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Mosquito vector monitoring system based on optical wingbeat classification

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ABSTRACT

We developed an automatic mosquito classification system which consists of an infrared recording device for profiling the wingbeat of the in-flight mosquito species and a machine learning model for classifying the gender, genus, and species of the incoming mosquitoes by the signatures of their wingbeats.

The recording device is a set of infrared emitters and receivers, which are attached to the wall of an apparatus. When the winged subject enters the apparatus, its flapping wings block the infrared beam from the emitters intermittently such that the receivers convert the wingbeat to the electrical waveform. To classify the incoming subjects, we proposed a machine learning method, which is the Gaussian mixture model trained using the expectation-maximization algorithm (EM-GMM), and compared it with the previously proposed algorithms, including the artificial neuron network model (ANN) and the nearest neighbor model.

To assess the performance of the system, we used the living male and female *Aedes albopictus*, *Aedes aegypti* and *Culex quinquefasciatus*. The results show that the accuracies of the proposed system are above 80% on identifying the gender and genus of the mosquitoes, with the precisions above 80% and 70%, respectively. The results also suggest that the EM-GMM algorithm outperforms the other two algorithms on the accuracy and precision of the classification of the classes of mosquitoes. In addition to the evaluation of the performance of the system, we also found that certain classes of mosquitoes share similar wingbeat characteristics, which implies that the distinctive wingbeat characteristics should be considered for the optimal accuracy of the classification of the insects of interest.

1. Introduction

Preventing humans, poultry, or livestock from mosquito-borne diseases reduces the economic losses which are caused by the disease infections. *Aedes* mosquitoes are important vectors of zoonotic arbovirus, including West Nile virus, yellow fever, dengue fever, and encephalitis (Gubler, 1989; Gubler and Clark, 1996; Eritja et al., 2005). In addition, filarial diseases transmitted by *Culex* are not only infectious to humans but also to buffalos, goats and sheep. While infection might cause an increase in medical expenses and a reduction of livestock production, effective mosquito control programs rely on statistical indices based on mosquito population monitoring. The conventional approach used for mosquito population monitoring is based on ovitraps, whose advantages are low-cost and convenience of deployment, but they suffer from low sampling frequency (Zeichner and Perich, 1999; Polson et al., 2002; Lenhart et al., 2005).

Some previous approaches applied to detecting and monitoring insect movements were based on wingbeat (Reynolds and Riley, 2002). The characteristics of mosquito wingbeat were studied through acoustic, optical, and radar approaches (Landois, 1867; Chadwick, 1939; Reed et al., 1942; Sotavalta, 1952; Jones, 1964; Belton and Costello, 1979; Unwin and Ellington, 1979; Moore, 1991; Mankin, 1994; Moore and Miller, 2002; Riley and Smith, 2002; Reynolds and Riley, 2002; Li et al., 2005; Pennetier et al., 2010), but there are certain difficulties for implementing a robust system for in-field mosquito population monitoring using these methods. On the measuring instrument for the features of mosquito wingbeats, the frequency of the wingbeats was measured using tuning forks in the early stage of this field of research (Landois, 1867; Sotavalta, 1952), a procedure which lacks quantitative precision and objectivity. Later, microphones were introduced in acoustic approaches, but microphones suffer from

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the inconvenience of sound-proof instruments (Williams and Galambos, 1950; Jones, 1964), although acoustic approaches have been widely used in studies on behavior related to insects' auditory organs (Johnston, 1855; Mankin, 1994; Göpfert and Robert, 2001; Gibson and Russell, 2006; Jackson and Robert, 2006; Robert, 2009; Cator et al., 2009). On the other hand, optical approaches were also proposed. Early studies used the stroboscopic approach to measure the changes of light intensity created by the wingbeat of insects (Chadwick, 1939; Williams and Galambos, 1950). More recently, experiments were performed using photo sensors working in a spectrum range, which provided more adequate signals within a spectrum range, which provides better signal-to-noise ratio (SNR) than the acoustic methods (Unwin and Ellington, 1979; Moore et al., 1986; Byrne et al., 1988; Riley, 1989; Oertli, 1989). Cameras were also introduced in the research on insect flight kinematics (Ellington, 1984; Hardie and Powell, 2002) and swarming (Ikawa et al., 1994), but due to the tiny size of the study subject, the optical methods suffer from the resolution of the sensor. Radar approaches were used in remote sensing of insect migration; the insects could be distinguished from other objects by the radar-derived wingbeat frequency. However, insect identification for intra-species was difficult due to the overlapped frequency distributions of the radar returns (Riley, 1989; Riley and Smith, 2002). Concerning the tools for analysis, spectral characteristics of wingbeat were used to identify insect species. The primitive approaches for identifying mosquito wingbeats relied heavily on researchers' absolute pitch (Landois, 1867) or accurate oscilloscopic records converted from acoustic signals (Williams and Galambos, 1950). With the rapid progress of computers, automatic classification algorithms were introduced in the studies on insect wingbeat. Artificial Neural Network (ANN) classifiers, for example, were introduced to automatically identify in-flight mosquitoes through spectral wingbeat characteristics (Moore, 1991; Li et al., 2005). Research papers on the identification of assorted insect species using different algorithms were proposed, but some mosquito species shared similar wingbeat frequencies (Moore, 1991; Moore and Miller, 2002; Li et al., 2005). Therefore, a system with a high-resolution measurement tool which is robust to the environmental noise and the corresponding tools for analysis for mosquito wingbeats has yet to be developed and is needed for the research on mosquito wingbeats and for large-scale vector monitoring.

To address the challenges mentioned above, we propose a mosquito classification system that consists of an infrared sensor array recording device, a set of software programs based on a classification algorithm, and a method that can be trained to identify *Aedes albopictus*, *Aedes aegypti* and *Culex quinquefasciatus* when they are in flight. The spiral infrared sensor array recording device proposed in this paper provides robustness to the environmental noise, and the structure is simple enough for large-scale deployment. The recorded wingbeat data are transformed into cepstrum to improve the identification performance of mosquito wingbeat (Moore and Miller, 2002). Then the Gaussian Mixture Model-based (GMM) classifier, which have been widely applied to human voice identification, is introduced in this research (Gish and Schmidt, 1994; Gauvain and Lee, 1994; Reynolds, 1995; Kinnunen et al., 2006). The proposed method is tested with experiments in classifying three mosquito species: *A. albopictus*, *A. aegypti* and *C. quinquefasciatus*, and their gender, based on the recorded optical wingbeat sequences.

2. Materials and methods

2.1. Mosquito colonies

Colonies of the three mosquito species: *A. albopictus*, *A. aegypti* and *C. quinquefasciatus*, were collected from Taipei City, Taiwan, and were raised and maintained by feeding the 5% sucrose solution in growth chambers under constant environmental conditions (Temp. = 25 °C, RH > 80%). The evaluation group consisted of 745 optical wingbeat sequences from 120 mosquitoes ($n = 120$, 20 individuals for each gender of the 3 species) and the training group consisted of 43 sequences from 12 mosquitoes. ($n = 12$; at least 2 individuals for each gender of the 3 species). The duration of extracted sequences ranged from 50 to 100 ms.

2.2. Infrared-based wingbeat sensor

The wingbeat recording device consists of three infrared emitters and the corresponding receivers (working wavelength = 830 nm). The pairs of emitters and receivers were arranged in a double helix pattern and attached to the observation apparatus (Fig. 1). The observation apparatus was made with a 15 ml conical polypropylene tube. In this research, the apparatus was closed-ended; it can be open-ended or closed-ended when being attached to the mosquito trap. The emitters and receivers were wired in parallel. Thus, the emitters and receivers formed three pairs of photo-interrupters. The receivers were powered by a 6 V DC power supply from the data acquisition card, and the emitters were powered by 6 V battery. Mosquitoes' flying directions and environmental lighting conditions were not under control during the experiments.

2.3. Wingbeat signal acquisition and processing

In each experiment, one mosquito was manually transferred into the observation apparatus to conduct wingbeat recording. The wingbeat waveform was recorded in the observation

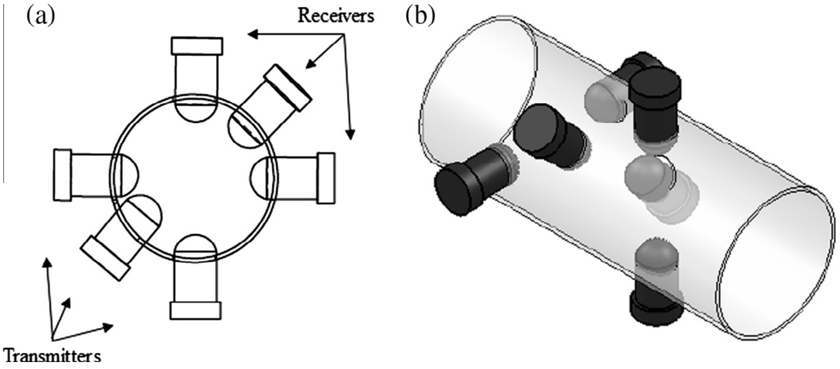

Fig. 1. The optical wingbeat recording device. The diagrams present (a) the configuration of the double helix arrangement of the transmitters and receivers, and, (b) the rendered sketch of the optical wingbeat recording device.