Measuring the flight trajectory and speed of a free-flying moth on the basis of noise-reduced 3D point-cloud time series

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Research Article

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Abstract

Pest management is essential in crop production; however, frequent application of chemical pesticides that are used as a main tool for pest control causes environmental issues and insecticide resistance in pests. To overcome these issues, laser zAPPING has been used to control insects such as cockroaches and mosquitoes. In Japan, laser zAPPING has been studied to physically control cotton leafworm, *Spodoptera litura*, which is nocturnal, has a high fecundity and some insecticide-resistant populations, and severely damages to a variety of crops. To regulate behaviors of adult *S. litura* by laser zAPPING, its flight trajectory including flight speed must be identified and then predicted precisely under night conditions. Therefore, we aim to establish the automatic detection pipeline for flight trajectory based on point-cloud time series considering the factors reflecting noise data. In this study, the 3D point cloud data were obtained from the recorded disparity images under infrared lights in a low-lux condition. We removed the noise using multiple filters calculating background noise, the size of point cloud, the length of point-cloud time series, and linear SVM (support vector machine) for classifying *S. litura* and noise. To eliminate noisy flight trajectory data, we computed the voxel volume and directional angle of the 3D point-cloud time series, and then visually inspected and removed the noise data. Obtained 68 flight trajectories in total showed that mean flight speed of free-flying *S. litura* was 1.81 m/s and directional angle different between true and noise flight trajectories can be a good indicator for noise detection.

Key Message

- Free-flying trajectories of *litura* under low-lux conditions were measured using infrared light and a stereo camera.
- The trajectories were extracted using 3D point-cloud data obtained from the disparity images.
- Most of noisy point clouds were removed by the automatic detection pipeline.
- Remaining noise point clouds were removed based on 3D animation of flight trajectories.
- Flight speed of free-flying *litura* has been measured for laser zAPPING.

1. Introduction

Damage by pests is one of the main causes of loss in agricultural production (IPPC Secretariat. 2021). Feeding damage by lepidopteran insects is particularly significant. *Spodoptera litura* (Lepidoptera: Noctuidae) is a major pest in the Asia-Pacific region (Bragard et al. 2019). Because it is an euryphagous insect that feeds on a wide variety of crops (Cheng et al. 2017), has a high reproductive rate, and some populations have insecticide resistance (Armes et al. 1997; Cheng et al. 2017) with middle- and older-instar larvae being particularly low susceptibility. At present, the management of *S. litura* is generally carried out by chemical control using insecticides. However, it is difficult to effectively control *S. litura* by chemical control alone, such as the spraying of agricultural chemicals, because of its resistance to insecticides and the ecology that *S. litura* is generally nocturnal, and the last instar larvae and pupae hide in the soil (Omino et al. 1973; Zhang et al. 2021). Therefore, integrated pest management (IPM), which
does not rely solely on chemicals, is required to control \textit{S. litura}. Delta endotoxins (Bt toxins) and nuclear polyhedrosis virus (NPV) have shown some success as a biological control (Kumari and Singh 2009; Alotaibi 2013); however, the practical use of physical control is limited to primary methods such as blocking with insect nets.

In recent years, laser zapping has been studied and proposed as a new physical pest control method. Previous studies have been conducted on pests, such as mosquitoes, cockroaches, aphids, psyllids, salmon parasites, and weeds (Mathiassen et al. 2006; Mullen et al. 2016; Keller et al. 2020; Bui et al. 2020; Gaetani et al. 2021; Rakhmatulin 2021a, b; Andreasen et al. 2022; Rakhmatulin et al. 2022). Research on \textit{S. litura} has also been conducted to kill flying individuals using laser zapping (Nishiguchi et al. 2023; Sugiura et al. 2023). Previous research has indicated that it is necessary to expose high-power laser to the thorax or head of this species to kill or disable flying individuals (Nishiguchi et al. 2023). To hit a small-sized target with a high-convergence-rate laser, it is necessary to accurately measure flight trajectories and speed, and to predict the trajectories a few steps ahead. In addition, because this species is generally nocturnal, its flight trajectories cannot be observed and recorded with a camera using visible light. Therefore, it is necessary to develop a system that can measure flight trajectories and speed under dark or low-light conditions.

Therefore, this study aims to measure the flight trajectories and speed under low-light conditions by recording videos of the flight of \textit{S. litura} using infrared light and a stereo camera and converting them into 3D point-cloud time series data. Because the 3D point cloud data obtained from these disparity images contained numerous noise data, we removed them by multistep processing considering background noise, the size of point cloud, the length of point-cloud time series, and using a noise classifier using flight trajectory. Remaining noise was removed from the selected flight trajectories by using 3D animation and descriptive statistics of the 3D point-cloud time series. We considered the flight speed from the noise-free flight trajectory data of free-flying \textit{S. litura} as their flight speed and compared with data from previous studies.

2. Materials and Methods

2.1 Sample collection and rearing

We fed an artificial diet (Insecta LFM, Nosan Co., Yokohama, Japan) to \textit{S. litura} larvae collected from sweet potatoes and reared them in Tsukuba City, Ibaraki Prefecture. The larvae were maintained at 24 °C. We used virgin females 2–4 days after eclosion in all flight experiments.

2.2 Stereo camera

A stereo camera (SceneScan Pro, Nerian Vision Technologies) was employed to acquire three-dimensional positions of a free-flying insect. The stereo camera consisted of two identical cameras located in parallel that synchronously captured visible images with a resolution of 1024 × 768 pixels. The distance between the two cameras, i.e., the baseline for stereo processing, was 10 cm. An internal
function of this stereo camera device performed stereo matching on the images from the two cameras to produce a disparity image in which the depth information with 12-bit gradation is recorded as image data. The resolution of the disparity image is 1024 × 768 pixels. The horizontal and vertical angles of view of the camera were 47.2 degree and 36.3 degree, respectively, and the spatial resolution was, for example, 1.6 mm at an imaging distance of 2 m. The stereo camera outputs the left and disparity images at a frame rate of 55 FPS and transmits them to the computer via an Ethernet cable. However, in this study, the visible image was not used in the subsequent processing, and only the disparity image was used.

2.3 Video Recording using Stereo Camera

We set up the recording video space of 1.8 m high × 1.8 m wide × 3.5 m deep (Fig. 1). The recording space was maintained at 24°C. It was enclosed in a mosquito net to prevent escape in the laboratory room and flew only in the recording area. A stereo camera (SceneScan Pro, Nerian Vision Technologies, 55 fps) was installed at the center of the short side on one side. Three infrared lights (850 nm, 6 W, 10 W, and 17 W, unbranded) were installed on the same side as the light sources for recording the stereo camera images. Ultraviolet light (315–400 nm, 27 W, FPL27BLB, SANKYO DENKI Co.) was installed on the opposite side as a guiding light for *S. litura*. Red light was used as the working light source. We turned on only infrared light as a light source and ultraviolet light as a guiding light during video recording, and turned off or blocked visible light, including the working light.

The experiment was conducted under free-flight conditions, without using a flight mill or tethering with a thread. *S. litura* was released from a position in the center of the long side of the recording area, and recordings were performed for about 5 seconds until it flew out of the recording range (sufficient to observe a flight time of about 3 seconds at the maximum). We obtained 52 flights recorded under this condition. Of the 52 recordings, one individual was released per recording in 48 of them, and multiple individuals were released simultaneously in four (three individuals twice, four individuals once, and seven individuals once). After confirming that the data from multiple releases could be handled in the same way as the data from a single release, the data were processed using the same methods for subsequent analyses.

2.4 Extracting *S. litura* flight trajectories

2.4.1 Extracting point cloud of flight trajectories

The 3D flight trajectory data were obtained using the following automatic detection pipeline (Sugiura et al. 2023) (Fig. 2). The disparity images captured by the stereo camera were converted into 3D point cloud data, which were sequenced in time series order. To remove the point cloud of the background noise from these files, the following process was performed. Cubic voxels were placed every 5 cm over the entire space. Voxels with more than two points in the first four frames from the start of recording were designated as background noise voxels. All point clouds included in the background noise voxels were removed in the subsequent frames. Points within 1 cm of each other were considered the same cluster.
object. Further, these files were obtained by removing an object having less than 20 points and more than 900 points. From these files, we treated centroids of point cloud in consecutive frames in time series in distance within 9 cm as point cloud by the same object. We removed those with a time series length of fewer than 10 frames from the 3D point-cloud time series. Finally, noise classification was performed using a linear support vector machine (SVM) (Sugiura et al. 2023) in which stationary and moving objects were classified based on two variables, namely, the standard deviation of the position and the standard deviation of the turning angle, both for 10 frames. The selected point cloud was treated as a candidate flight trajectory in the subsequent analysis.

2.4.2 3D animation of 3D point-cloud time series

The visualization software ParaView (Ver. 5.11.0, Kitware Inc., https://ParaView.org/) was used for animating and visualizing the 3D point-cloud time series as each of the flight trajectory candidates. Using these 3D animations, we visually confirmed the existence of a point cloud with continuous movement while changing the viewpoint to confirm whether it was appropriate as the true flight trajectory of *S. litura*, aiming to remove the remaining discontinuous noise data. In addition, the 3D point-cloud time series was converted into text data using ParaView. We used R (Ver 4.3.1, R Core Team 2023) on the text data to calculate the speed, turning angle, distance from the camera using centroids of measurement point cloud as well as the volume of the outline box containing point cloud, the number of point cloud and point cloud density in each frame, of which descriptive statistics (i.e., mean, median, and quartiles) were calculated.

2.4.3 Remaining noise removal process

From the descriptive statistics of 3D point-cloud time series, we visually inspected the trajectories, including the outliers in turning angle and outline voxel volume on the 3D animation frame-by-frame, forwarding from the candidate trajectory point cloud, including outliers with the noise point cloud. This process was performed until no noise point clouds were observed. The candidates including noise were separated as noisy point cloud data. The point cloud data, including only the flight trajectories of *S. litura*, was treated as *S. litura* point cloud data. In addition, we compared the statistical data of the *S. litura* point cloud data and the noisy point cloud data, examined the difference in features for improving the automatic flight trajectory processing pipeline.

3. Results

3.1 3D point cloud of flight trajectories

Most of point cloud from disparity images (Fig. 2a) were noise point cloud such as background noise (Fig. 2b). A few point clouds were left in these files, in which constant background noise was removed (Fig. 2c). These point clouds include *S. litura* point clouds that moved smoothly and continuously while noise point clouds that were isolated and disappeared without moving. Most of the noise point clouds were removed in the final files of the pipeline. Although our program could obtain the true flight trajectory
of *S. litura* from disparity images, the point clouds included not only the true flight trajectories, but also noisy point clouds as a result of the visual inspection using 3D animation.

### 3.2 Removal of remaining noisy point cloud

The 3D visualization of the flight trajectories indicated that the *S. litura* point clouds had continuous and smooth trajectories (Figs. 3a and 3b), whereas the noise point clouds showed discontinuous and limited movement (Figs. 3c and 3d). We found two parameters, namely the volume of the outline voxel and the turning angle, to be effective for noise detection. For instance, volumeless outline voxels (i.e., no thickness; volume = 0) were abnormal data in which all point clouds existed on the same surface. In addition, the turning angle of the 3D point-cloud time series in the range of $110^\circ < \theta \leq 180^\circ$ contained noisy point clouds that repeated reciprocating motions in a fixed area.

We classified the obtained point cloud data into three categories, "entire point cloud data" (all point cloud data obtained by pipeline processing), "*S. litura* point cloud data" (only flight trajectories point cloud data from which remaining noise point cloud was removed from entire point cloud data), and "noisy point cloud data" (point cloud data containing noise removed in *S. litura* point cloud data). The entire point cloud data consisted of the *S. litura* point cloud data and the noisy point cloud data. When these three datasets are compared in terms of speed and turning angle (Fig. 4), the outliers of the turning angle existing in the entire point cloud data (approximately $100^\circ < \theta \leq 180^\circ$) and the existence range of the noise data ($110^\circ < \theta \leq 180^\circ$) are close to each other (Figs. 4a and 4b). The *S. litura* point cloud data, the data of the turning angle of the outlier were removed (Fig. 4b), and in contrast, it is shown that the proportion of the point cloud data of the corresponding turning angle exists at a high frequency in the noisy point cloud data (Fig. 4c). However, in contrast to the turning angle, the speed was not useful for classifying the *S. litura* point cloud data and the noisy point cloud data (Fig. 4).

### 3.3 Flight speed based on 3D point-cloud time series

We obtained information on the free-flight speed of *S. litura* based on centroids of the measurement point cloud only from the *S. litura* point cloud data. This speed information was compared with the flight speed data from previous studies using flight mills. The flight speed of free-flying *S. litura* was $1.81 \pm 0.68$ m/s (mean ± SD), while the maximum flight speed was $0.88 \pm 0.33$ m/s (mean ± SD, non-laying adult females 3 days after eclosion) in a previous study (Noda and Kamano 1988) of which the mean value and standard deviation were approximately half the results of this study.

### 4. Discussion

In this study, we obtained noise-removed flight trajectories of free-flying *S. litura* by recording videos using infrared light and stereo cameras, results of which were then processed using the 3D point-cloud time series pipeline. Noise data with an outline box volume of 0 existed only around 0.9 m from the stereo camera, which is analogous to the minimum effective range of the stereo camera. That is, it is difficult to accurately measure the *S. litura* point clouds near the effective range limit of the stereo camera. In this study, the flight trajectory data with large turning angles ($110^\circ < \theta \leq 180^\circ$) were noise data. Adding this
information to the 3D tracking pipeline for free-flying *S. litura* can improve noise removal in the pipeline. There are two types of the noisy point cloud data: noise-only point clouds and mixtures of the *S. litura* flight trajectory and noise point clouds. Therefore, flight trajectory data containing both *S. litura* and noise data must be partially adopted for the practical application of pest control by laser zapping. For this reason, a new pipeline may be required to deal with noisy 3D point clouds by early detection and substitution to a realistic position in the trajectory. The higher resolution and frame rate of the stereo camera imaging may capture free-flying *S. litura* in more detail. The accuracy of this measurement system may be improved by testing and further calibrating the denoising method based on *S. litura* tethered to flight mills or other models with a speed control motor within the 3D point-cloud measurement system developed in this study.

Flight speed is an important factor for designing automatic tracking and laser-based control system against pest insects. The flight speed data in this study were approximately twice as large as the speed data measured by a flight mill in the previous study (Noda and Kamano 1988) (Flight mill in previous study: 0.88 ± 0.33 m/s, Free flight in this study: 1.81 ± 0.68 m/s, mean ± SD). One reason for this result is absence of behavioral limitations in this study compared to tethering on flight mills in the previous study. The stress from the catch and release by human might have increased the flight speed as an escape behavior. However, the method of this study enables measurements under dark or low-light conditions, and it has become possible to measure the complex 3D flight trajectories and speed, including sudden changes in direction and deceleration of nocturnal flying insects, such as *S. litura*, for which detailed analyses of flight have been difficult. It is unprecedented that this method can be used for detailed measurement of 3D flight trajectories and speed under low-light and free-flying conditions. These changes cannot be observed using a measurement method such as flight mills. In previous studies, insect flight speed has often been measured by flight mills or tethering with a string (Noda and Kamano 1988; Ribak et al. 2017; Naranjo 2019). Recently, a system for measuring 1D flight speed of insects combining the Scheimpflug principle and lidar was proposed (Li et al. 2020). The data on the flying ability of *S. litura* in this study are an important basis for pest control; however, further investigations are required to accumulate more data considering various factors affecting the behaviors of *S. litura*.

The pipeline in this study has already been incorporated into a real-time tracking system with a Kalman filter (Sugiura et al. 2023). To cope with noisy 3D point clouds in real-time settings, the coordinates, flight speed, and turning angle in the current frame may be used to improve the short-term prediction of free-flying *S. litura* flight trajectories. Considering the time lag between stereo camera imaging and laser zapping, a fast and accurate short-term prediction is indispensable for effective pest control. Furthermore, this measurement system can be applied to investigate the flight ability of other flying insects by adjusting the detection settings. In particular, in the case of nocturnal flying insects, observation of a more natural state of flight ability may be preferred compared to conventional measurement methods because visible light and tethering are not necessary. Further improvement of laser-based pest control will benefit from such information as flight speed of flying pest insects under natural conditions.
Declarations

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Author contributions

Ryo Sugiura, Ryo Nakano, and Kazuki Shibuya conceived, designed, and performed the experiments. Ryo Nakano and Kazuki Shibuya collected and reared samples. Ryo Sugiura wrote the point cloud extraction pipeline programs and Shinji Fukuda wrote statistics analyses programs. Koji Nishisue visualized and analyzed the data. The first draft of the manuscript was written by Koji Nishisue and was revised by Shinji Fukuda. All authors commented on the previous versions of the manuscript and suggested revisions. All authors read and approved the final manuscript.

Data availability

The datasets and programs used in the current study are not publicly accessible due to confidentiality agreements.

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Conflict of interest

The authors declare no conflicts of interest.

Ethics approval

None of the organisms that required ethical approval were included in this study.

Consent for publication

Not applicable to this study.

Consent to participate

Not applicable to this study.
References


Figures
Figure 1

Schematic diagram of the video recording environment. View of the recording arena from above. The height of the arena was set at 1.8 m. During the recording, only infrared and ultraviolet lights were turned on for recording and luring light resources, respectively. Visible light was turned off and blocked.
Figure 2

Schematic diagram of the noise removal pipeline process. The series of images in (a), (b), and (c) of the right column is an example of the corresponding data. The point cloud data obtained from the disparity images (a) contained a large number of noise point clouds (b). The pipeline process for selecting only *S. litura* point clouds by noise removal was performed as follows: In the first step, to remove the noise point clouds that were always displayed, the point clouds in the background voxels (2.5 cm units per side) that
existed for the first four frames of recording were considered as noise and removed. In the second step, point clouds within 1 cm of the remaining point clouds were considered the same object, and point clouds with a point cloud size (PCS) of less than 20 or more than 900 were removed as noise (c). In the third step, point clouds spanning consecutive frames in the time-series were considered the same object, and point clouds with a time-series length (TSL) of less than 10 frames were considered noise and removed. Finally, a linear support vector machine (SVM) based on the time-series coordinate data was used for classification, and the remaining data were selected as *S. litura* point clouds. Red circles indicate the locations of the point clouds selected at each step. (a) Pair of disparity images of the original data recorded by a stereo camera. Because the stereo camera is not an infrared camera, disparity images are almost exclusively visually black. (b) and (c) are images of point cloud data visualized using ParaView.
Figure 3

Examples of the entire 3D point-cloud time series in a dataset. The left and right columns show the same data for the different display angles. (a) and (b) are the *S. litura* flight trajectories, and (c) and (d) are the noise point clouds that remain after the pipeline. The frame sizes of each dataset were (a) 82 frames, (b) 65 frames, (c) 58 frames, and (d) 42 frames. The arrows in (a) and (b) indicate the direction of the movement based on the time series. There were no consecutive movement directions in (c) and (d).
Histogram and boxplot of flight speed and turning angle based on the centroids of point-cloud time series: upper row (entire point cloud data) (a), middle row (S. litura point cloud data) (b), and lower row (noisy point cloud data) (c). The left and right columns represent flight speed and turning angle, respectively. The dotted line in the histogram indicates the mean value, and the solid line in the boxplot indicates the median value.