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Development of an Automated Multidirectional Pest Sampling Detection System Using Motorized Sticky Traps

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ABSTRACT Insect detection and counting constitute a considerable challenge in the field of agriculture. However, among various biotic issues of agricultural production, pest infestation is a major challenge, with the humid environment surrounding the crops encouraging the survival and proliferation of pests. In addition, electronic traps need protection, especially from rain. This study describes the design and development of a prototype for an automatic pest sampling and detection system for agricultural crops. To the best of our knowledge, the proposed system is the first motorized automatic trap developed to handle monitoring operations in two directions of precise movement (i.e., clockwise and counterclockwise) and cover four directions of insect sampling that provides additional details of insect infestation direction. A square-shaped sticky box was designed, and an optical sensor was attached to a scalable arm. The movements of the sticky box and the camera arm were generated by motors. Preprocessing was conducted by using morphological operations, whereas insect detection and counting were implemented by an algorithm of connected components labeling that applied by using MATLAB image processing toolbox. Different kernel functions, such as disk, diamond, square, and sphere, were used as matching functions for the insect detection and counting algorithm. The average accuracy of the highest sphere kernel was 85.2%. Test results of the hardware show the reliability, flexibility, and system protection of the automatic system to provide accurate movements in two degrees of freedom.

INDEX TERMS Automatic trap, insect sampling, insect counting, motorized trap, morphological image processing, pest detection, yellow sticky box trap.

I. INTRODUCTION

Agricultural crops are among the most important sources of food worldwide, especially in tropical countries. The relationship between insects and diseases is one of the direct damages of insects that occurs by transmitting various diseases to healthy plants [1], [2]. Hence, agriculture crops may lose their quality and quantity when different pests attack plants.

To evaluate pest species and densities based on machine vision, a clear image of an insect must first be obtained. However, insects, especially flying ones, constantly move around, making it difficult to capture clear images directly. Some studies [3], [4] have chosen insect specimens that have been well preserved in an ideal laboratory environment to avoid problems, and images can be captured at high resolution; however, given that less environmental issues are considered in this method, they are limited in specific applications. A more realistic approach is to use traps, which attract insects by several ways, based on light [5], color [6], [7], and pheromones [8], [9].

Yellow sticky paper traps consider an attractive color for the insects; these traps have been widely used in insect sampling practices as an effective tool associated with pest preference [10]–[12]. Sticky traps usually consist of a piece of paper containing a sticky substance to trap insects and are placed in fields or greenhouses [13], [14]. Sticky traps are then photographed for automatic counting [7], [9], [13].

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This strategy offers a smooth and neutral surface, making insect counting easier.

Sampling is an important method of detecting insect infestation and estimating species abundance [12], [15], [16]. The use of traps for sampling insect pests is commonly practiced and is a vital part of pest detection, delimitation, suppression, and eradication programs worldwide. Insect sampling system traps can help assess insect activity and estimate insect populations that can effectively protect crops. Moreover, the use of insect traps can directly reduce or monitor insect populations.

The assessment of pest population density in agricultural crops is crucial for proper planning of pest forecasting. Nowadays, farmers have to use sweep nets, traps, or beat sheets for sampling pests in the fields [17], [18]. The insects caught by various traps are transported to the laboratory for manual counting and identification by experts or counted manually by human experts observing them on screen [19]. Typically, crop technicians are responsible for manually identifying and segregating insects based on species and counting the main pests separately. The resulting counts are used for estimating pest density, but the large number of sites and frequency of counting of agricultural pests is a time-consuming and tedious process for crop technicians. Such a challenging situation can result in low accuracy in counting, leading to incorrect decisions on crop pest management. In addition, humans are usually much slower than machines in performing simple tasks, such as counting. Sampled insects with trap by acquiring images automatically is rapid technology to detect and count insects. This technology reduces labor and resource costs and simultaneously monitors population dynamics on a large space scale with an adjustable temporal resolution.

The advantages of using the sticky trap method, which is a useful tool for sampling most insect populations, are as follows:

- Sticky traps are easy to use in terms of deployment, collection, and examination, whereas wireless electronic traps may be cumbersome to handle in terms of system complexity.
- Sticky traps are more reliable than pheromone traps based automatic counting through a sensor passage to count insects without killing them resulting in erroneous counting due to insect flying movements [20].
- The inability to recognize insects due to the damage to defining characters. Nevertheless, camera-based sticky traps have been developed to overcome this issue by capturing images directly. Easy to adopt camera as well as pheromones for a specific species of insects as well as in sensor based-traps that can be used for all seasons.
- Image-based traps allow for the verification of the automatic counting method. By contrast, sensor-based traps cannot perform verification and thus need to use a specific pheromone [21].
- Sticky traps are more effective and have a lower cost than complicated systems, such as sensor and electronic traps (e.g., Trapview).
- Sticky traps are environmentally friendly and nontoxic. Furthermore, sticky traps combined with a camera system provide a simple insect detection setup with a low rate of mechanical error.

Although traditional traps for monitoring insect population are effective (when applied properly), they still have several major drawbacks, including the following:

- It is a costly practice because staff are required to visit the traps and record the population, thus increasing the total cost of the sampling program.
- Lags in the flow of information occur because the staff only visits the traps once a week.
- Sticky traps do not always result in a quick death for insects. Thus, insects could escape in some cases (e.g., low quality of glue).
- Sticky traps have become common in recent years because they are used as a disposable object rather than a reusable one; moreover, they are not recyclable.
- Cases of insect overlapping occur due to insect movement after gluing to sticky traps.
- Sticky surfaces are efficient traps, but it may shortly be rendered useless by contamination with dust and insects other than the target insect.
- Tracking the population's evolution over time is nearly impossible because of the low sampling level.

The rapid development and advances in digital technology have opened opportunities to deploy image processing technologies for agricultural research, thereby assisting researchers in solving complex problems in insect detection. With regard to temporal resolution, image-based traps can usually offer day-to-day data by taking and transmitting images of insects on boards and providing a time stamp [21]. In addition, in the near future, several insects can be monitored by using image-processing devices concurrently [8]. Imaging-based traps can capture images of a surface holding insects and then send these images to a server. Hence, pest counting is performed automatically by an image processing approach [5], [8], [22], [23]. Additionally, the systems using visual information, such as the aforementioned traps, also detect nontarget species to improve the accuracy of the monitoring data.

This study adopts image processing and extends its implementation to the estimation of pest population by using an automated detection mechanism to assist crop technicians/experts in counting pests from collected specimens conveniently and accurately. As such, appropriate and efficient pest management procedures can be implemented to enhance the quantity and quality of crop production. This automated system facilitates the dynamics of pest sampling.

The present study focuses on designing and developing an automated pest sampling and detection (PSD) system for sampling insects from various plants and different stages of growth. The main objective is to develop an automatic, low-cost PSD system that can be motorized dynamically and demonstrate a self-protected system of the PSD components, based on custom electronics and the-self components. Also,

(a) The sticky box (b) The plastic base

FIGURE 1. Yellow sticky papers on the box, and the rotating mechanism.

the system is developed to be capable of operating in real infield conditions, overcoming the drawbacks of the classical sticky-based traps thereby significantly improving the traditional way of sampling the pest population.

II. MATERIALS AND METHODS

The PSD system used for sampling the population distribution of pests in different agricultural crops in Universiti Putra Malaysia is composed of four yellow sticky sheets to attract insects from multiple directions. This concept inspires the development of an automatic sampling trap, which incorporates a protection system. The pests come in different sizes, which need to be sampled. Accordingly, the imaging-based detecting approach is selected.

III. AUTOMATIC PSD SYSTEM DESIGN

The proposed automated PSD system comprises two main parts:

1) The electromechanical part, which is concerned with tripod modifications, and the controller part, which focuses on controller boards, sensors, and actuators to control vertical and rotational movement. In detail, the Raspberry Pi board controls the Raspberry Pi camera, and the Arduino UNO board controls the wind speed and rain sensors.
2) The software part is concerned with the design and implementation of the pest detection algorithm and controlling the input and output of the PSD system.

The operational modes of the developed PSD device have been articulated to work in two modes, namely, active mode (AM) and protected mode (PM). Furthermore, during the AM, the automatic closure lid, sticky box, and camera arm are up in active positions to allow the camera to take pictures. During the PM, the camera arm, sticky box, and automatic closure lid are down in rest positions protected by the protection box. These modes are used to protect the system from environmental conditions, such as rain and windy weather.

A. STICKY BOX AND PSD ACTUATORS

Sampling the insects is a critical issue in the estimation of the population of insects in agricultural fields. Therefore, the sampling process must consider the directions from which the insects come, as well as the density in each direction. However, this study proposes a square box design to sample the four primary directions, namely, north, south, east, and west, for the PSD system.

The light weight of materials is a vital aspect in this study to reduce the loading on motors. However, the sticky box is made of four polystyrene plates whose dimensions are 20 cm × 25 cm × 20 cm (height × width × length). The dimensions of the plates follow the standard measurements of the yellow sticky paper (i.e., 20 cm in width and 25 cm in height). A 15 cm × 15 cm piece of polystyrene is installed in the middle of the cube cavity, and a 5 cm × 7 cm piece of plastic material is fixed at the bottom part of the polystyrene to support the upper part of the servo motor. The bottom part of the servo motor is mounted on top of the tripod, as shown in Fig. 1.

The mechanism of the movement behavior for the sticky box has two vertical directions, namely, up and down. These directions are synchronized with the working modes of the PSD system (i.e., AM and PM). During lifting of the sticky box, the DC motor is triggered by utilizing a high torque clockwise to achieve the maximum point in the vertical axis for capturing images out of the protection box. However, the downward movement is responsible for triggering the DC motor counterclockwise to reach the reset point, which is the lowest position in the vertical movement.

The camera arm is a modified selfie stick camera holder. The reason behind using this selfie stick is to have a scalable

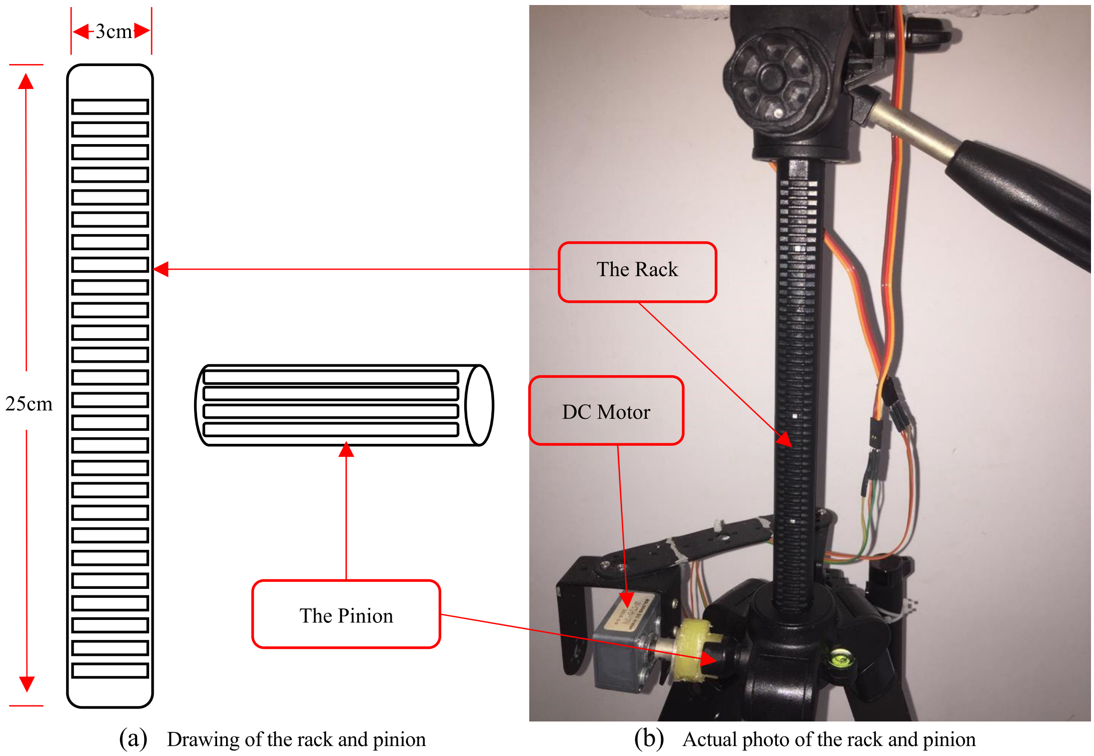


FIGURE 2. **Drawing and actual photos of the rack and the pinion gear.**

and flexible arm that can adapt to various scales and movements. The base of the stick is attached to a servo motor to provide an accurate position control for the camera. The camera arm has two main movement positions. First, when the system powers on, the camera holder moves from the PM to the AM, where the camera is located in front of the sticky box. Second, the holder returns to the PM once the sensors of the system sense rainfall and/or wind.

Motors are considered the heart of the mechanical system because they control the PSD system accurately. In the current study, the servo motor model RDS3128 featuring metal gearing, the DC motor model JGY-370, and an operating voltage of 6 V are used. The servo motor is used to provide accurate positional control to the sticky box because the servo motor is a closed-loop system that changes positions during AM and PM.

Generally, the advantage of using the worm gear DC motor in this study is its capability of high torque (12 kg.cm) worm gear self-locking model. This motor offers a brake feature to prevent destruction on the rack and motor pinion gear. Meanwhile, the L293D motor driver's 16 pins are used to control the DC motor between the two modes. To interface the eight pins of the L293D motor driver with the microcontroller, the motor driver is connected to the Arduino board model UNO through jumper wires to regulate the DC motor.

The servo motor is used to implement two main functions in the work of the sampling system. First, the servo is used to move the camera arm vertically from PM to AM and to the opposite movement from AM to PM. Second, servo motors are used to rotate the sticky box to capture images from four directions. Meanwhile, the sticky box movements in four directions are covered by using two servo motors with a 180° angle in each unit and then attached together. The first servo motor is fixed on the base of the tripod camera, whereas the second servo motor is fixed on the base of the first servo motor.

The DC motor is connected to the pinion gear for raising and lowering the sticky box that is installed on a U-long-shaped bracket and mounted on the tripod. The sticky box is moved up and down vertically through a 25 cm rack bar, as shown in Fig. 2.

B. TRIPOD STAND

The portable tripod is used as a platform for supporting the weight and maintaining the stability of the PSD system. Moreover, the tripod (i.e., Leegoal Tripod 360 Degree) is scalable by changing the suitable height according to the plant growth stage. Furthermore, the tripod is modified to achieve the purpose by containing electromechanically components of the PSD system. Hence, the tripod carries other parts, such as the microcontroller board, the camera arm, and the Raspberry Pi camera.

Brackets are mechanical components made of aluminum. Aluminum is a light material that can make the system portable and be used under different weather conditions; it is also rust resistant. Brackets are used in this study to build a robust mechanical system by connecting and fixing U-long-shaped, short, and multifunctional servo brackets on

TABLE 1. The sticky box clockwise movement with servo motors angles.

Box Movement	Image Capture	Servo-1 Angle	Servo-2 Angle	Servo-2 Angle
Direction-1	Picture one	0º	0º	5 sec
Direction-2	Picture two	90º	0º	5 sec
Direction-3	Picture three	90º	90º	5 sec
Direction-4	Picture four	90º	180º	5 sec

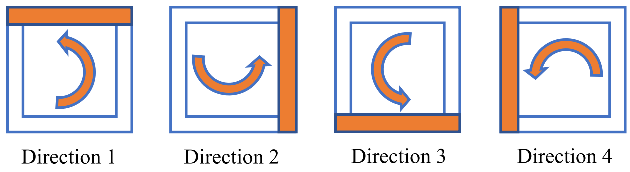


FIGURE 3. The sticky box with clockwise rotation.

TABLE 2. The sticky box counterclockwise movement with servo motors angles.

Box Movement	Image Capture	Servo-1 Angle	Servo-2 Angle	Servo-2 Angle
Direction-4	Picture four	90º	180º	1 sec
Direction-3	Picture three	90º	90º	1 sec
Direction-2	Picture two	90º	0º	1 sec
Direction-1	Picture one	0º	0º	1 sec

the tripod stand. These brackets have been used to build the base of the camera arm and the DC motor, as well as the base of the sticky box.

C. THE PSD SYSTEM OPERATION

During the operation of the PSD system, the camera is in the AM to capture images; for capturing the first image, the first and second servo motors are at an angle of 0°. After capturing the first image, the first servo motor is rotated at a 90° angle, and the second servo motor remains at the 0° angle to take the second picture. To acquire the third image, the first servo motor remains at a 90° angle, and the second servo motor rotates 90°. To take the fourth image, the first servo motor remains at a 90° angle, and the second servo motor rotates 180°, as shown in Table 1 and Fig. 3.

In other words, the first servo motor is used to rotate the sticky box from 0° to 90° to capture images from two directions (0°, 90°), and the second servo motor from the 90° angle continues up to 270° to create a 360° angle that covers four angles (180°, 360°). The process takes 20 sec to complete the clockwise rotational movements.

Table 2 shows the counterclockwise rotation of the sticky box to return to the initial position, and Fig. 4 illustrates the counterclockwise rotational direction of the sticky box. The process takes 4 sec to complete the counterclockwise rotational movements.

D. PROTECTION BOX

The protection box protects the PSD system components from several environmental conditions. This box consists of two main parts: the automatic closure lid and the protection box. This protection box consists of four polystyrene panels

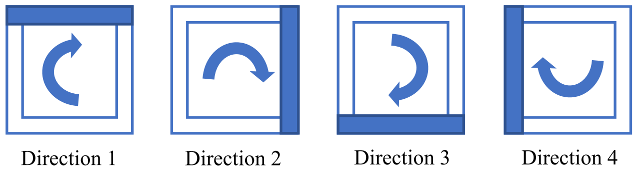


FIGURE 4. The sticky box with counterclockwise rotation.

whose dimensions are 125 cm × 60 cm × 65 cm (height × width × length). These panels are connected by using silicone to form a box. Consequently, an 80 cm slot is made at the front side of the protection box to facilitate the movement of the camera arm. The physical dimensions of the automatic closure lid are 60 cm × 65 cm (width × length).

The role of the automatic closure lid is to control the opening and closing actions for the upper part of the protection box. The automatic closure lid is controlled by a motorized arm that is actuated by a servo motor. The servo motor controls the angle steps and drives the automatic closure lid between the PM and AM. The motorized arm consists of one joint (two U-short-shapes brackets) that offers one degree of freedom for the opening and closing action.

IV. PSD SYSTEM CONTROL

A. CONTROLLER

The Raspberry Pi and Arduino boards are used to control the devices (e.g., sensors, screen, actuators, and camera) of the PSD system. In detail, an active and essential part (camera) is controlled and attached to the single board computer for capturing images. The reason behind using Raspberry Pi SBC is due to its compatibility with the Raspberry Pi camera. The Raspberry Pi 3 Model B+ is used to control the camera module V2.1 to capture images and save them into a secure digital (SD) card for data analysis. The camera data line is attached to the Pi board via a dedicated camera interface. The camera data line (100 cm) is a flexible cable that allows the camera arm to have multiple free movements.

Given its compatibility and flexibility for connection to various actuators and drivers, the Arduino microcontroller board is effectively used to regulate the system's actuators and sensors. Similarly, the Arduino board's main use lies in interfacing with devices and sensors. Therefore, the board is an ideal choice for our prototype to respond easily to several sensor readings.

The PSD system is designed to deal with substantial computing tasks to achieve the aspired goal. The connection between these two single-board controllers is to send data to and from the devices. The communication between Raspberry Pi and Arduino is performed by a serial port via the USB cable. The TFT display with a touch screen is connected via high-definition multimedia interface and used for purposes of configuration, viewing captured images, transfer of images, and control.

Furthermore, the rain sensor module (RSM) model YL-83 is utilized as a switching device activated by rainfall (that is, when a raindrop falls through the raining board), and it

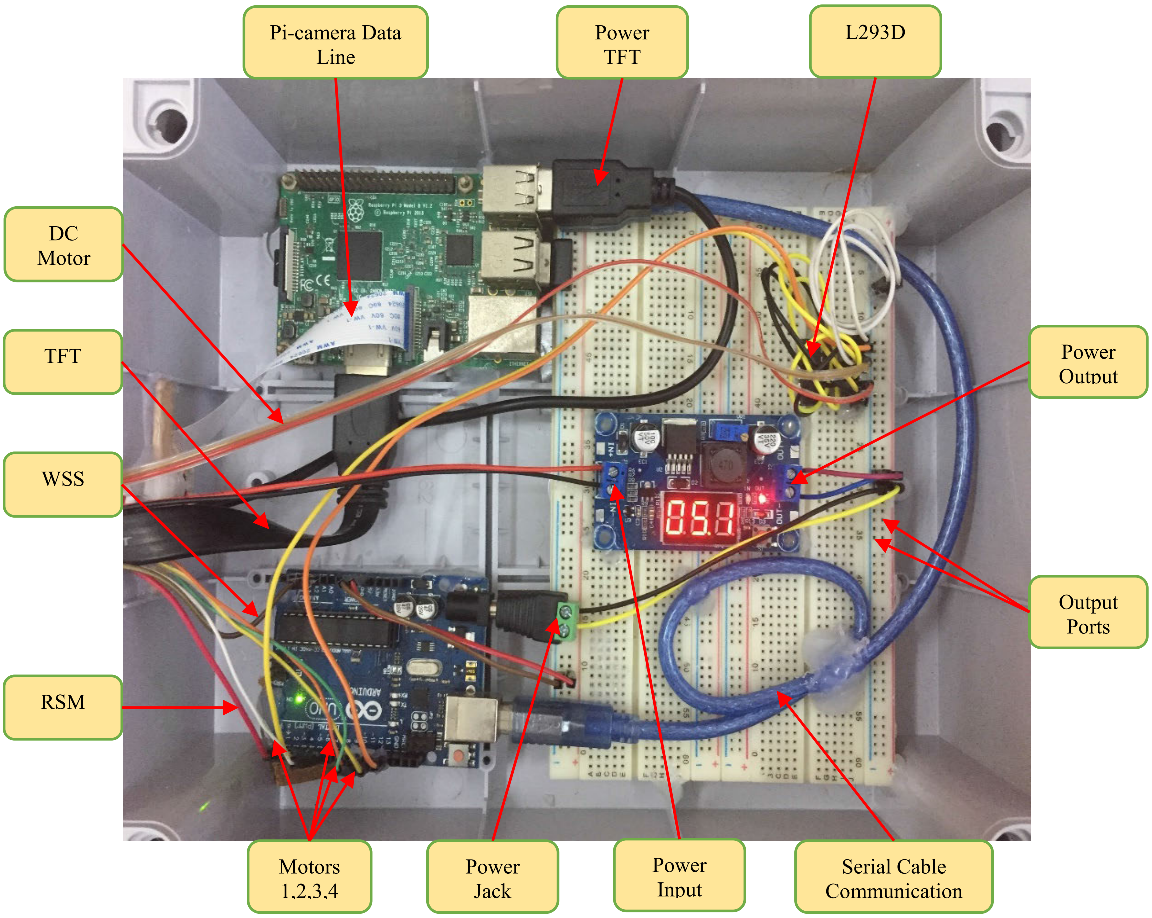


FIGURE 5. **The PSD embedded system.**

measures rainfall intensity. The wind speed sensor (WSS) is a device used for measuring wind speed, and it is a common weather station instrument.

B. POWER SUPPLY

A sealed rechargeable battery is used due to its low cost, long life cycle, robustness, common use in general purposes of projects, and less maintenance. Therefore, this study uses the external power that plays a crucial role in providing the necessary power for the PSD system.

Most components of the PSD system work with 5 V power consumption; therefore, the DC–DC regulator module LM2596 is used in this research to reduce the power (12 V to 5 V, 7.2 A to 2 A) and protect the PSD electrical system components from damage caused by power overload. This module comes with an adjustable power supply with display voltage for convenience.

C. SYSTEM OF THE EMBEDDED PSD

The system of the embedded PSD shows the communication among system components. Fig. 5 shows the embedded PSD system. The system components consist of Arduino UNO and Raspberry Pi as controllers, servo motors, a motor driver, a DC motor, an LM2596 module, a rain sensor, a wind sensor, a power source, a TFT display screen, and a Raspberry Pi camera module. The breadboard is a solderless device with electronics and test circuit designs. Most components in electronic circuits are interconnected by inserting their leads or terminals into the holes and then making connections through jumper wires.

In addition, two servo motors (1, 2) are used to control four directions of the sticky box rotation movement, and another servo motor (3) vertically controls the movement of the camera arm that controls and connects with Arduino UNO. Meanwhile, another servo motor (4) is used to control the automatic closure lid. The signal pins of the four servo motors (1, 2, 3, and 4) are connected to Arduino UNO digital pins (D10), (D11), (D6), and (D12), respectively. The DC motor is used to control the vertical movements of the sticky box controlled by the L293D motor driver that controls and connects with Arduino UNO. The L293D motor driver pins Enable, Input1 and Output1 are connected respectively to Arduino UNO board 5 V, digital pin (D5) and DC motor1, while Output 2, Input 2, and VCC are connected to DC motor2, digital pin (D13) and battery, respectively.

Furthermore, the RSM is connected to the analog signal pin (A1) to estimate rain intensity and is connected to Arduino UNO as well. The digital pin (D0), GND of the Arduino board and 5 V (VCC) are connected respectively to digital pin (D2), GND of the RSM and 5 V to Arduino UNO board. Moreover, the Arduino UNO board is used to connect the black wire (GND) of the WSS to the GND of the Arduino UNO board while connecting the sensor red wire to the analog of the Arduino UNO board (A0). Finally, all the components, such as sensors, motors, and motor drivers, are connected to the breadboard for powering after power (5 V, 2 A) has been distributed from an external battery that reduces the power by using the LM2596 module.

V. AUTOMATED PEST DETECTION

This process involves several tasks, such as image acquisition, image preprocessing, morphological operations, pest detection, and insect counting. In addition, the proposed PSD system software mainly depends on mathematical morphology. The main reason for this selection is to maintain the simplicity and low overhead of the algorithm to implement and guarantee that the subsequent code can be handled in much lower processing complexity. The MATLAB function is used in all the aforementioned procedures.

A. IMAGE ACQUISITION

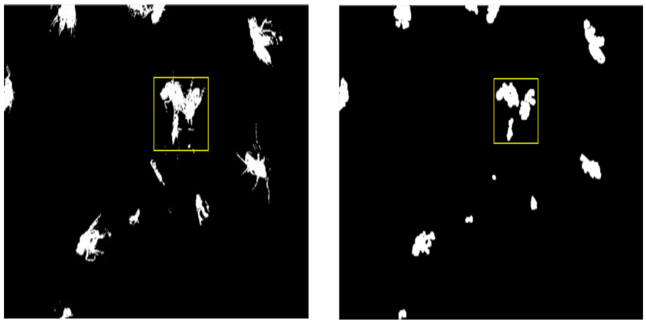
Image acquisition is the first process in pest detection and counting. The Raspberry Pi camera is used as an image acquisition device, and the resolution is set to 3280 x 2464 pixels. The image acquisition process of the PSD system starts in the AM, and the camera arm is triggered to be in front of the sticky box. The sticky box in the PSD system consists of four sticky papers assigned to four directions. Every hour, the camera captures four images from each direction. The device is installed in locations at 7 am and starts to collect data from 8 am to 5 pm. Lastly, all the acquired images by the PSD system are saved to an SD card with a JPG extension. The images are saved with timestamps representing the date (year, month, day, hour, minute, and second).

B. IMAGE PREPROCESSING

Image pre-processing is considered a crucial process to enhance captured images from fields and reduce error reading. The captured images are in red, green, and blue, where the color model is described by their corresponding intensities. Therefore, these colored images need space for storage and take time to process three different channels. Consequently, the acquired images by the PSD system are cropped and converted to grayscale to minimize the processing/computing time because of processing only one channel. Additionally, the grayscale image is converted into binary form during morphological operations.

C. MORPHOLOGICAL IMAGE PROCESSING

Morphology is a broad set of image processing operations that process images based on shapes. Morphological operations apply a structuring element to an input image, creating an output image of the same size. In a morphological operation, the value of each pixel in the output image is based on a comparison of the corresponding pixel in the input image with its neighbors.



(a) Binary image (b) After processes

FIGURE 6. A case of separating overlapping insects.

The primary goal of the morphological operation is to eliminate the noise from the distortion that mostly affects the shape and texture in a given image. The morphological operation is often used in the preprocessing and postprocessing of images. Consequently, these procedures are based on mathematical and logical operations in which a small shape is translated across the image to produce the processed image. In this study, the preprocessing based on these morphological operations is conducted to eliminate noise from the captured image by the PSD system [24]–[26].

Agricultural insects' original binary images comprise small spots within the image. These small spots are assumed to be noise and must be eliminated from the image. Therefore, morphological operations can expel these noises by utilizing the opening process (i.e., erosion followed by dilation) and the closing process (i.e., dilation followed by erosion). In addition, some agricultural insects overlap in the images. This overlapping may cause errors in the insects' detection and counting if the insects are not well separated. Image morphological operations based on erosion and dilation play a major role in eliminating noise and separating the overlapping among agriculture insects, as shown in Fig. 6.

D. PEST DETECTION AND COUNTING

Insect detection and counting is the last step of the PSD system computing. This process relies completely on the previous image processing steps. Hence, discriminating between the background and the insects in colored and grayscale images is difficult. Therefore, the preprocessing step of converting the colored image into a binary image acts as a vital process to facilitate the determination of agricultural insects in a given image. An original, grayscale, binary, opening, and closing image are shown in Fig. 7. The process of insect detection and counting is implemented by using the connected components' labeling algorithm. The basic idea is to use structure elements with certain shapes/kernels to measure the corresponding shape in the image to detect and count the object. Different kernel functions, such as disk, diamond,

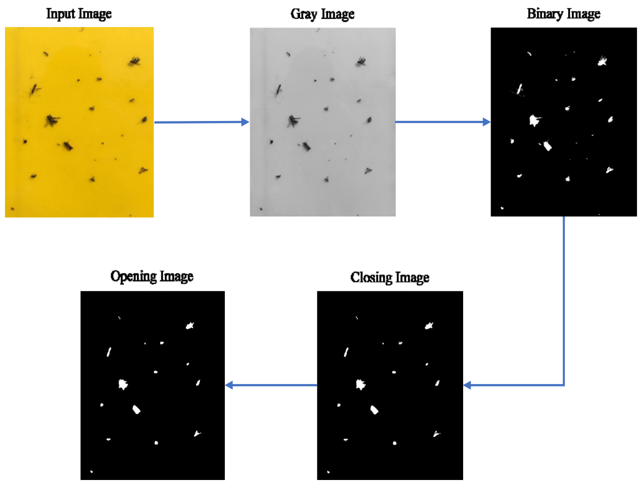


FIGURE 7. Sequence of the resulting image after processing.

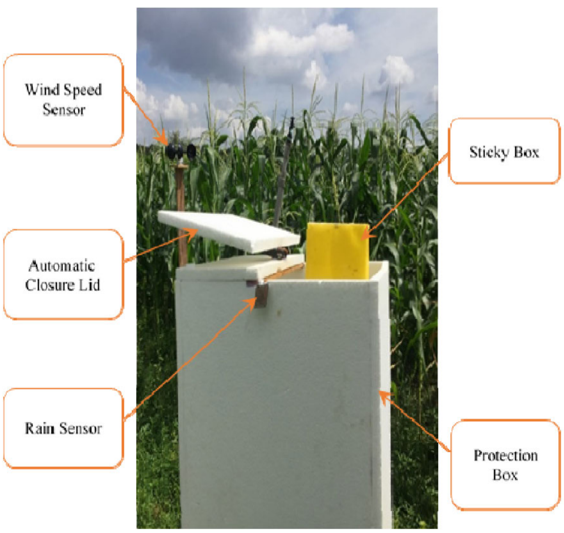


FIGURE 8. The PSD system at the field.

square, and sphere, are used as a matching function for the insect detection and counting algorithm.

VI. EVALUATION OF THE PSD SYSTEM

The performance of the PSD system is evaluated at the fields. Three different locations with various crops, such as maize, okra, pineapple, and chili, at UPM are selected. The design of the PSD system was able to capture images of an insect from four directions in a one-hour interval in 2019. Fig. 8 illustrates the setup of the PSD system at the field, whereas Fig. 9 shows the sequence of operation of the PSD system during data collection.

1. Fig. 9-1 shows that the pest sampling and detection (PSD) system is in a protected mode (PM) where all components are at initial positions.
2. Fig. 9-2 shows that the automatic closure lid is opened once the controller reads the data from the weather sensor (rain and wind data). At this stage, the PSD system is in active mode (AM) because the weather is in good condition.

TABLE 3. Longitude and latitude for data collection of the PSD system.

Site	Coordinates	Date	Plant type
Farm 10	2°59'21.4"N/ 101°42'58.2"E	8 May 2019	Maize
	2°59'29.5"N/ 101°42'48.8"E	30 July 2019	Chili
Ekspo (TPU)	2°59'11.7"N/ 101°42'23.8"E	11 May 2019	Maize
	2°59'19.1"N/ 101°42'23.4"E	14 May 2019	Okra
Faculty of agriculture	2°59'09.2"N/ 101°44'07.7"E	24 July 2019	Maize
	2°59'06.1"N/ 101°44'06.4"E	27 July 2019	Pineapple

3. Fig. 9-3 shows that the sticky box is moving vertically and is ready to trap insects.
4. Fig. 9 (4,5) shows that the camera arm moves toward the sticky box and is ready to capture images of the insects on sticky papers.
5. Fig. 9-6 shows that the PSD system is in PM after the rain sensor and wind speed sensor detected rain and wind, respectively; then, all PSD system components return to the rest positions.

A. PSD SYSTEM MODEL

The operation of the automated trap is schematically described in Fig. 10. Once the PSD system powers on, the system checks the condition of the automatic closure lid, that is, whether it is closed or not. If the automatic closure lid is closed, then the system checks for rain and wind conditions. If the wind speed and rain intensity are above the threshold value, then the automatic closure lid remains closed and protects the PSD system. If the rain intensity and wind speed are below the threshold value, then the PSD system is ready to collect insect data. Then, the closure lid automatically opens, the sticky box moves up vertically, and the camera arm rises up and positions camera in front of the sticky box to capture images. Once the data collection process is complete within the specified operation hours, the PSD system automatically switches back to the PM.

B. FIELD DATA COLLECTION

The PSD system is tested in various locations. Fig. 11 shows the data collection locations acquired from Google map. Furthermore, the first location is Farm 10 (Ladang 10) for maize and chili crops. The second location is Bukit Ekspo (TPU) for maize and okra crops. The third location is in the Faculty of Agriculture for maize and pineapple crops. The details of the locations of the experimental fields and the date of the experiments are shown in Table 3. The directions of each field are acquired by using a compass navigation app of a mobile device.

VII. RESULT AND DISCUSSION

The effective system sampling of the population of insects is a daunting but critical activity for the protection of plants and their crops against harmful insects. Through this activity,

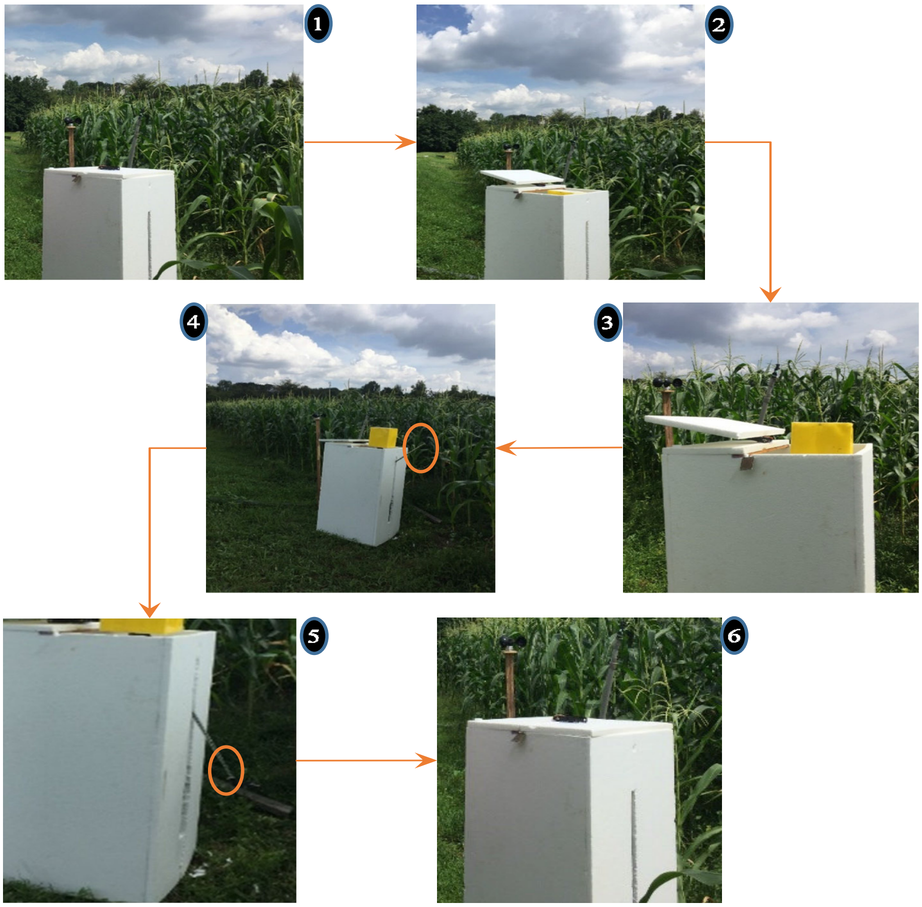


FIGURE 9. The PSD system during the evaluation.

efficient and effective pest control is achieved. The design, implementation, and evaluation of an automated PSD trap system for the sampling of the insect population under real in-field conditions is described in this study. The key benefits are the ability to deliver on date (year, month, day, hour, minute, and second), accurate, valid, and unbiased information directly from the fields.

In addition to the pictures obtained from its interior, the proposed system provides automatic insect detection and counting. Even in cases of overlaps and low-quality images (noise conditions) [24], [25], the suggested connected component labeling algorithm with morphological operations could measure the number of insects.

To estimate the number of captured insects automatically, the total number of most insects that came (peak direction) was considered. In the first location, we manually calculated 32 insects (peak direction was from the east) for the first, and the algorithm provided an accuracy of 84% by estimating 27 captured insects. In the second location, the manual estimation method counted a value of 47 insects (peak direction was from the north), and the algorithm provided 83% accuracy with the value of 39 insects. The third location represented the highest accurate estimation. Manual counting reported 23 insects (peak direction was from the north), and the automated approach estimated 20 insects (accuracy level 87%). Moreover, all three locations' aforementioned results were shown for one-day calculation (40 images per day). Experiments were also conducted; the total images were 720 images from the three locations during this study.

Different kernel functions, such as disk, diamond, square, and sphere, were used as a matching function for the insect detection and counting algorithm. Moreover, the result of the experiment showed that the highest accuracy (100%) is achieved by using the sphere kernel function with kernel size 5 in comparison with manual counting. The aforementioned kernels in different sizes were used to nominate the best one for detecting insects with different sizes and shapes. Additional details on the achieved accuracy via different kernel functions tested on the sample image are presented in Table 4.

Results of the detection algorithm implemented using different kernel functions with different sizes were statistically analyzed using analysis of variance (one-way ANOVA). This analysis was conducted to check whether any significant differences are found among the kernel functions, namely, diamond, disk, sphere, and square, while being utilized in the PSD detection algorithm. The statistical comparison of the four kernels demonstrated a significant difference among these kernels because the P-value is 0.03, which is less than

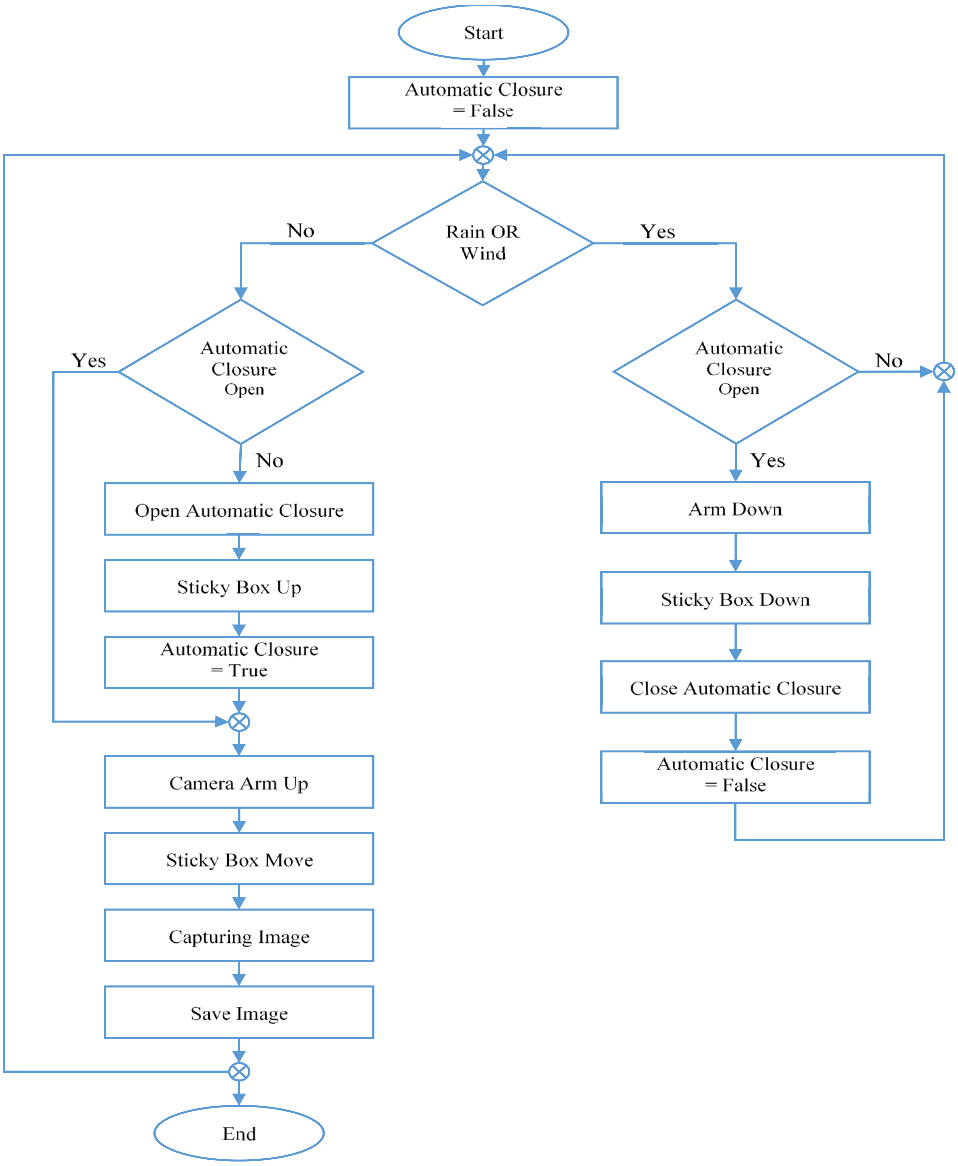


FIGURE 10. The flowchart of the PSD system.

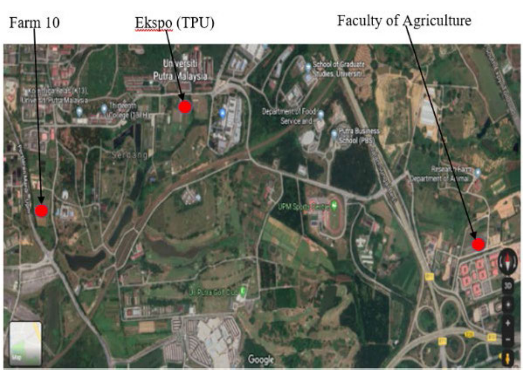


FIGURE 11. Satellite image for three locations in UPM.

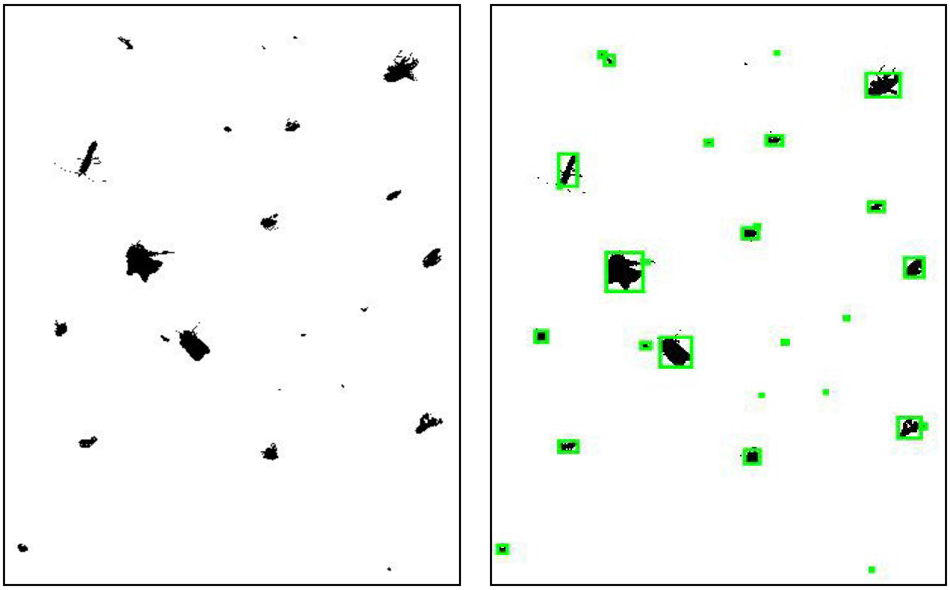
0.05. Therefore, the PSD detection algorithm based on sphere kernel function was selected for deployment in the software system because it achieved 85.2% average accuracy, which is the highest average among the kernels.

Fig. 12 illustrates indicative results for the algorithm applied by utilizing sphere kernels in a randomly selected image. In sphere kernels, the first subfigure depicts the image complement before kernel application, whereas the second one shows the results of the detected insects after kernel application.

Our experiments are consistent with previous works of sticky pheromone traps because the PSD system documented various insects, including small ones [21], [27]. As many weeds, grasses and trees are surrounded within crops caused the individuals of presence Epilachna Indica (beneficial insect). They can also easily be separated from harmful insects because of their colored wings [28]. Non-pest individuals were clearly distinguished from other insect species, such as Sepsidae and Sarcophaga, due to the slightly larger

TABLE 4. The achieved accuracy by different kernel functions.

Kernel		Size	Manual Count	Detected NO.	Accuracy (%)
Kernel	Diamond	1	23	31	74
		2	23	29	79
		3	23	29	76.8
		4	23	25	92
		5	23	23	100
		Mean			**84.4**
	Disk	1	23	31	74
		2	23	29	79
		3	23	27	85
		4	23	27	85
		5	23	24	95.8
		Mean			**83.8**
	Sphere	1	23	31	74
		2	23	29	79
		3	23	27	85
		4	23	26	88
		5	23	23	100
		Mean			**85.2**
	Square	1	23	57	40
		2	23	48	47
		3	23	33	68
		4	23	31	74
		5	23	27	85
		Mean			**62.8**



(a) Image complement (b) Detected insects

FIGURE 12. Detected insects by using sphere kernel.

size of the latter species found trapped in the sticky box. By using the images provided by the automated PSD system, the captured harmful insects, such as Bothrogonia Ferruginea and Leptocorisa acuta Thunberg, could also be easily distinguished by expert entomologists. Although technicians and farmers can easily discern other species (with the naked eye) from insects, the existing version of the proposed automated insect counting technique (image processing algorithm) is currently not feasible. In the future, the research team plans to fix this problem and further develop the algorithm's efficacy by better tuning and selecting the appropriate thresholds to make it capable of distinguishing other nonharmful insects from harmful ones. As far as the attractiveness of the proposed PSD is concerned the study results indicated that for the yellow sticky color, the mean number of captured insects per time was significantly higher [10]–[12].

The problem lays in the difficulty of identifying insects on traditional sticky traps based on their characters that are damaged because of weather conditions and some attacks by beneficial insects. Thus, the PSD system was developed to overcome this issue by capturing images directly and protecting the sticky sheets through the protection box. The potential of protection box that may reduce the dirt and droplets that affect the detection result and give the opportunity to increase the effectiveness of the sticky box compare with traditional sticky traps [29].

The efficiency attractiveness of the proposed PSD system by color was vital to attract various insects; in addition, the system is friendly to the ecosystem and is nontoxic. By contrast, some studies add insecticides to attractant-based traps; this approach reduces trap catch and causes frequent insect death even before entering the traps, resulting in decreased trap capture efficiency [30] and toxicity for the ecosystem.

To evaluate the relative effectiveness of the system design on the basis of cost, we estimated the structure and assembly cost to compare the total cost of the PSD system with that of other traps. This simple evaluation demonstrates the relative affordability of the PSD system. Our system ($500) is more affordable than other commercial systems, such as sensor and electronic traps (e.g., Trapview) ($10000–$20000, excluding shipment fees).

The design of the sticky box reduced system maintenance; by contrast, a study reported that bucket sticky traps add additional cost of maintenance as a result of spider and frog attacks [31]. Moreover, the PSD system reduces the cost of visits (labor intensive and time consuming) to the trap and can overcome the constraints of data delay by providing insect population daily data within certain time intervals. By contrast, traditional traps are almost impossible due to the relatively low sampling frequency and the need for trained scouts to visit the field weekly. Moreover, the sticky area can quickly become covered with dirt and dust so that only a limited number of insects can be captured; such limitation must be considered when using sticky traps. Furthermore, during peak periods of insect population, sticky sheets must be replaced daily or from time to time, thus requiring increased maintenance. By contrast, sensor-based traps eliminate this kind of maintenance but cannot be used for verification [21].

To the best of our knowledge, no other authors have addressed that to monitor insect population from four directions via the sticky sheet approach. Furthermore, previous works have addressed static traps and cover only one [22] or two directions [32]. The most remarkable advantage of our system is the coverage of four directions with an automatic precise movement of the sticky box. As such, the system provides additional details of insect infestation direction as a crucial parameter.

The creation of an insect trap is a difficult task because many unpredictable parameters, such as the installation of different electronic components that can cause possible electromagnetic interference or even its nontransparent protective box top, affect its functionality and attractiveness. To improve its appeal and make it comparable, the research team conducted further tests and modifications on the first version of the automated PSD.

An important advantage of the proposed PSD is its ability to be easily adopted for the sampling of other crops pests after the necessary modifications, adjustments, and evaluation. Future initiatives include the necessary adjustment and enhancement of the proposed automated PSD to enhance its attractiveness and endow it with the ability to provide valuable information about insect behavior. Additionally, easy to adopt pheromones for sampling a specific species of insects as well.

The installation of even higher-quality digital cameras and the implementation of an improved image processing algorithm into the embedded trap system could provide several advantages, such as (i) improved automatic insect counting efficiency; (ii) ability to differentiate between male and female insects, which is essential for the first spray application schedule; and (iii) substantial decrease in the amount of data to be transmitted.

The system can be extended as a mobile pest monitoring system. It can also be extended to long-term powered by using renewable energy (clean power), such as solar panels and wind power. In addition, the PSD system can be implemented and tested in a different case study of crop fields (e.g., at night for trapping nocturnal pests); data can be analyzed to evaluate its efficiency.

There is a critical case of noise regarding sticky papers which is of paramount importance for all images due to environment conditions i.e., temperature, humidity and rain around the PSD which add extra pending and curves on that papers. These papers updates cause extra noise on the captured images for that papers, and this noise can significantly affect the accuracy of insect detection and counting.

VIII. CONCLUSION

Monitoring insect pest populations is an essential activity in agriculture and forestry protection. A common method to monitor pests is utilizing traps placed at strategic spots over the determined monitoring area. The drawbacks of conventional monitoring approaches include its labor-intensive nature, poor temporal resolution measurement, and the dynamic nature of pest population density in the field, which defies accurate monitoring. As a result, the approximation for a target pest population is constrained to a long-term scale.

To enhance these detection systems, this research suggested a system based on an imaging approach that accurately monitors insect population with a high temporal resolution and a substantial decrease in insect monitoring costs. Furthermore, a PSD system was developed for monitoring operations in two directions (clockwise and counterclockwise, as well as the vertical movement of the camera arm). Hence, the process of insect detection and counting was implemented by the connected components labeling algorithm by utilizing the MATLAB image processing toolbox, which was implemented with different kernel functions. Results of the testing hardware of the PSD system showed reliability and flexibility to provide accurate movements in multiple degrees of freedom, as well as dependability in protecting the entire system. The result of testing the software system connected component labeling algorithm showed that the highest mean counting accuracy was 85.2% (i.e., when a sphere kernel function was used). Furthermore, the proposed prototype of an automatic PSD system can play a major role in increasing crop productivity and managing pests in agricultural fields. Finally, several potential applications, such as early warning of insect pest infestation, pesticide control, and insect behavior studies, can be further applied on the basis of the proposed system after applying necessary adjustments.

FOR FUTURE WORK AND RECOMMENDATION

- LED/ UV light can be used to attract and monitor nocturnal insects during the night by using a night-vision camera for additional field information and application accuracy, as well as ecological information to help decision-makers.
- In consideration of environmental conditions, a non-destructive material (e.g., plastic, PVC) can be used to structure the trap protection box, and multiple traps can be deployed in large areas of agricultural fields for long-term monitoring.
- Another substance material that is anti-curving can be used for sticky papers to reduce the erroneous reading of insect detection and counting;
- Sticky traps are not recommended for those who want to use the background-subtracted image technique for counting without killing the insects because they move on the gluing sheets when trying to escape.
- To minimize pollutants and save the environment, traps made of biodegradable or recyclable materials would be ideal.
- A motion sensor can be used to activate the traps during insect capture to save power and extend operation time.

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REFERENCES

[1] T. W. Culliney, ‘‘Crop losses to arthropods,’’ in *Integrated Pest Management*. Dordrecht, The Netherlands: Springer, 2014, pp. 201–225.

[2] J. Timsina, ‘‘Can organic sources of nutrients increase crop yields to meet global food demand?’’ *Agronomy*, vol. 8, no. 10, p. 214, Oct. 2018.

[3] J. Wang, L. Ji, A. Liang, and D. Yuan, ‘‘The identification of butterfly families using content-based image retrieval,’’ *Biosyst. Eng.*, vol. 111, no. 1, pp. 24–32, Jan. 2012.

[4] S.-H. Kang, S.-H. Song, and S.-H. Lee, ‘‘Identification of butterfly species with a single neural network system,’’ *J. Asia–Pacific Entomol.*, vol. 15, no. 3, pp. 431–435, Sep. 2012.

[5] K. Bjerge, J. B. Nielsen, M. V. Sepstrup, F. Helsing-Nielsen, and T. T. Høye, ‘‘An automated light trap to monitor moths (Lepidoptera) using computer vision-based tracking and deep learning,’’ *Sensors*, vol. 21, no. 2, p. 343, 2021.

[6] J. Cho, J. Choi, M. Qiao, C.-W. Ji, H.-Y. Kim, K.-B. Uhm, and T.-S Chon, ‘‘Automatic identification of whiteflies, aphids and thrips in greenhouse based on image analysis,’’ *Red*, vol. 346, no. 246, p. 244, 2007.

[7] Y. Sun, H. Cheng, Q. Cheng, H. Zhou, M. Li, Y. Fan, G. Shan, L. Damerow, P. S. Lammers, and S. B. Jones, ‘‘A smart-vision algorithm for counting whiteflies and thrips on sticky traps using two-dimensional Fourier transform spectrum,’’ *Biosyst. Eng.*, vol. 153, pp. 82–88, Jan. 2017.

[8] W. Ding and G. Taylor, ‘‘Automatic moth detection from trap images for pest management,’’ *Comput. Electron. Agricult.*, vol. 123, pp. 17–28, Apr. 2016.

[9] S.-J. Hong, S.-Y. Kim, E. Kim, C.-H. Lee, J.-S. Lee, D.-S. Lee, J. Bang, and G. Kim, ‘‘Moth detection from pheromone trap images using deep learning object detectors,’’ *Agriculture*, vol. 10, no. 5, p. 170, May 2020.

[10] C. Daniel, S. Mathis, and G. Feichtinger, ‘‘A new visual trap for Rhagoletis cerasi (L.)(Diptera: Tephritidae),’’ *Insects*, vol. 5, no. 3, pp. 564–576, Jul. 2014.

[11] W. L. Yee, ‘‘Efficacies of Rhagoletis cerasi (Diptera: Tephritidae) traps and ammonium lures for western cherry fruit fly,’’ *J. Insect Sci.*, vol. 18, no. 3, p. 14, May 2018.

[12] O. F. Aidoo, C. M. Tanga, S. A. Mohamed, F. M. Khamis, S. B. S. Baleba, B. A. Rasowo, J. Ambajo, M. Sétamou, S. Ekesi, and C. Borgemeister, ‘‘Detection and monitoring of ‘Candidatus’ Liberibacter spp. Vectors: African citrus triozid Trioza erytreae Del Guercio (Hemiptera: Triozidae) and Asian citrus psyllid Diaphorina citri Kuwayama (Hemiptera: Liviidae) in citrus groves in East Africa,’’ *Agricult. Forest Entomol.*, vol. 22, no. 4, pp. 401–409, Nov. 2020.

[13] Y. Zhong, J. Gao, Q. Lei, and Y. Zhou, ‘‘A vision-based counting and recognition system for flying insects in intelligent agriculture,’’ *Sensors*, vol. 18, no. 5, p. 1489, May 2018.

[14] B. Ramalingam, R. E. Mohan, S. Pookkuttath, B. F. Gómez, C. S. C. S. Borusu, T. W. Teng, and Y. K. Tamilselvam, ‘‘Remote insects trap monitoring system using deep learning framework and IoT,’’ *Sensors*, vol. 20, no. 18, p. 5280, Sep. 2020.

[15] D. G. Riley, J. Kicklighter, and A. N. Sparks, ‘‘Sampling of the cowpea curculio, Chalcodermus aeneus, with traps in southern peas,’’ *Crop Protection*, vol. 67, pp. 72–76, Jan. 2015.

[16] F. S. Silva, M. C. Lopes, E. S. Farias, R. A. Sarmento, P. S. Pereira, and M. C. Picanço, ‘‘Standardized sampling plan for common blossom thrips management in melon fields from north Brazil,’’ *Crop Protection*, vol. 134, Aug. 2020, Art. no. 105179.

[17] H. Liu and J. S. Chahl, ‘‘A multispectral machine vision system for invertebrate detection on green leaves,’’ *Comput. Electron. Agricult.*, vol. 150, pp. 279–288, Jul. 2018.

[18] D. Silva, J. Salamanca, V. Kyryczenko-Roth, H. T. Alborn, and C. Rodriguez-Saona, ‘‘Comparison of trap types, placement, and colors for monitoring Anthonomus musculus (Coleoptera: Curculionidae) adults in highbush blueberries,’’ *J. Insect Sci.*, vol. 18, no. 2, p. 19, Mar. 2018.

[19] A. Guarnieri, S. Maini, G. Molari, and V. Rondelli, ‘‘Automatic trap for moth detection in integrated pest management,’’ *Bull. Insectol.*, vol. 64, no. 2, pp. 247–251, 2011.

[20] G. A. Holguin, B. L. Lehman, L. A. Hull, V. P. Jones, V. P. Jones, and J. Park, ‘‘Electronic traps for automated monitoring of insect populations,’’ *IFAC Proc. Volumes*, vol. 43, no. 26, pp. 49–54, 2010.

[21] E. Goldshtein, Y. Cohen, A. Hetzroni, Y. Gazit, D. Timar, L. Rosenfeld, Y. Grinshpon, A. Hoffman, and A. Mizrach, ‘‘Development of an automatic monitoring trap for Mediterranean fruit fly (Ceratitis capitata) to optimize control applications frequency,’’ *Comput. Electron. Agricult.*, vol. 139, pp. 115–125, Jun. 2017.

[22] T. Fukatsu, T. Watanabe, H. Hu, H. Yoichi, and M. Hirafuji, "Field monitoring support system for the occurrence of Leptocorisa chinensis Dallas (Hemiptera: Alydidae) using synthetic attractants, field servers, and image analysis," *Comput. Electron. Agricult.*, vol. 80, pp. 8–16, Jan. 2012.

[23] Y.-S. Chen, C.-S. Hsu, and C.-L. Lo, "An entire-and-partial feature transfer learning approach for detecting the frequency of pest occurrence," *IEEE Access*, vol. 8, pp. 92490–92502, 2020.

[24] X. Bai, M. Liu, Z. Chen, P. Wang, and Y. Zhang, "Multi-focus image fusion through gradient-based decision map construction and mathematical morphology," *IEEE Access*, vol. 4, pp. 4749–4760, 2016.

[25] K. P. Seng, L.-M. Ang, L. M. Schmidtke, and S. Y. Rogiers, "Computer vision and machine learning for viticulture technology," *IEEE Access*, vol. 6, pp. 67494–67510, 2018.

[26] T. Chen and F. Meng, "Development and performance test of a height-adaptive pesticide spraying system," *IEEE Access*, vol. 6, pp. 12342–12350, 2018.

[27] R. D. Selby, S. H. Gage, and M. E. Whalon, "Precise and low-cost monitoring of plum curculio (Coleoptera: Curculionidae) pest activity in pyramid traps with cameras," *Environ. Entomol.*, vol. 43, no. 2, pp. 421–431, 2014, doi: 10.1603/EN13136.

[28] L. Doitsidis, G. N. Fouskitakis, K. N. Varikou, I. I. Rigakis, S. A. Chatzichristofis, A. K. Papafilippaki, and A. E. Birouraki, "Remote monitoring of the bactrocera oleae (Gmelin) (Diptera: Tephritidae) population using an automated McPhail trap," *Comput. Electron. Agricult.*, vol. 137, pp. 69–78, May 2017.

[29] R. Hodges, "Detection and monitoring of larger grain borer, Prostephanus truncatus (Horn)(Coleoptera: Bostrichidae)," *Integr. Pest Manage. Rev.*, vol. 7, no. 4, pp. 223–243, 2002.

[30] E. B. Jang, "Effectiveness of plastic matrix lures and traps against Bactrocera dorsalis and Bactrocera cucurbitae in Hawaii," *J. Appl. Entomol.*, vol. 135, no. 6, pp. 456–466, Jul. 2011.

[31] S. Guerrero, J. Brambila, and R. L. Meagher, "Efficacies of four pheromone-baited traps in capturing MaleHelicoverpa(Lepidoptera: Noctuidae) moths in northern Florida," *Florida Entomol.*, vol. 97, no. 4, pp. 1671–1678, Dec. 2014.

[32] P. J. T. White, K. Glover, J. Stewart, and A. Rice, "The technical and performance characteristics of a low-cost, simply constructed, black light moth trap," *J. Insect Sci.*, vol. 16, no. 1, p. 25, 2016.

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