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DEVELOPMENT OF AN AUTOMATED DETECTOR AND COUNTER FOR BAGWORM CENSUS

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By

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DEVELOPMENT OF AN AUTOMATED DETECTOR AND COUNTER FOR BAGWORM CENSUS

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MOHD NAJIB B AHMAD

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Chairman : Professor Sr. Gs. Abdul Rashid Mohamed Shariff, PhD, C.Eng.
Faculty : Engineering

Bagworms (*Thyridopteryx ephemeraeformis*) are one of the main species of vicious leaf eating insect that is a threat to the oil palm plantations in Malaysia. The economic impact from a moderate bagworm attack of 10%-50% leaf damage may cause 43% yield loss. The population of bagworms if not controlled often increases to above its threshold limits, thereby causing serious losses. Due to this, monitoring and detection of bagworm population in oil palm plantations is required as preliminary steps to ensure proper planning of control actions. A precise bagworm monitoring system is required to overcome recurrence of an outbreak. This study, investigates and explores a thermal imaging technique to detect the bagworms and identifying the bagworms through spectral reflectance properties (bagworm characterization) at different stages of the bagworms life cycle. Furthermore, this study develops an automated bagworm detection and counting technique for bagworm census through image processing analysis and this automated solution is found to be more efficient method in determining the bagworm population when compared to manual census techniques. As for detection, the reflector method was applied to find the reflected apparent temperature and emissivity of the bagworms using thermographic measurement techniques. Then, the experiment on identification of bagworm under thermal imaging is conducted using a thermal infrared camera, T 440 at different sites. It was revealed that the bagworms' surfaces exhibited emissivity values was recorded approximately at 0.88±0.01 and 0.89±0.02. The statistical results from three rounds of experiments showed that the object/bagworm temperature during the evening, night, and morning were significantly different, $p<0.05$, as compared to the surrounding/frond temperature, with consideration of emissivity, solar radiation, and snapshot distance. The living and dead bagworm spectral reflectance properties were determined using spectroradiometer, GER1500 under the Visible/Near Infrared and Short-wave Infrared wavelength regions, 350 – 1050 nm, and the results were statistically confirmed using Student's t-Test with two tailed distributions, principal component analysis and Boxplot

Quantiles. The development of an image processing algorithm for detection and counting of *Metisa plana* Walker, a species of Malaysia's local bagworm using image segmentation was proposed as it was found to be better than the thermal approach after some preliminary field tests. Color and shape features from the segmented images, combined with deep learning and Faster Region-based Convolutional Neural Networks for real time object detection showed an average detection accuracy, of 40% and 34%, at 30 cm and 50 cm camera distance, respectively. By applying deep convolutional neural network, the percentage of detection increased up to 100% at a camera distance of 30 cm in close condition. The proposed solution was also designed to distinguish between living and dead bagworms using motion detection which results in approximately 73-100% accuracy at a camera distance of 30 cm in the close condition. The fabrication of the prototype was accomplished and field tested. The classification of the larval and pupal stages was carried out by grouping the larval and pupal stages based on their real size; Group 1: larvae stage 1-3, Group 2: larvae stage 4-7 and Group 3: pupal stage. The results showed that the average percentage of the detection accuracy was 87.5% and 78.7%, respectively for the living and dead Group 1 larvae. Meanwhile, the average percentage of the detection accuracy for the living and dead Group 2 larvae was same 79.2%, respectively. As for pupa in Group 3, the result showed that the average percentage of detection accuracy of the prototype to detect the living and dead pupae against manual census was 77% and 75%, respectively. The limitations of this study were determined, such as the camera distance and snapshot condition during image capture were limited at 30 cm and 50 cm, and set in three conditions; open, half open and close condition, damage, brownish leaflet and hole were found as natural limitations, characteristic of the bagworm in term of colour and material of its bag attributed to difficulties to extract the bagworm from its surrounding and SOP for bagworm census. There are several recommendations from this study that have been suggested including the use of hyperspectral imaging to detect bagworms, application of radio frequency to detect live bagworms, open system detection of the bagworms, application of pseudo colour concept and method to detect early stage of bagworm attack.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN ALAT PENGESAN DAN PENGIRA AUTOMATIK UNTUK BANCIAN ULAT BUNGKUS

Oleh

MOHD NAJIB B AHMAD

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Ulat bungkus (*Thyridopteryx ephemeraeformis*) merupakan serangga perosak pemakan daun tanaman sawit yang utama di Malaysia. Kesan ekonomi dari serangan ulat bungkus peringkat sederhana, iaitu 10-50% kerosakan daun sawit boleh menyebabkan kehilangan hasil sebanyak 43%. Populasi ulat bungkus tanpa sebarang kawalan akan meningkat, melebihi paras ambang dan seterusnya menjurus kepada kerosakan yang lebih serius. Berdasarkan senario ini, pemerhatian dan pengesanan populasi ulat bungkus adalah diperlukan bagi memastikan perancangan sistematik untuk aktviti kawalan di kawasan serangan berjalan lancar dan berkesan. Sistem pemerhatian ulat bungkus yang jitu adalah diperlukan untuk mengatasi masalah serangan berulang. Kajian ini meneroka dan menyelidik potensi kaedah pengimejan termal untuk mengecam ulat bungkus menggunakan kamera termal inframerah dan penentuan data spectral refleksi ulat bungkus pada pelbagai peringkat untuk ulat bungkus hidup dan mati. Selain itu, kajian ini membangunkan teknik pengesanan dan pengiraan ulat bungkus secara automatic untuk bancian ulat bungkus menggunakan analisis pemprosesan imej dan kaedah penyelesaian automasi ini didapati lebih efisyen untuk menentukan populasi ulat bungkus berbandingkan kaedah manual bancian ulat bungkus. Untuk pengecaman ulat bungkus, kaedah reflektor telah digunakan untuk mencari suhu jelas refleksi dan emisiviti ulat bungkus melalui teknik ukuran termografik. Disusuli dengan ujikaji pengenalpastian ulat bungkus melalui pengimejan termal dengan menggunakan kamera termal inframerah, T440 di beberapa kawasan kajian berbeza. Nilai emisiviti permukaan ulat bungkus telah dicatatkan pada nilai 0.88±0.01 dan 0.89±0.02. Keputusan statistik daripada dua ujikaji menunjukkan suhu ulat bungkus semasa waktu petang, malam dan pagi adalah berbeza secara signifikan, $p<0.05$, berbandingkan suhu pelepah/sekitaran, yang mana ia bergantung juga kepada nilai emisiviti sekitaran, radiasi matahari dan jarak penggambaran. Data spektral ulat bungkus hidup dan mati telah diperolehi dengan menggunakan instrumentasi spektroradiometer, GER1500 di bawah julat panjang gelombang

spectrum *Visible/Near Infrared* dan *Short-wave Infrared.* Hasil ujikaji disahkan secara statistik dengan menggunakan analisis *Student's t-Test* dengan dua edaran ekor, analisis komponen principal (PCA) dan *Boxplot Quantiles*. Pembangunan algoritma pemprosesan imej untuk pengesanan dan pengiraan ulat bungkus spesis tempatan, *Metisa plana* Walker, telah dicadang dan diusahakan setelah didapati teknik ini lebih berkesan berbanding dengan teknik pengimejan termal selepas beberapa siri ujian ladang yang telah dijalankan. Warna dan ciri bentuk daripada imej yang disegmentasi, digabungkan dengan kaedah pembelajaran mendalam dan model *Faster Region-based Convolutional Neural Networks* untuk pengesanan pada masa sebenar, telah menunjukkan purata ketepatan pengesanan sebanyak 40% dan 34%, masing-masing pada jarak kamera 30 cm dan 50 cm. Dengan mengaplikasikan pembelajaran mendalam rangkaian neural sahaja, peratus pengesanan meningkat sehingga 100% pada jarak kamera 30 cm dan dalam keadaan tertutup. Kaedah penyelesaian ini juga mengambilkira pembezaan ulat bungkus hidup dan mati melalui pengesanan pergerakan, yang mana, ia menghasilkan 73-100% ketepatan pada jarak kamera 30 cm dan dalam keadaan tertutup. Fabrikasi prototaip alat pengesan dan pengira ulat bungkus telah berjaya dihasilkan dan dicubalari di ladang sawit. Klasifikasi kumpulan ulat bungkus mengikut peringkat dan saiz sebenar larva dan pupa telah dilakukan; Kumpulan 1: larva peringkat 1-3, Kumpulan 2: larva peringkat 4-7 dan Kumpulan 3: pupa. Keputusan percubaan ladang menunjukkan purata peratus ketepatan mengesan larva Kumpulan 1 yang hidup dan mati, masing-masing ialah 87.5% dan 78.7%. Purata peratus ketepatan mengesan larva Kumpulan 2 adalah sama, masing-masing ialah 79.2%. Manakala untuk pupa, iaitu Kumpulan 3, purata peratus ketepatan mengesan pupa hidup dan mati, masing-masing ialah 77% dan 75%. Kekangan kajian ini telah dikenalpasti, antaranya ialah jarak kamera dan keadaan penggambaran semasa pengambilan imej dihadkan kepada masing-masing, 30 cm dan 50 cm dan terhad kepada tiga keadaan iaitu, terbuka, separuh terbuka dan tertutup. Daun pelepah yang rosak, berwarna coklat dan berlubang menjadi kekangan semulajadi kajian, diikuti oleh sifat ulat bungkus dengan ciri warna dan bahan bungkusannya menyebabkan kesukaran memisahkan ulat bungkus dari sekitarannya dan yang terakhir ialah piawaian bancian ulat bungkus. Hasil kajian ini telah dicadangkan beberapa syor iaitu penggunaan pengimejan hyperspektral bagi mengesan ulat bungkus, aplikasi frekuensi radio untuk mengecam ulat bungkus hidup, sistem terbuka untuk pengesanan ulat bungkus, konsep warna *pseudo* bagi mengecam ulat bungkus dan kaedah untuk pengesanan awal ulat bungkus.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
ANN	Artificial Neural Networks
AoI	Area of interest
CCD	Charge-coupled device
CHT	Circular Hough Transformation
CNC	Computer numerical control
CRD	Completely randomized design
CUDA	Computer Unified Device Architecture
cuDNN	CUDA Deep Neural Networks
CV	Computer vision
DAC	Digital-to-Analog converter
DBM	Deep Boltzmann Machines
DBN	Deep Belief Networks
DC	Direct current
DL	Deep learning
EMI	Electromagnetic interference
FoV	Field of view
GA	Genetic algorithm
GPU	Graphics processing unit
HOG	Histogram of oriented gradients
HSL	Hue, saturation & lightness
IDE	Integrated development environment
IoT	Internet of Things
IRT	IR thermography

GUI	Graphical User Interface
LIF	Laser induced fluorescence
LSD	Least significant difference
LWNIR	Long-wave near-infrared
MCU	Microcontroller unit
MV	Machine vision
NMR	Nuclear Magnetic Resonance
OMA	Optical multiple analyzer
OS	Operating system
PCA	Principal component analysis
PCB	Printed circuit board
R-CNN	Regional Convolutional Neural Networks
RFS	Remote fluorescence spectroscopy
RoI	Region of interest
RPN	Region proposal network
RPW	Red palm weevil
SE	Structuring element
SPP	Spatial Pyramid Pooling
SVDD	Support vector data description
SVM	Support vector machine
SWIR	Short-wave Infrared
TIR	Thermal infrared
TTL	Transistor-transistor logic
UK	Unknown detection
Vis	Visible

VSWNIR	Visible and short-wave near-infrared
WiSN	Wireless imaging sensor nodes

CHAPTER 1

INTRODUCTION

1.1 Background

In Malaysia, the palm oil sector is described as one of the key contributors to the national economy and currently, the palm oil industry has contributed a Gross National Income (GNI) RM 79.9 billion in 2017 (National Transformation Programme Annual Report, 2017). The palm oil industry extents the significance series from upstream sectors to downstream areas. Whereas, oil palm planted area in Malaysia was around 5.9 million hectares in 2019 (Malaysian Oil Palm Statistic, 2019).

The major insect pests capable for causing outbreak are bagworms and nettle caterpillars. A moderate bagworm attack causing 10-50% leaf damage may lead to 43% yield loss (Wood *et al*., 1972; Basri and Kevan, 1995). The population of bagworms without control often increased to above its threshold limits, thereby causing serious outbreak. The bagworm is a leaf-eating caterpillar concealed within its carrot-shaped bag, which is constructed from bits of material from the plant upon which it feeds (Barlow, 1982). Bagworms are a repeated problem in oil palm plantations that causes by several factors, including nonstop routine of chemical insecticides, deficiency of beneficial plants cultivated to attract natural enemies, and ballooning in neighboring plantations (Ramlah *et al*., 2007). The outbreaks are also related to the dry season because of feeding behavior of the bagworms. It becomes more vigorously and moving faster in hot and dry weather (Chung and Sim, 1991). Integrated pest management (IPM) is recommended for combating bagworm outbreaks in oil palm plantations.

In order to control bagworm in oil palm plantation effectively, it is vital to conduct census. Census is a method to calculate number of insect pest unswervingly so that control actions can be planned. The method includes apparent monitoring for any indication of pest occurrence or 'enumeration' (Corley *et al*., 2003). Collected data of census will conclude the level of insect pest outbreaks. Furthermore, the data will project a suitable and right timing of pest control. Currently, census is done manually through naked eyes observation and counting method. To address this, an automated device was developed in this research.

The automated device is a simple, accurate and has scanning system which is easy to use for detecting and counting bagworms on the palm leaflet. The technology is based on developed deep learning with Faster R-CNN technique towards real time object detection. The device was developed to assist bagworm

counting for field work and is the first developed instrument and though not yet being tested for enumeration purposes. It can be calibrated at different intervals to ensure high accuracy and precise detection of the insect pests. The object recognition, stage identification, counting population and determination of live and dead bagworms based on video processing were conducted in advanced controller programming software, for example MATLAB™, Python, C++, Java, Ruby and others. Upon scanning the leaf area using the device, the image produced was analyzed by the program, based on set point and characteristic that have been set to determine the density of the insect per area.

The development of an automated detector and counter for bagworm census is essential as it would greatly benefit planters and smallholders in term of plant protection scope. By applying this device, control actions can be planned and carried out at the right time and exact bagworm larval stages. This will help oil palm industry in term of saving expenses for pesticide supply for a whole year. Besides, labour shortage problem could be overcome and time spent for census will be shorten tremendously. In addition, precise data collection can be compiled for further analysis and assessment of control measures taken in combating bagworm and it can be analysed and evaluated for better FFB yield incomes in the future. Furthermore, the development of the ground-based device is the first innovation ever and pioneer in oil palm industry, in which, it reduces human error in census and promoting precision agriculture practice. By applying infrared sensor and image processing algorithms, this device can be effectively used by the farmers and planters to monitor bagworm population in their farm and subsequently can increase yield productivity.

1.2 Problem statement

This project is carried out based on problem occurred during bagworm census, which is a crucial monitoring work at infested area in oil palm plantations. Any report on the bagworm outbreak from oil palm plantations has to be solved and manage according to standard operating procedures (SoP). As an initial action, assessment of infested area and a check of the level of seriousness of bagworm attack is conducted via census. At the same time, species and bagworm density are determined. In common practice, census is carried out manually by counting the number of bagworm population per frond through naked eyes. Accurateness and exact census data collection are suspicious, sometimes involves human errors such as underestimating, dishonest and generating data. Precise data is important for planning and conducting any bagworm control at the infested area. According to SoP of controlling bagworm produced by MPOB (2016), the action threshold level (ATL) for bagworm species of *P. pendula* and *M. plana* is around 5-10 larvae per frond (LPF). It means that the action control effectiveness is validated through ATL and all oil palm planters need to apply the rules for sustainability of oil palm industry. Furthermore, to date, no bagworm characterization study in term of spectral reflectance properties has been established. The spectral properties of bagworms are important for detection using spectroscopy method such as short-wavelength infrared (SWIR) camera.

The specific wavelength of bagworm needs to be determined prior to establishing SWIR camera detection method.

1.3 Objectives

The main aim of this study is to develop an automated detector and counter for bagworm census by using several methods such as thermal imaging, spectroscopic technique and image processing analysis. The final target is to develop a prototype of an automated detector and counter and validate it's accuracy in the fields.

Hence, the objectives of this study are as follow;

1) To investigate and explore thermal imaging technique using thermal IR camera to detect bagworms.

2) To determine and characterize the spectral reflectance properties of live and dead oil palm bagworms at different stages of their life cycle.

3) To develop an automated oil palm bagworm detector and counter using deep learning and machine vision techniques.

4) To validate the effectiveness of the automated field oil palm bagworm detector and counter versus manual census technique.

1.4 Scope and limitation of study

The scope of research involved in this study is as follows:

1) Thermal imaging experiment to detect objects/bagworms using thermal IR camera

2) Spectroscopic studies to determine the spectral properties of live and dead bagworms at different stages.

3) Image processing using deep learning convolutional neural networking with Faster R-CNN to detect and classify the living and dead bagworms and categorize them into 3 different groups.

4) Integration of software and hardware platform to run the developed algorithm as a computing unit for prototype.

5) Fabrication and development of the prototype according to its functions and mode of selection.

6) Field test of the prototype to validate effectiveness to identify the bagworms.

The limitations of this study are determined and listed as follows:

1) Device has limited operation and cannot be operated in ambient light. The camera distance and snapshot condition during image capture are limited at 30 cm and 50 cm, and set in three conditions; open, half open and close condition to optimize ambient light effect, shadow movement and any movement or environment variable which are varied depending on sunlight intensity and movement speed.

2) During detection of bagworms on the fronds, damaged leaflet, brownish leaflet and holes were found as natural limitations or disturbances to detect the bagworms. This can lead to wrong object detection and resulting low percentage of detection accuracy.

3) Census carried out following a standard operating procedure (SOP) in terms of frond selection and amount of frond to be cut down for field trial of the prototype.

4) Characteristics of the bagworm in term of colour and material of its bag attributed to difficulties to extract the bagworm from its surrounding. The bag is formed by damage leaflet and has a same texture with the leaflet. Colour processing method failed to detect it accurately on the damaged frond, and subsequently, a deep learning with neural network was chosen to be used as an algorithm platform for the bagworm detection.

5) The complete process algorithm or software of the automated detector and counter was outsourced to a programming company that has a capability to develop a software for the prototype. The coding for the software was submitted for copyright filing and received registration number in 2019, under Voluntary Notification of Copyright No. CRLY 00022664 entitled ‘an image processing algorithm for auto detector and counter of bagworm’.

1.5 Thesis contribution

The thesis contribution or novelty of this study are compiled and listed as follows;

1) The design and development of automatic detection system of the oil palm bagworms using deep convolutional neural networks (Conv

Net), normal camera and consisted of motion-tracking and false color analysis to detect and count the number of living and dead larvae and pupae of *M. plana* population per frond, corresponding to three major groups or sizes classification, which is applied using ground basis application and close system.

2) The false color method is a new image processing approach to differentiate between the living and dead pupae of the bagworms. This method is following the slope of spectral reflectance for the living and dead pupae under Vis/NIR wavelength using spectroradiometer. The slope values for both pupae was calculated based on average pixel counting of the images. This involved the use of two light sources, red and infrared vision at specific wavelength, 630nm and 940nm, respectively. The calculated slope values were used to distinguish between the living and dead pupae.

1.6 Thesis organisation

The thesis write-up is structured into five chapters. Chapter 1 is an introductory chapter consisting the background of the study, problem statement, objectives and scope of the study. Then, Chapter 2 explains a literature review on the bagworm characteristic and sizes, spectroscopy and its application in agricultural practice, thermal imaging, machine vision, image processing and its application and development of prototype. In Chapter 3, description on the overall methodology including experimental overview, source of insects, analysis on thermal imaging and spectral properties of the bagworms, image processing includes segmentation, morphology, classification, countering number of bagworms, methods on detection of the living and dead larvae and pupae, hardware and software integration, fabrication of prototype and field trial. Chapter 4 explains the experiment results and discussions. In Section 4.1, the reflected apparent temperature and emissivity of the bagworms were determined. Different times of thermal imaging experiments were conducted and described based on the results. Section 4.2 concentrates on finding of spectral properties of live and dead bagworms to detect larval and pupal stages according to its life cycle. In Section 4.3, describes result on development of image processing algorithm including colour processing method, deep learning and determination of living and dead larvae and pupae, as well as software part of prototype. Then, Section 4.4 focuses on integration of software and hardware platform or fabrication of the prototype. In Section 4.5, validation on effectiveness of the prototype was carried out at different fields with further improvement. Finally, Chapter 5 concludes the findings from this study and suggests several recommendations for future research.

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BIODATA OF STUDENT

Mohd Najib b Ahmad was born in Seremban, Negeri Sembilan on 14th June 1979. He received his primary education at Sekolah Rendah Kebangsaan Bandar Baru Bangi, Bandar Baru Bangi, Selangor from 1986 to 1991. He continued his secondary education at Sekolah Menengah Kebangsaan Agama Ma'ahad Hamidiah, from 1992 until 1994 and proceeded to Kolej Islam Sultan Alam Shah (KISAS), from 1995 to 1996. After finishing his secondary education, he entered a matriculation programme in 1997 at Kuala Pilah Matriculation Centre. Then, he continued his study in Bachelor Degree of Chemical and Process Engineering at Universiti Kebangsaan Malaysia (UKM) and graduated in July 2001.

In September 2001, he was appointed as production supervisor at Etika Dairies Sdn Bhd in Meru, Klang from 2001 until 2004. He worked in production line to produce sweetened beverage creamer and sweetened condensed filled milk. He has an ability to run production line and arranged man power in order to achieve company's target. In July 2004, he left Etika Dairies and joined Malaysian Palm Oil Board as research officer in Biological Research Department. He was assigned to manage fermentation pilot plant and conducted biomolecular research for biopesticides production based on biological agent, *Bacillus thuringiensis*, Bt. In Dec 2007, he was admitted to join a Master Degree in Bioprocess Engineering at UPM under the supervision of Dato' Prof. Dr. Mohd Ali Hasaan. Throughout his study, he has been given chance to carry out his research in MPOB and UPM. In Sept 2016, he pursued his study for a Degree of Doctor of Philosophy, in Agriculture and Biological Engineering at UPM specializing in GIS under Prof Sr Gs Dr Abdul Rashid Mohamed Shariff. He has conducted experiments in MPOB and UPM. Then, he also carried out field trial at Slim River estate, Perak and Banting smallholdings, Selangor.

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