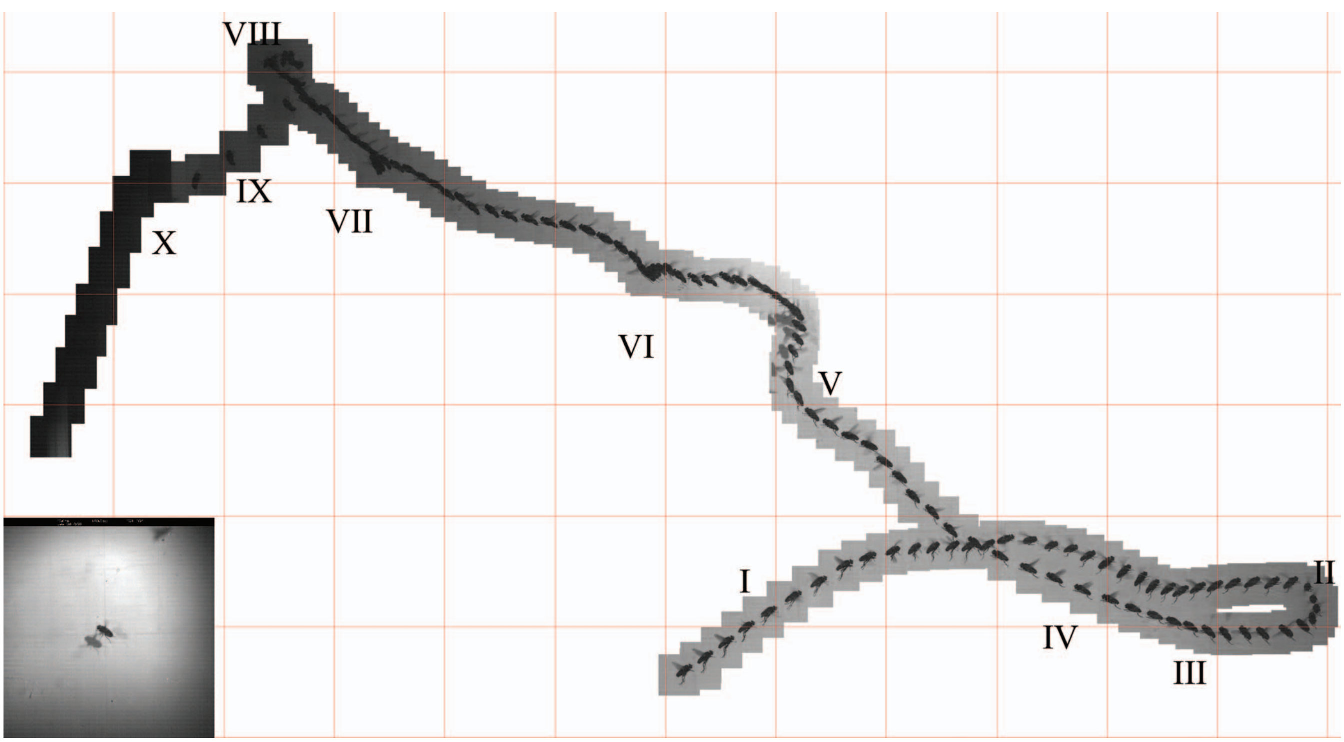


FIG. 2. Successive images of the fly in flight. The time interval of the images is 20 ms. The overlaid grid represents an interval of 50 mm in actual coordinates (enhanced online).[URL: http://dx.doi.org/10.1063/1.3694569.1]

order to capture images efficiently in this situation, the mirror was continuously actuated to scan the whole domain of the chamber until the system detected an object. Once the system detected an object, images were recorded until the fly reached the edge of the chamber.

Figure 2 shows successive images of a fly in flight taken by the observation camera. A video movie file is also available as electronic supplementary material. Each image was extracted from the central part of the original image and placed at the actual location, which was estimated from the galvano mirror angle at each instant. The time interval between images was 20 ms and the total duration of the image sequence was 2.82 s. The image shown in the lower left corner represents the size of the original image. The physical size of the overall area is roughly 600 mm $\times$ 300 mm, which is equivalent to a single image consisting of 6000 $\times$ 3000 pixels. It is evident that the object is captured in the center of the frame and tracked along its path over an area ~18 times larger than that of the original image.

The fly traveled on an arc (I) and then executed a quick, 90° turn within 20 ms (II). This turning time was shorter than the value of 50 ms reported by Fry *et al.*[1] After the turning motion, the fly leveled its body (III) and started to accelerate (IV) to climb upwards. The flight speed reached up to 0.7 m/s. Since the fly was approaching the back wall, some shadows are visible behind the body (V). Then the fly turned its flight direction away from the back wall (VI) and continued to climb up. Suddenly the fly stopped traveling and hovered for 100 ms (VII), then accelerated again. During this brief hovering period, the fly was observed to excrete a small amount of urine. At the top of the path, the fly made another turn but accidentally hit its body against the back wall (VIII), and then twisted and rolled its body immediately after. The fly started to fall down backward (IX), and then disappeared (X) behind the column of the container.

The periodic behavior of the wing beat is most evident in Fig. 3, where a temporal power spectrum of the pixel intensity of the image is shown. The peak is found at 200 Hz, which is comparable to the wing beat frequency of the typical housefly[9] and *Drosophila melanogaster*.[10] Higher harmonics were found at 400 Hz, which is expected to be the result of the nonlinear interaction of the fluid and wing.

Recently, Mamiya *et al.*[2] examined the movement of the antenna of flying *Drosophila* during active turning, and found that *Drosophila* detects the change of wing-induced airflow by its antennae, and feeds this information back to regulate the magnitude of the steering responses. Since the length of the antennae is typically 200 $\mu$m and their thickness is on the order of microns, higher resolution of the images would be required to resolve their motion. While Mamiya *et al.* tethered the flies at a fixed position to make the recording of a magnified image possible, the optical tracking system of the present study can be a powerful tool to analyze such small elements, even during free flight.

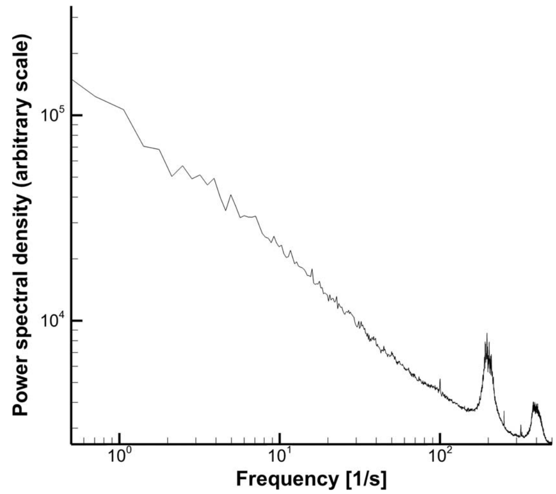


FIG. 3. Power spectrum of the pixel intensity of images.

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