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A GSM-based remote wireless automatic monitoring system for field information: A case study for ecological monitoring of the oriental fruit fly, *Bactrocera dorsalis* (Hendel)

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ARTICLE INFO

Article history:

Received 1 October 2007

Received in revised form

7 January 2008

Accepted 8 January 2008

Keywords:

Precision agriculture

Environmental parameter monitoring

Wireless communication technology

Mechatronics technology

Bactrocera dorsalis (Hendel)

Ecological environment

ABSTRACT

Monitoring field conditions is the foundation of modern agricultural management. In order to improve the efficiency of the data collection procedure, and to improve the precision with which agricultural operations are managed, it is necessary that we have an automated system that collects environmental data, especially to record long-term and up-to-the-minute environmental fluctuations. The purpose of this study was to design a remote pest monitoring system based on wireless communication technology. This system automatically reports environmental conditions and traps pest in real-time. The data we acquired was integrated into a database for census and further analysis. The system consists of two components, a remote monitoring platform (RMP) and a host control platform (HCP). Furthermore, based on the bio-characteristics of the oriental fruit fly, a high precision automated trapping and counting device was designed. This device counts the number of trapped flies and then sends the information back to the RMP. The RMP is in charge of acquiring the environmental data and the number of trapped flies, and it sends all the data back to the HCP in the form of a short cell phone message through the wireless Global System of Mobile Communication (GSM). Our system then transmits the data via a commercial base station. The system can work properly based on the effective coverage of base stations, no matter the distance from RMP to HCP. The function of the HCP is to receive and store, display, and analyze the database on line. It also provides functions like inquiries, early warning, and announcements. The system was field tested over a 1-year period (March 2006 to July 2007), and the experimental results demonstrated that it can monitor the environmental parameters and population dynamics of the oriental fruit fly in real-time. Based on the long-term monitoring database acquired by our system, the relationship between the population dynamics of the fruit fly and the environmental changes can be easily analyzed. With the help of this system, researchers can judge the correlation of the occurrence of the oriental fruit fly and climate conditions. Since the long-term database provides us with the details of the population dynamics of the fruit fly, the system allows us to control the pest in time and reduce agricultural losses. The experimental results demonstrate that large scale, long distance,

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doi:10.1016/j.compag.2008.01.005

and long-term monitoring for agricultural information can be achieved by using our proposed monitoring system. Much improved spatial resolution and temporal resolution is obtained compared to traditional methods for monitoring the data of the oriental fruit fly based on environmental changes.

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1. Introduction

Integrated pest management (IPM) relies on the accuracy of the pest population monitoring technique. Without gathering information of population dynamics together with the related ecological factors it is almost impossible to execute the appropriate pest control at the right time in the right place. However, most insect pests are spread across large areas and across many boundaries. Like other insect pests, with their strong reproductive ability the oriental fruit fly, *Bactrocera dorsalis* (Hendel), is one of the top major pests in the Asia-Pacific region, causing serious fruit damage and agricultural losses throughout the whole of Taiwan, year after year. In this article, we report for the first time a Global System of Mobile Communication (GSM)-based remote wireless automated system for monitoring the population dynamics of the oriental fruit fly by means of modern wireless communication technology. By integrating the traditional trapping method with modern communication technology, our system is able to provide real-time information on the field conditions and the dynamics of the pest population at different monitoring sites. This makes the system especially helpful for large scale monitoring in mountainous areas, which is a major obstacle for the traditional monitoring methods.

1.1. Agricultural ecology and pest management

Ecological factors in the environment can be classified as physical (e.g. temperature and humidity), chemical (e.g. chemical composition of the soil), and biological factors (e.g. pathogens and pests). As far as cultivation and management of the land is concerned, the ecological factors are crucial to the quality and productivity of the crop. Among these factors, pests are those insects that directly damage the crop, and pest control has always been considered the most difficult challenge to overcome. To reduce the loss of agricultural products caused by insect pests, thousands of methods, including physical and chemical ones, have been developed over the years. Each of these methods needs to be applied in the right place and the right time, and many ecological models have been developed specifically for this purpose. However, without accurate field information, no theoretical estimations or strategies for pest control will be able to hit the target and reduce the enormous costs to both agriculture and ecology.

Since all ecological factors have a dynamic connection with time, and each of these factors may interact with others, traditional monitoring techniques which rely on manpower to collect data from trap to trap, point to point are no longer efficient enough for modern pest management (Shen, 2003). There are two main drawbacks with traditional pest monitoring: (1) it is labor intensive and therefore costly and (2) all monitoring points cannot be synchronized to measure the variables, not even between two recording instruments at a

single site. Given that the traditional monitoring techniques are labor intensive with a poor temporal property, the dynamics of pest population density in the field cannot be accurately monitored. Consequently, a proper estimation for a target pest population will be limited to a long-term scale, such as pest numbers per 10 days or per 30 days. An example is, the oriental fruit fly (*B. dorsalis* (Hendel)), which is one of the major pests of many fruits and many commercial crops in the Asia-Pacific region. The methyl eugenol trapping method has been used for more than 30 years, yet we still know very little about the dispersion of the insect in the field. The oriental fruit fly is highly fecund, 8–9 generations per year, and is active throughout the entire year in the tropical and sub-tropical countries (TACTRI/COA, 2006). Previous studies have indicated that the oriental fruit flies attack 173 different fruits and vegetables (Metcalf and Metcalf, 1992), and several of them are economically important. By stinging the fruit for oviposition, the fly infests the fruit in the early stage of fruit development. The larvae hatching inside the fruit causes the fruit to rot, or to make the fruit ripen and drop before maturation (On News Report, 2004; Lin et al., 2006). Since the population growth and activity of the oriental fruit fly can be influenced by many ecological parameters, e.g. temperature, rainfall, wind speed and diurnal rhythm (TAPHIQ/COA, 2006), an automated system for accurately integrating real-time monitoring information is needed to better know the related parameters and the dynamic population in different loci.

1.2. Research purpose

The rapid improvement of today's micro-fabrication technology and embedded systems allows for a tiny electronic sensor to integrate multiple functions, like precise sensation and calculation (Gschwind et al., 2001; Ali et al., 2004; Joshua et al., 2005). By integrating the latest in sensory chips and micro-fabrication technology with traditional sensor modules and the pest trapping device, an automated pest and environment monitoring system can be established, together with powerful processing ability. Furthermore, it will reduce the labor cost of collecting environmental data by combining the automated monitoring system with wireless telecommunication technology. By having real-time environmental data available to us we can better understand the variation among cropland areas, increase the effectiveness and the precision of cultivation management and establish a highly reliable pest forecast system. As a result, the automated, wireless pest monitoring system can serve as the major information source for our agriculture development and insure our competitiveness.

Given that GSM wireless communication has been well established over all of Taiwan, both in the low-lying areas and the mountains (He, 2003), transporting data and signals using the GSM framework will be much more economical than any other communication technique, especially in the rural

areas (He, 2003; Jiang et al., 2003). Tseng et al. (2006) demonstrated the practicability of transporting data by mechatronics and Global System of Mobile Communication and Short Message Service (GSM–SMS) technologies (ETSI, 1999). Integrating the sensor modules and GSM wireless communication system will extend the transmission of the recorded environmental data from hundreds of kilometers away. In addition, an integrated system will facilitate the accumulation of long-term data and determination of the relationship between these environmental variations and pest occurrences, and hence may be the critical reference source needed for effective pest management. The trend of modern agriculture is to introduce, sensor techniques, long-distance wireless communication (like GSM–SMS), or global positioning systems (GPSs) and to proceed with automation, precision, and IT. Therefore, the main purpose of this study is to construct a wireless and automatic monitoring system that will be useful for monitoring pest population dynamics and related environmental variations.

1.3. Research background

1.3.1. Pest monitoring methods

Many devices have been developed for trapping specific insect pests, based on the biological characteristics of the pests (Yang, 1988; Reynolds and Riley, 2002). Today's research in the methodology of field surveys for various pests also uses modern technologies, such as radar technologies for monitoring pest migration or flight (Chapman et al., 2002; Riley and Smith, 2002), video equipment to observe flying insects in the field (Riley, 1993), thermal infrared imaging for the monitoring of rainfall in relation to the control of migrant pests (Milford and Dugdale, 1990), chemiluminescent tags for tracking insect movement in darkness (Spencer et al., 1997), electric systems for detecting moths (Hendricks, 1989), the micro-bar-code system for monitoring honeybee behavior (Sasaki, 1989), the remote sensing technique used to detect the effects of insects on their host plants (usually damage to crops or forests) or to monitor environmental factors (Riley, 1989; Hay et al., 1997), GPS for wildlife telemetry and habitat mapping (Hurlbert and French, 2001), the high-frequency echo-sounding method to detect the movements of larvae (Eckmann, 1998). However, the financial burden for building the fundamental hardware of these high-tech facilities may only be affordable to governments or very large agricultural corporations. At the same time, real-time communication between data collection and control terminals may not be easy to achieve since the automatic data may be collected in remote areas and the communication coverage may be restricted. Therefore, constructing a monitoring system based on an automatic and real-time communication platform is urgently needed for modern agriculture.

1.3.2. Control history of the oriental fruit fly in Taiwan

The subject insect pest of this research is the oriental fruit fly, *B. dorsalis* (Hendel) (Diptera: Tephritidae). It is the major pest for various fruits in Taiwan and is also the target insect of a quarantine law. The females lay their eggs into fruits by punching their ovipositor through the fruit's skin, thereby greatly reducing the quality of the fruit (Liu, 1981; Chiu and

Chu, 1986). The history of fighting the oriental fruit fly in Taiwan can be traced back for 50 years. In 1955, the poisonous protein hydrolysate was airdropped in the fields to attract the fly; in 1975, sterile males which were exposed to ^{60}Co irradiation were released, coupled with poisonous methyl eugenol as an integrated pest management (Liu, 1981). In addition, several other methods have been used to control the oriental fruit fly since then, e.g. chemical control, yellow sticky paper trapping, fruit bagging, etc. (Chu and Chu, 1987; Chiu, 1990; Wu and Chu, 1990; Chang, 1994; Liu and Hwang, 2000; Chen et al., 2002; Liu, 2002). Ho (2003) reported that traps containing methyl eugenol as attractant can trap the most male oriental fruit flies. Therefore, in the present study we use the male oriental fruit fly as the subject of auto-monitoring and methyl eugenol as the male-specific attractant.

Traditionally, the population dynamics of the oriental fruit fly in Taiwan is monitored by yellow plastic traps containing methyl eugenol. The distributing, hanging, and collecting of the traps in the field are labor intensive and the trapped amount of the oriental fruit fly is then counted manually, which makes it even more costly and time consuming. The survey results of the population dynamics in Taiwan are therefore measured on a 10-day scale. It is evident that the traditional method is not economical, nor very efficient considering the limited resolution in space and time scales, and the lack of environmental parameters. Even though the detection, attraction, and biological characteristics of the oriental fruit fly are very well known (Liu, 2002; Chen et al., 2002), nevertheless we still lack a precise pest detection mechanism.

The wireless auto-monitoring system can readily cope with this problem. Our previous investigation on the auto-monitoring of the Diamondback moth, *Plutella xylostella*, one of the major pests of Brassicaceae (Cruciferae) convincingly demonstrated the application of an automatic sensory system on pest control (Jiang et al., 2003; Lu et al., 2004; Tseng et al., 2004, 2006). The moth is attracted by a synthetic sex pheromone, detected and counted with sensors made of electric grid. In this study, with this experience in mind, we propose an automated and wireless system which simultaneously records both the environmental variations and the pest population dynamics. This technology reduces the costs of both labor and resources and at the same time monitors the population dynamics with an adjustable temporal resolution in a large space scale. In addition to the collecting of field data, the developed system is also able to communicate, integrate, and analysis data in real-time. All the information is received and processed at the server end, and thus a pest forecast system is constructed with temporal and spatial precision.

2. Materials for experiment and system mapping

The software and hardware used to develop our proposed GSM-based remote wireless automatic monitoring system are listed as follows:

Software: MSP GCC, PHP, LabVIEW, MySQL, Apache server.

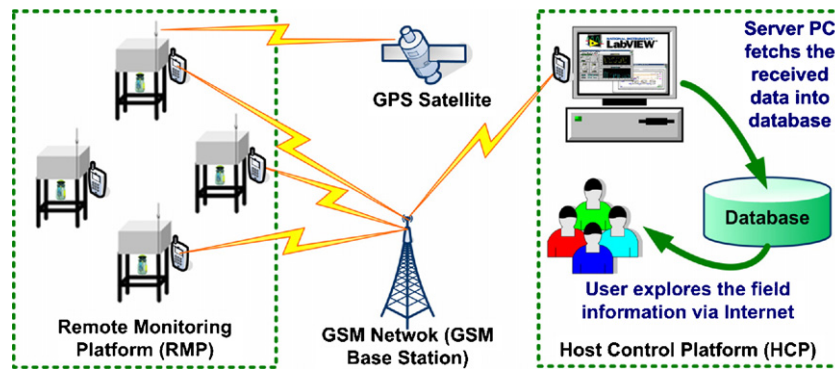


Fig. 1 – Structural diagram of our proposed remote wireless automatic monitoring system.

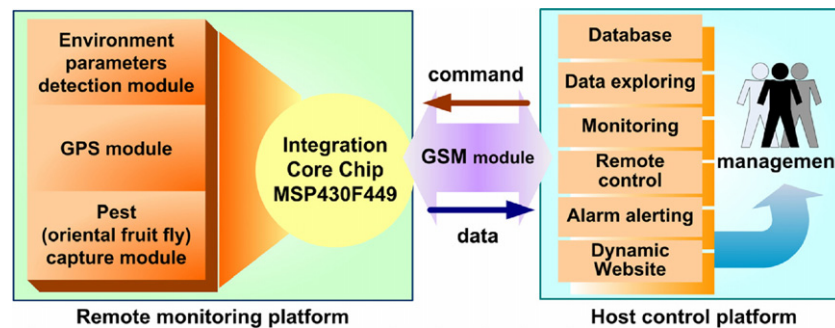


Fig. 2 – The information flow of our proposed remote wireless automatic monitoring system.

Hardware: sensors for measuring wind speed, temperature, and humidity, microcontroller (TI MSP430F449 chip), GSM module, GPS receiver, PC.

The basic make-up of our system can be divided into two major parts: the Remote Monitoring Platform (RMP) and the Host Control Platform (HCP) for monitoring and statistical analysis of field information, respectively. The RMPs are located at measuring places, and each RMP is equipped with an anemograph, temperature and humidity sensors, GPS receiver, and GSM module to measure the environmental variants, as well as a pest trap to determine the number of the insect pest *locus in quo*. The commercial GSM network system is adopted for data transmission to the HCP in short message (SM) format. The GSM module enables the HCP to receive and transmit field data to a PC for further analysis. The format design for short message packets used in this study follows our previous work (Tseng et al., 2006). The graphics user interfaces (GUIs) of the HCP are programmed and integrated on a Laboratory Virtual Instrument Engineering Workbench (LabVIEW) development platform (Bitter et al., 2001; Ritter, 2002). The HCP receives field data from the RMPs and stores the information in the database designed by MySQL (Kofler, 2001). Via the Worldwide Internet, the user can then explore the environmental variants and the collected insect pest numbers from the homepage of the RMPs which is programmed in PHP (Brown, 2002) and stored in the Apache (Melanie, 2001) server.

2.1. The structure of the RMP

The structure of the RMP is described as follows: the MSP430F449 microcontroller developed by Texas Instruments, Inc. (MSP430F4xx Manual, Texas Instruments, Inc., 2006) is adopted as the core-processing chip of the RMP. This chip serves to create data packets, transmit, and dispatch control commands among the modules used in the RMP. Based on mechatronics technology, the RMP is designed in a modular fashion. In addition, the RMP also includes an anemograph, temperature and humidity meters, a pest-detecting trap, a GPS receiver, and a GPS module. The anemograph used here

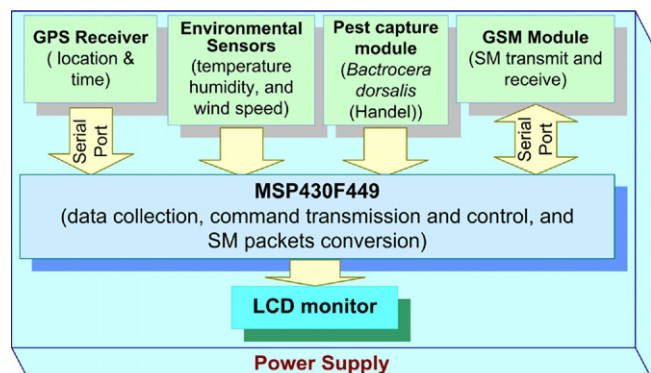


Fig. 3 – System architecture of the remote wireless monitoring platform.

is the type of AM-4203 with an accuracy of $\pm 2.0\%$ made by the Lutron Company. The AM-4203 possesses an RS-232 serial port and provides 16 bits string output function such that it can communicate easily with the MSP chip. The sensor used in the present study for both temperature and humidity measurements is a Sensirion SHT75, which has a built-in microcontroller to measure the temperature and the relative humidity simultaneously. The SHT75 provides long-term stability and high measurement accuracies of $\pm 2.0\%$ for relative humidity and $\pm 0.4^\circ\text{C}$ for temperature. The GSM module (model no.: FASTRACK M1203A) created by WAVECOM Corpo-

ration is used in both the RMP and the HCP. The GSM module meets both GSM900 and GSM1800 specifications, and has the same basic capability with the cell phone. The GPS receiver (GM44, San Jose Navigation Corporation) with an RS-232 interface is used in our system. The GPS receiver characterizes a 15 m positioning accuracy, and mainly provides the geographic information and correct time tag for the RMP.

Using serial communication ports, the MSP microcontroller collects each module's data including environmental information, number of pests, and the RMPs geographical location. The monitoring data is then packed and becomes a short mes-

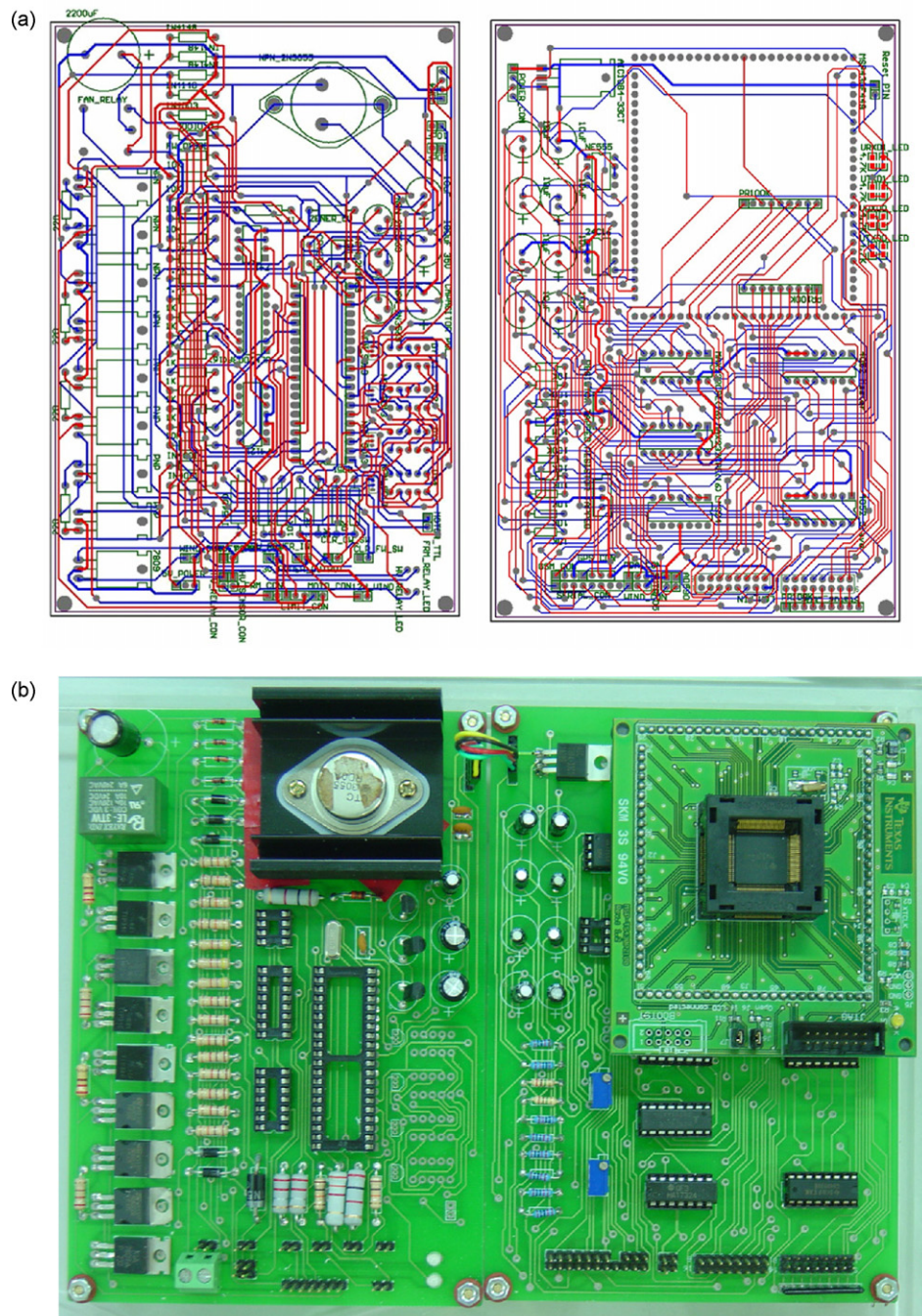


Fig. 4 – Construction of remote monitoring platform and finished product: (a) circuit layout, (b) PCB, (c) assembly of RMP components, and (d) finished product.

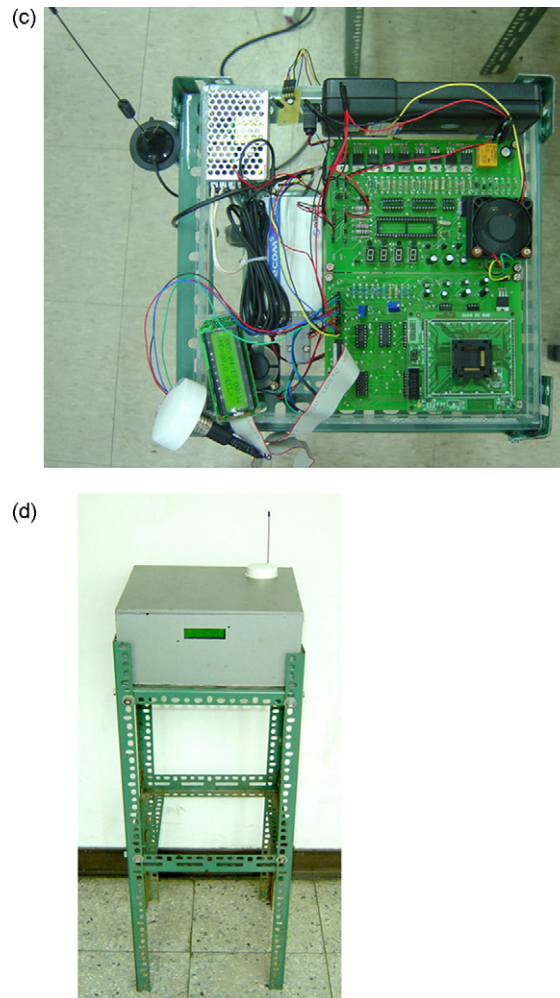


Fig. 4 – (Continued).

sage which is transmitted by GSM module to HCP. As a result, the system is capable of collecting and transmitting the field information automatically.

2.2. The structure of the HCP

In addition to the data transmission of the GSM module, the HCP contains GUIs written in LabVIEW (National Instruments, Inc.) to control the data transmission from the GSM module (Bitter et al., 2001; Ritter, 2002). The GUIs are linked to a MySQL database (Kofler, 2001) and can save the field data received from the RMP into the database of the HCP. The HCP also contains a dynamic homepage so that the users can explore the field data collected from the field in real-time as well as the statistical analysis of historical records via the Internet. The server adopted in the HCP was established by Apache (Melanie, 2001), PHP (Brown, 2002), and MySQL. Thus, we can perform remote monitoring and collect the number of pests and the environmental parameters, and then save this field data in the MySQL database. The user and the superintendent of the system can quickly search data from the PHP dynamic homepage and each item of field information

or the statistical data can be graphically displayed. This is particularly useful for future work to establish an identification model for the quantity growth of the oriental fruit fly.

2.3. System integration and implementation

2.3.1. System architecture

Combining the GSM network with the technologies of the Internet, mechatronics, and wireless communication, this study constructs a wireless automatic pest monitoring system. The structural diagram of the system is shown in Fig. 1. The system can be divided into two major parts: the RMP and the HCP. The RMP uses MSP430F449 as the core-processing chip and the GPS module for positioning information. The data recorded by sensors, including the number of trapped flies, is transferred to the HCP through the commercial GSM network. The user will be able to monitor the field information via the Internet. Users can obtain the historical records from the database of the HCP if necessary. Fig. 2 shows the information flows of the designed remote wireless automatic monitoring system.

2.3.2. Implementation of the RMP

The system architecture of the RMP is shown in Fig. 3. The MSP430F449 is the core-processing chip of the RMP for integrating the GPS and the GSM modules, as well as the environmental information sensory modules. The environmental information, including temperature, humidity and wind speed, and the number of trapped flies are the parameters for measurement. Several serial ports are reserved for future applications. A liquid crystal display (LCD) is also installed in RMP. Via LCD, users can monitor the collected information in *locus in quo*, which is particularly useful for maintaining the system. Fig. 4 shows the construction of the RMP. Fig. 4(a) is the circuit layout which is designed with software Protel 99SE. Fig. 4(b) shows the printed circuit board, including MSP430F449 receptacle, the temperature/humidity sensory circuit, the circuits for USART voltage level conversion and channel switching, and several output ports which can connect with the anemometer, the LCD, the GPS and GSM modules. In addition, it also provides a voltage output to supply the electrical power for other circuits. The completed assembly of components is shown in Fig. 4(c). The photograph of the finished RMP is shown in Fig. 4(d). The outer covering of the RMP is made of acrylic plates, and the electric circuits of the RMP are fixed in the box. The whole box is set on an angle-iron support. The GPS module is the white disc on the top right corner of the RMP. The anemograph and humidity/temperature sensor are mounted at the bottom of the box away from the ground.

2.3.3. Implementation of the HCP

The HCP is set up in a personal computer (PC). The function flow of the HCP in this monitoring system is shown in Fig. 5. After receiving the monitoring data by GSM module, the HCP analyzes the received data and the information regarding the RMP operational status. If there is an error, the HCP immediately sends a request command for re-transmission, and the RMP will send the data again. If the trapped pest number is over the pre-set threshold, the HCP will alert authorized per-

sonnel. The main program and the associated GUIs are based on the planned functions and are developed using LabVIEW. At the same time, a PHP-programmed dynamic homepage is developed so that users can retrieve the historical monitoring data via the Internet. The homepage is very user-friendly.

2.3.4. GUIs design of the monitoring system

According to the system operation requirements, the designed GUIs are described as follows.

2.3.4.1. Login page. When the program is activated, the login page appears. The user is then requested to enter his/her account and password. If the account and password are correct, the user is then allowed to start the HCP to execute the setting function.

2.3.4.2. Setting and testing page. Fig. 6 shows the setting and testing window of the monitoring system. In this page the user can set up the connection port of the man-machine interface to the GSM module of the HCP. After choosing the proper connection port, the system will automatically test the connecting status of the GSM module to the HCP. If the GSM module works, then the indicator for the module connecting status will be turned on. Also, the power strength of the received signal is shown to tell the user the connecting condition of the GSM module. If the GSM signal is weak, then a weak indication will remind the user to adjust the antenna for a stronger signal or change the HCPs location.

After the GSM module is connected, the user starts to set the RMPs. After choosing the RMP number and entering its phone number, one can click the “set” button followed by the “start” button; the system is then automatically activated. By clicking the “start” button, the HCP will send a ready performance file (RPF) as the starting message to the RMP for the initial handshake. As the HCP receives the acknowledgement confirmed by the selected RMP, the start indicator of the RMP will be turned on to inform the user that the RMP is ready to use. An instant information frame is located below this

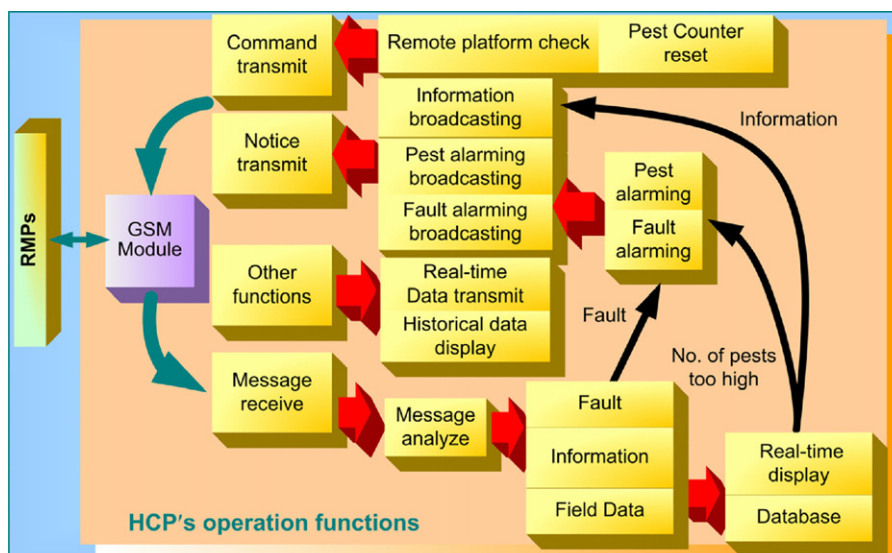


Fig. 5 – Function flow diagram of the host control platform.

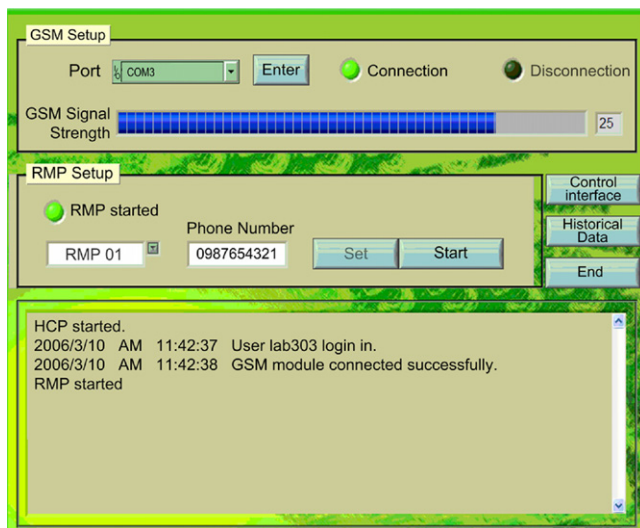


Fig. 6 – The setting and testing window for the GSM module and the RMP.

window, and will list all the information about any action performed by the HCP and its relevant time.

2.3.4.3. Control interface window. After setting the RMP, clicking the “control interface” button (Fig. 6) the user can enter the control interface window as shown in Fig. 7(a). On the upper left side of the window are the indicators of the system status. There are three kinds of system-status indication, start regular transmission (Tx), start broadcasting, and fault alarming. When the HCP receives an error message sent from the RMP, the fault alarm is turned on to inform the user, and the system will send an error message to the maintenance staff. When the maintenance is finished, one can press the “fault reset” button on the window and turn off the fault alarm. In the middle above the window shown in Fig. 7(a) is the latest information in an SM transferred back from the field. It contains the RMP information, including the RMP number, the location coordinates of the RMP, temperature, humidity, wind speed, pest number, and time of data transmitted back. All the field information will be saved in the database for further inquiry and analysis. The partial portion of the VI file for performing the “save data” function is shown in Fig. 7(b). Located in the center of the window is the real-time command line for requesting the RMP to send the current information immediately or to set the counter to zero. Once the expected data was lost, the fault alarming module is triggered and the supervisor will be noticed to request the RMP to retransmit the data promptly or inform the worker *locus in quo* to fix the malfunction of the RMP. Any information about the executed action is displayed on the message board in the lower part of the window (Fig. 7(a)).

2.3.4.4. Advanced setting window. Fig. 8(a) shows the advanced setting window which contains the regular transmission (Tx) setting and the broadcast setting functions. The function of the regular transmission setting allows users to set the time interval between transmissions and keep the RMP automatically transmitting data. This function is

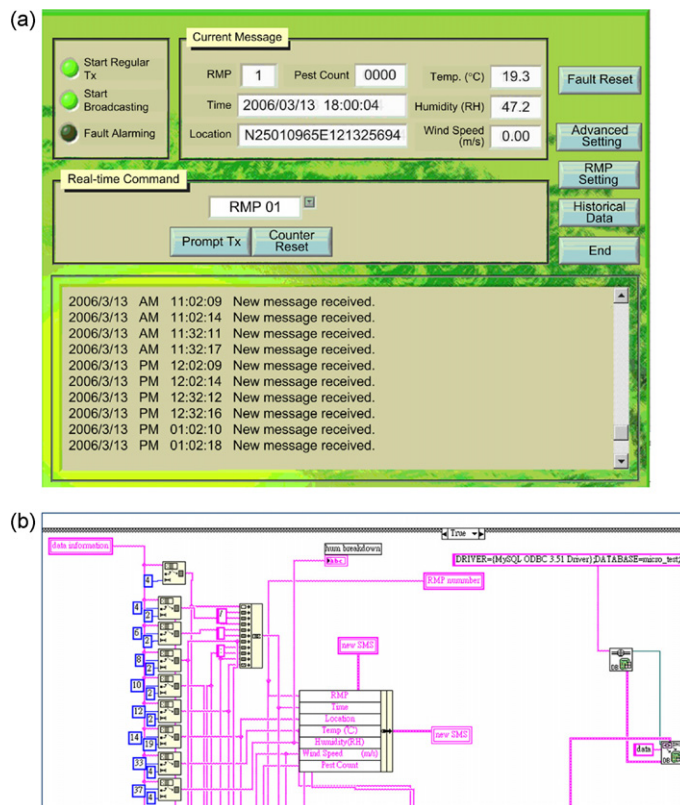


Fig. 7 – The control interface window for the operating RMP at the HCP: (a) GUI and (b) partial portion of VI file for setting the “broadcast” function in the control interface window.

particularly useful for long-term monitoring. The broadcast setting function includes the information broadcast, the fault alarm broadcast, and pest alarm broadcast. The portion of the VI file for setting the “broadcast” function is shown in Fig. 8(b). The information broadcast can send the collected field information to the user after receiving the sensing data, and thus the user can keep informed and does not need to stay in front of the computer monitor. If a RMP fault occurs, the fault alarm broadcast will automatically notify the maintenance staff. In addition, when the number of trapped pests is larger than the threshold, which is pre-set by the user, information will be sent to the user by the pest alarm broadcast to reduce the possible pest damage. From the perspective of agricultural applications, Tseng et al. (2006) reported that the system, which uses GSM–SMS to transmit data, can ensure that the remote data arrives on the user’s screen in 30–60 s without any error found in the data content. Therefore, the GSM–SMS technology used in this study is feasible and reliable.

2.4. Trapping facility for the oriental fruit fly

Traditionally a mixture of chemical attractant and insecticide is being used to attract and kill the fruit fly for long-term monitoring of its distribution. The attractant placed in the tube is for attracting male flies (Steiner, 1952). The trapping device we adopted in our proposed system is a modification of the

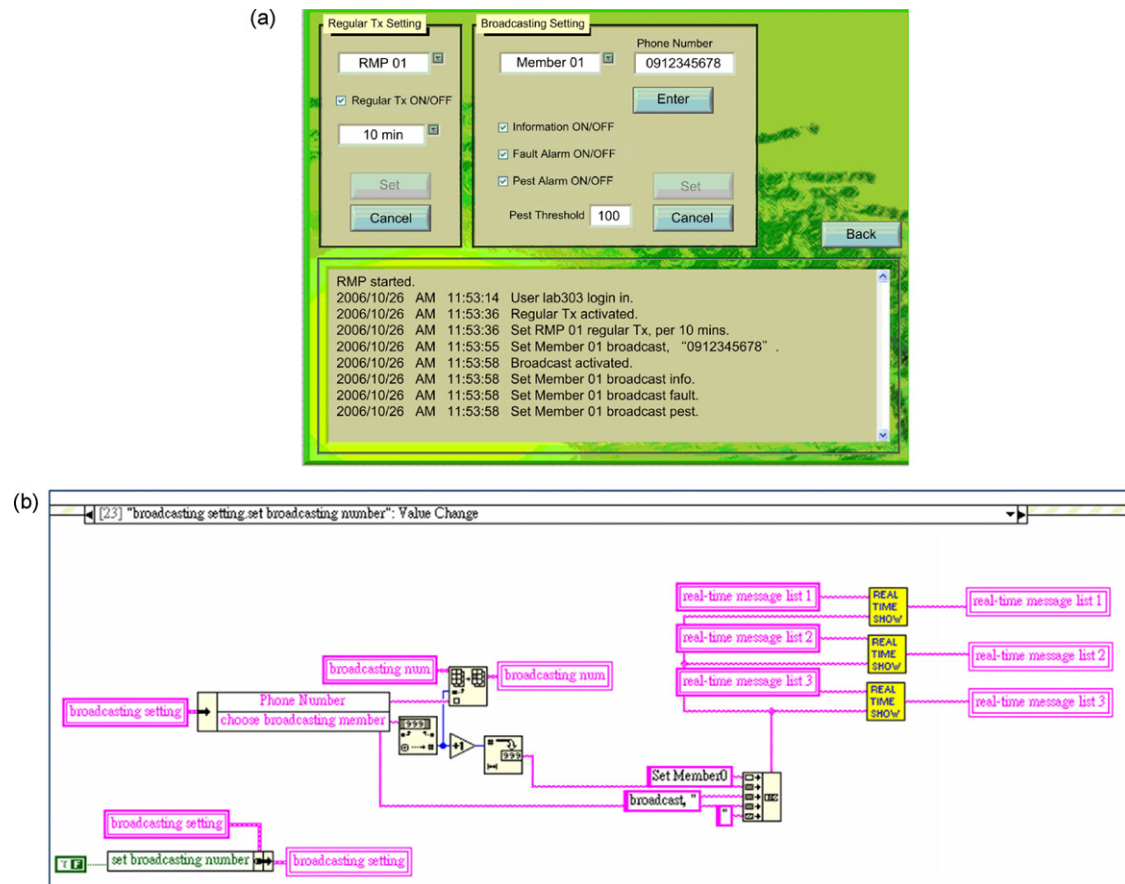


Fig. 8 – Advanced setting window for operating the RMP at the HCP: (a) GUI and (b) partial portion of VI file for setting the “broadcast” function in the advanced setting window.

traditional fruit fly trapping tube, with an automatic counting module placed in the tube.

The trapping device in our system uses a double-counting mechanism (Lin et al., 2006). The number of trapped flies is counted as they cross the infrared interruption sensor. In general, this kind of counter needs a gate or an inhler to avoid counting the same fly more than once. To reduce the complexity as well as the cost of the device, and at the same time obtain a correct count, a double-counting solution was designed. This system consists of a set of optical sensors installed along the trap pathway the fly will pass through. Fig. 9 shows the double-counting optical sensors which are indicated by the arrows. The correct counting can be obtained by a microprocessor which takes the signal interruption into account only when the fly crosses both optical sensors sequentially. The fly which hovers around is then excluded by the double counting mechanism. From our observations we found that there are four possible actions for the fly crossing the double-counting optical sensors, thus we set our counting rules based on these conditions:

1. If a fly enters the trap and hovers around the first sensor or even stays on it, the processor then holds the first sensor in *interrupting status* until the fly crawls across the second sensor.
2. If the fly crosses the first sensor and has not yet arrived at the second sensor, the processor then holds the first sensor in *interrupting status* until the second sensor is interrupted.
3. When the fly arrives at the second sensor and both sensors are in *interrupting status*, the processor will increase the count and reset the status of both sensors.

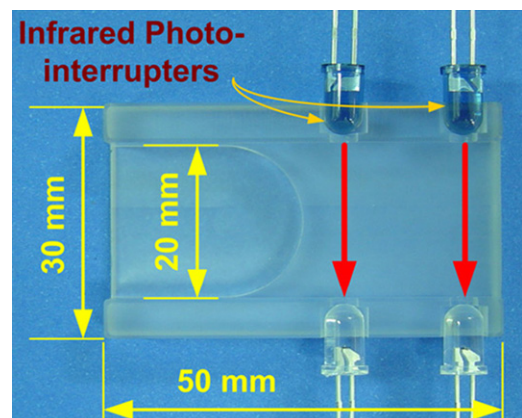


Fig. 9 – The double-counting optical sensors deployed along the pathway.

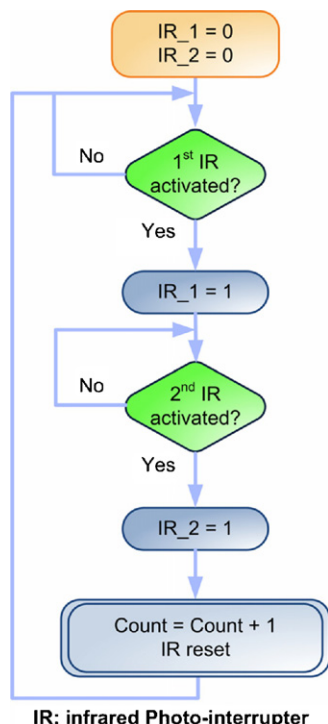


Fig. 10 – Flowchart of double-counting mechanism for the designed fly trapping tube.

4. If the fly hovers around the second sensor, the processor only increases the count once and clears the redundant signal caused by the hovering. Because the first sensor is not in the interrupting status, the processor will ignore the second sensor's signal even it is interrupted continuously. This will avoid the fly from crawling back to interrupt the first sensor again.

Based on the above-mentioned fly behavior, Fig. 10 shows a flow chart of the double-counting mechanism. Only the occurrence of two consecutive interruptions triggers the counter to add one. By using this mechanism, compared to the single-counting method, the double-counting optical sensory set can be more accurate in counting the trapped flies. Note that in order to reduce the device complexity, this study ignores the following conditions: (1) the fly crawls back to the entrance of the pathway passing through the optical interruption sensors 1 and 2 and (2) the distance between two flies entering the pathway is less than 2 cm. In this paper, the pathway is designed to reduce the occurrence of these conditions.

3. Experimental results of system performance evaluation

3.1. Testing the GPS positioning accuracy

According to the GM-44 manual of the GPS receiver (On Web of GM-44 Manual, 2006), its positioning accuracy is 15 m. To confirm if the actual positioning accuracy of a GPS receiver can provide accurate geographic information for monitoring



Fig. 11 – Test for GPS positioning accuracy of the GPS receiver of the RMP. The test experiments were conducted at the top balcony of the BIME building, NTU between 19 April 2005 and 26 April 2005.

cultivated land, we analyzed the longitude and latitude information collected by the RMP. The RMP was mounted at a fixed location on the top balcony of the building of the Department of Bio-Mechanical Engineering (BIME), National Taiwan University (NTU), as shown in Fig. 11. There was no canopy over the top balcony of the BIME building and no other surrounding buildings to affect the reception of the satellite signal. The GPS receiver of the RMP received the longitudinal and latitudinal data from the GPS signal every 30 min and delivered it to the HCP. The system collected 522 data during this operation lasted about 10 days, and the distribution of the data is shown in Fig. 12. The red point in Fig. 12 indicates the average of all data points, which represents north latitude 25.011007° , or equally $25^\circ 0' 39.63''$, and east longitude 121.325819° or equally $121^\circ 19' 32.95''$.

During test, the RMP with its single GPS receiver was located in the fixed location mentioned above. Due to the fact

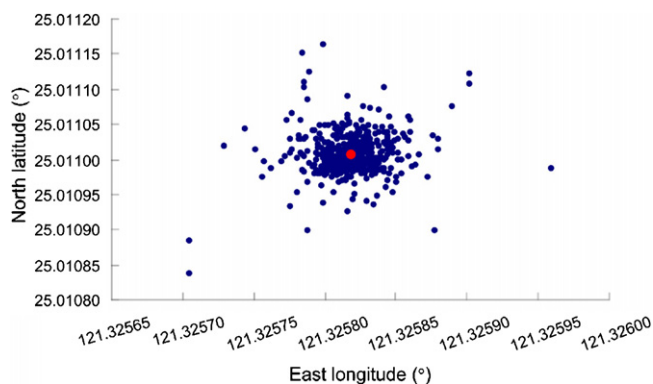


Fig. 12 – The distribution diagram of the received longitude and latitude data for the positioning accuracy test of the GPS receiver of the RMP between 19 April 2005 and 26 April 2005.

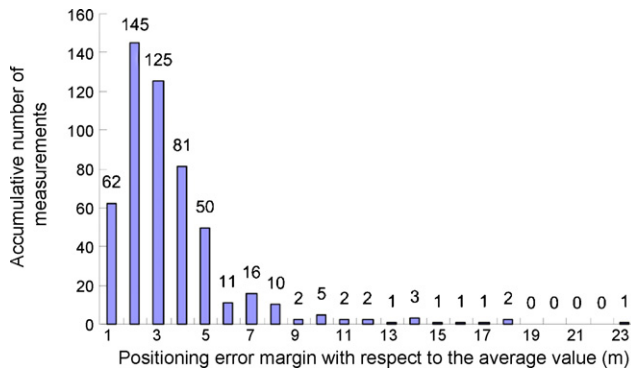


Fig. 13 – Distribution diagram of the positioning error margin for the received GPS signals.

that there is no information available on the exact longitude and latitude of the location of the RMP, we could only take the average longitude and latitude data as a reference coordinate for judging the positioning error margin of the GPS receiver. Comparing every received longitude/latitude data with the mentioned reference coordinate, the average positioning error margin was 3.01 m, the maximum error was 22.22 m, the minimum error was 0.13 m, and the standard positioning error was 2.61 m, respectively. The distribution diagram of the positioning error margin of the GPS receiver is shown in Fig. 13. About 90% of the GPS received signals providing positioning data had a margin of error that fell within 5 m in longitude and latitude compared with the average data. This implies that the positioning accuracy of the adopted GPS receiver was quite reliable. Within the scope of this margin of error, if we treat the average longitude and latitude values as definite ones for a single RMP, it is acceptable. But, if we consider monitoring many points, we should use a more sophisticated GPS technique or incorporate the present technique with an electronic map to fix the RMPs' position exactly. Then we can effectively build up a distribution diagram for monitoring the field information over a wide area.

3.2. Testing the counting accuracy of the fly trapping tube

The purpose of this experiment was to determine the counting accuracy of the fly trapping tube we designed. The experiment was done outdoors, and we compared the number of flies counted by the system and also counted them manually. Fig. 14 shows the OrCAD layout and a photograph of the actual finished product of the flattened pathway of the fly trapping tube applied in this paper. The cross-section of the entrance is made larger in order to distribute the attractant and to permit the flies to enter the trapping tube easily. The height of the back pathway is lowered to increase the effect of the signal interruption when a fly passes by, thereby further increasing the counting accuracy.

The finished product with the double-counting device installed in the fly trapping tube is shown in Fig. 15. The oriental fruit fly is lured by methyl eugenol and crawls into the pathway via the entrance and passes by the double-counting optical sensors mechanism, resulting in the fly being automat-

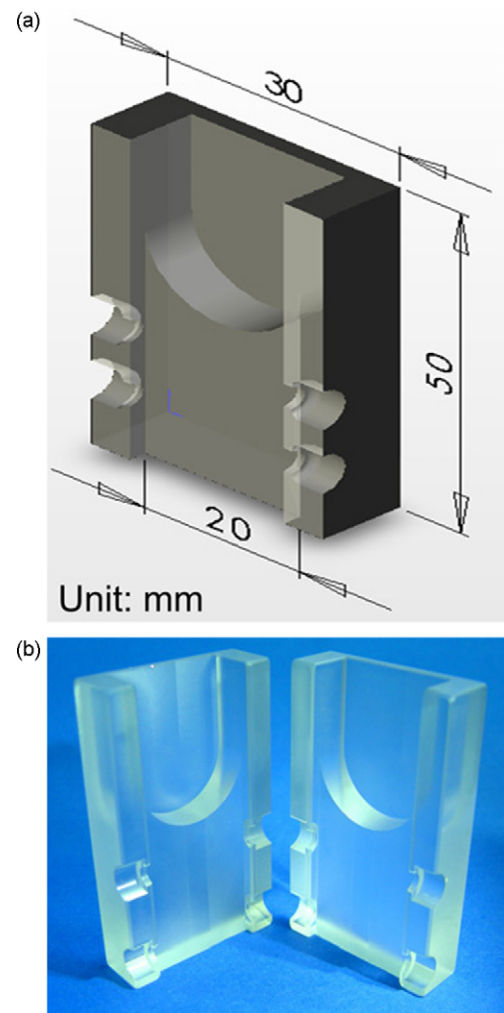


Fig. 14 – The cross-section of the fly entering pathway in the designed fly trapping tube: (a) OrCAD layout and (b) entity photograph of finished product.

ically detected and counted. Fig. 16 shows the enlarged picture of the RMP equipped with the fly trapping tube. To prevent sunlight influencing the counting accuracy, the upper half of the fly trapping tube was coated with a dark paint.

Fly trapping tubes equipped with electronic counting circuits were placed under the trees outside of the BIME building on NTU campus in May 2006. The experimental results are summarized in Table 1. The average counting accuracy of the fly trapping tube with two flattened pathways was around 78.1% in this test. From the experimental results, the counting accuracy of the 6th experiment was only 56.5%. After careful examination, we found that when the oriental fruit flies crawl over different pathways, some flies might hide in the corner inside pathway or retrace the pathway towards the entrance. This fact also causes the variation in the counting accuracy. To cope with this problem, we refined the dimension of the designed pathway and tuned the alignment of the optical sensors. The optimal dimension of the pest-entering pathway is as shown in Fig. 14(a). The average accuracy is 80.2% without the 6th experiment since the alignment of optical sensors was missed during the maintenance work. The accuracy is

Table 1 – The experimental results for the counting accuracy of the fly-trapping tube equipped with two flattened pathways

Evaluation items	Experimental course							Total
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	
Counted number	11	53	30	18	35	13	36	196
Actual number	12	74	35	25	43	23	39	251
Accuracy (%)	91.7	71.6	85.7	72.0	81.4	56.5	92.3	
Average accuracy (%)								78.1

further confirmed in accordance with the long-term experimental results of the entire monitoring system described in the next section. With the features mentioned above, the automatic detecting device in this study can attract male oriental fruit flies and effectively count their number.

3.3. Field test

Originally two prototypes of RMPs were produced and set up in the farm on the NTU campus to test their performance, as shown in Fig. 17(a). Later on, to ensure that the numbers of trapped flies and the monitored data collected by the system were matched, the two RMPs were moved to outside the department building of the BIME for outdoor testing as shown in Fig. 17(b). The HCP of the monitoring system was placed in our Lab on the 3rd floor of the BIME building, and the distances between the HCP and two RMPs were about 20 and 30 m, respectively. Since the experimental location was in a bosket on the NTU campus, the quantity of oriental fruit flies was smaller than in the farm field. For monitoring field information and trapping oriental flies, however, this fact did not actually affect the performance evaluation of our system. The RMP system includes the following items: the core-processing system integrated by the MSP430F449 chip, the temperature/humidity sensing module, the GPS receiver module, the GSM module,

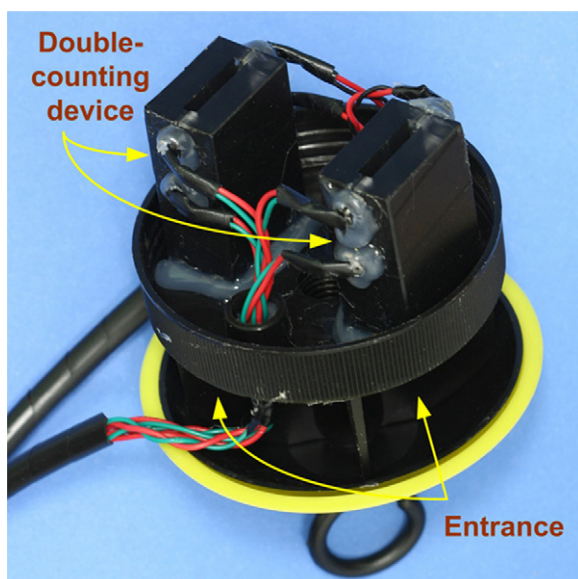


Fig. 15 – The photograph of the double-counting device installed in the fly trapping tube.



Fig. 16 – Our proposed automatic counting trap for the oriental fruit fly installed in the RMP.

and the anemometer. The fly trapping tube, the anemometer, and the temperature/humidity sensing module were put in the bottom of the box so as to be shaded and so decelerate any possible damage of these modules due to severe environmental variation. This arrangement of the sensing modules can effectively measure the variation of the environmental parameters.

The whole system has been tested outdoors as of 1st March 2006. At the beginning, the number of flies counted by the fly trapping tube did not match the number we counted manually, so we changed the standard fly trapping tube with our improved fly trapping tube in May 2006. After that, the number counted by fly trapping tube became more accurate and reliable. The temperature, humidity, wind speed, and the number of trapped flies were then recorded, and the information was statistically analyzed in the HCP. Fig. 18 shows the monitoring data for a single day as collected by RMP #2 on 4 August 2006. The fly trapping tubes were manually emptied, and the

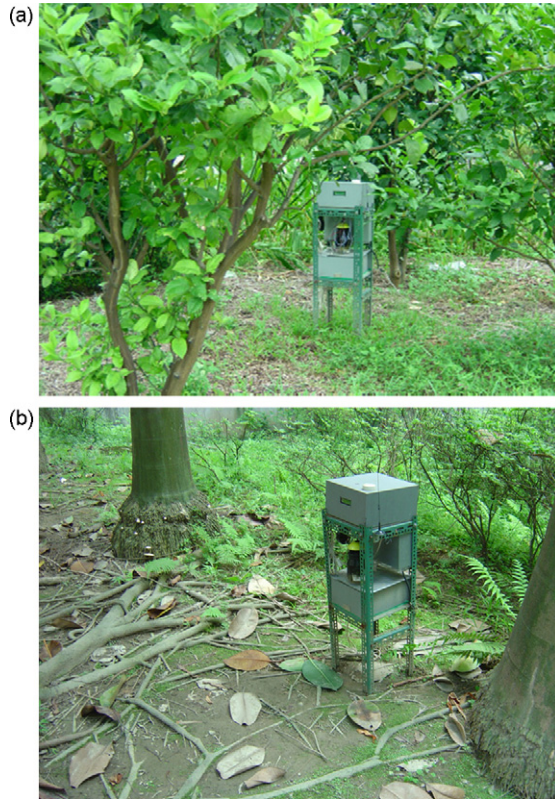


Fig. 17 – Deployment test of the developed remote monitoring system for the oriental fruit fly: (a) pretest of the RMP conducted at the farm field on the NTU campus and (b) long-term test of the RMP conducted at the basket near the BIME department building, NTU.

number of flies trapped in the fly trapping tube was also manually counted at 10 p.m. each day to verify the accuracy. Except for the days we performed maintained on the instruments, we have tested and verified the entire system for 304 days, from 1st July 2006 to 30th April 2007. During these 304 days, we deleted the data for 90 days because no flies were trapped due to rain or extreme low temperature or the number of flies trapped was lower than 5. The latter recordings were excluded because in such cases the counting accuracy of the trapping fly tube varied severely, some were very high and some were very low to the point that no statistical contribution for long-term performance evaluation could be obtained. Under these circumstances, the mean accuracies of monitoring oriental fruit flies by the two RMPs (#1 and #2) deployed on the NTU campus were 84% and 76%, respectively.

Our proposed system provides different time resolutions for recording field information, so it is possible for users to set the time interval for sending the data from the RMPs to the HCP as required. An interval of 30 min was set in the present study. For example the data monitored by RMP #2 on 4th August 2006 (Fig. 18), was sent to the HCP every 30 min. The information included the number of trapped oriental fruit flies, temperature, humidity, and the mean of the wind speed. The humidity (%RH), temperature ($^{\circ}\text{C}$), wind speed (cm/s), and the accumulative number of the trapped oriental fruit flies are depicted by blue bars, red line, green line, and black line, respectively. Fig. 18 also shows the trends in humidity and temperature during the recording time. The highest temperature and the lowest humidity were observed at noon. As it was getting dark, the temperature became and the humidity increased, as expected. Based on the monitored information, we could estimate the local daily activity of the oriental fruit fly.

The HCP system we developed provides various inquiry functions for field information. After logging in to the PHP webpage of our monitoring system, users can set the inquiry functions at their PC. The daily, weekly, and monthly averaged

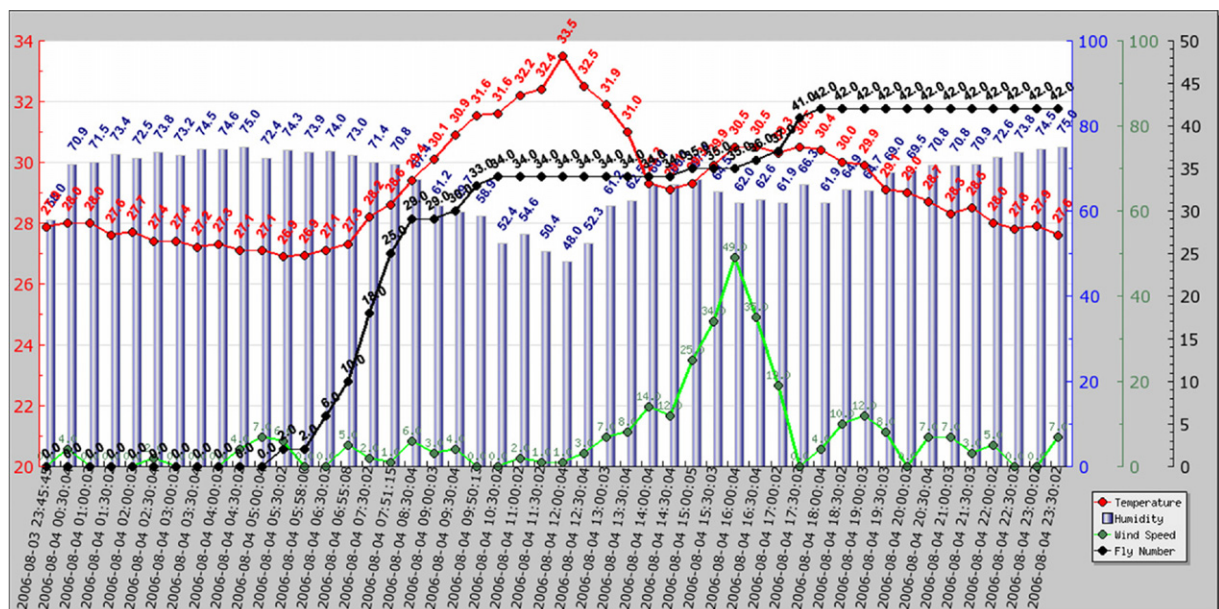


Fig. 18 – Monitoring data for a single day collected by RMP #2 in 4 August 2006.

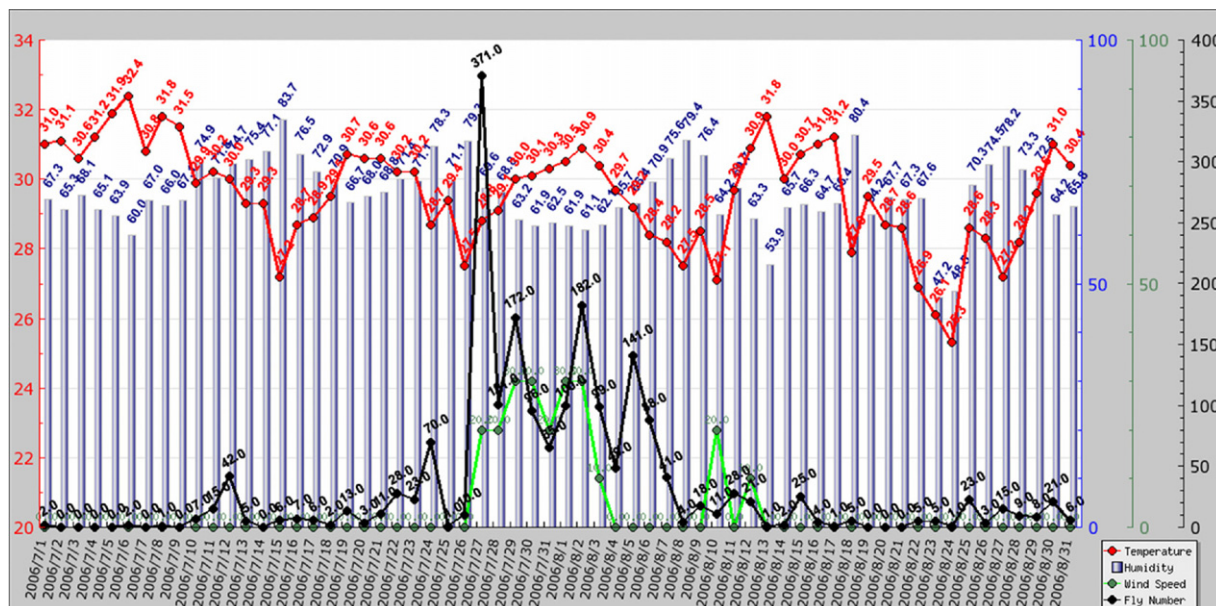


Fig. 19 – The average recordings per day from July to August in 2006 monitored by RMP #1.

data to individual/complex field information can be inquired from our system. For example, as shown in Fig. 19, the average recordings of every day from July to August in 2006 monitored by RMP #1 can be displayed. The system can provide us with long-term observations on both the environmental variations and the fly population dynamics in a local area by calculating the information for each day. Thus the effects of environmental variations on the ecological pattern of oriental fruit fly can be investigated in a good temporal and spatial resolution if more RMPs are deployed.

In this study we planned and designed the HCPs database of the monitoring system in detail so that the database can offer

many kinds of statistical analysis functions for the long-term recordings of ecological information and various inquiry services for complex data. Thus, if we inquire the data per week, the influence of more long-term environmental changes on the population dynamics of the oriental fruit fly can be readily observed via our system. When obtaining the weekly data points, the correlation between the environmental parameters and the population dynamics of the fruit fly can be observed. For example, in Taiwan the daily temperature rises from June until September. Taiwan lies in the subtropical zone in the northwestern Pacific Ocean. In the mentioned 4-month period, this area is subject to frequent thunderstorms

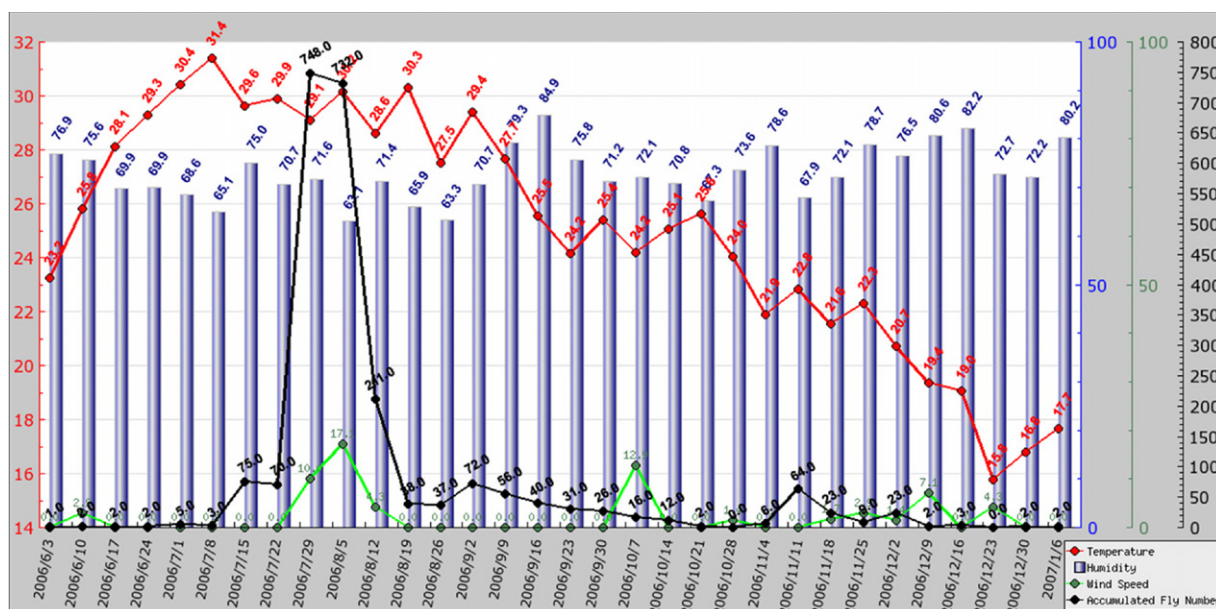


Fig. 20 – The average environmental data and the total population of flies per week monitored by RMP #1 on the NTU campus.

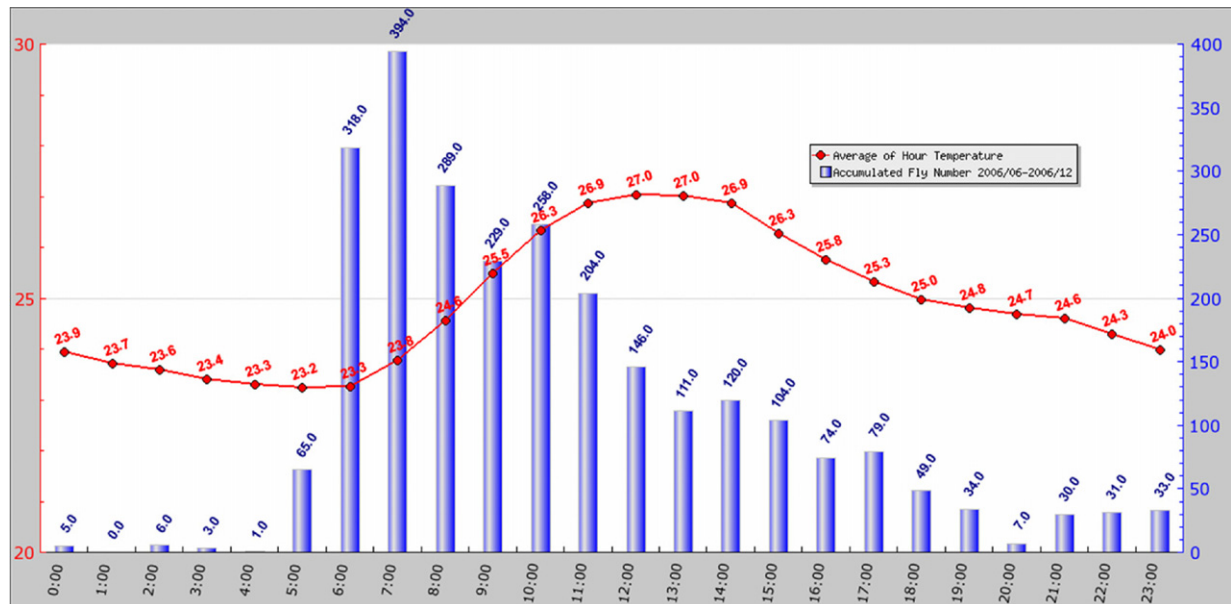


Fig. 21 – The hourly records averaged from each day by RMP #1 during the period of 1 June 2006 to 31 December 2006.

in the afternoon, as well as the occasional typhoon. Therefore, the temperature is not evenly distributed in the mentioned period. As a result, the number of oriental fruit flies trapped is closely related to the changes in climate. In northern Taiwan, July–August is the peak period of the oriental fruit fly activity. However, their activity reduces gradually when the weather turns cooler after September.

Fig. 20 shows the average environmental data and the total population of flies per week detected by RMP #1 of our monitoring system on the NTU campus during the period from June to November, 2006. According to the data of our long-term recordings, it rained nearly every day between 1 June 2006 and 17 June 2006. In addition, there were four typhoons during 1 July 2006 to 12 July 2006 and 26 July 2006 to 17 August 2006. The climate records from the Taiwan Weather Bureau also confirmed the recordings from our system. Fig. 20 clearly indicates that the fly population was quite low during June and the first 2 weeks of July due to rainy weather. Also, the population curve of trapped flies lowered significantly since the end of July due to a typhoon over North Taiwan. The fly population increased slowly after around the third week of August, but went down following the temperature after September as shown in Fig. 20. This experiment demonstrates that a long-term and a good time resolution can be achieved by our system in the monitoring of the population of the oriental fruit fly in correlation to the environmental changes.

With the long-term recording and high temporal resolution provided by our system, the population dynamics of the oriental fruit fly correlated to climatic parameters can be further investigated. Since this system offers a huge database of long-term recordings from each of monitoring site, the information can be extracted from the database with any time interval, be it hourly, daily, weekly or monthly. For example, we can extract the average data of each hour to analyze the dynamics of the number of trapped flies and its relationship

to the recorded environmental physical parameters within a day. Fig. 21 shows the information (collected by RMP #1) of the averaged hourly records from each day for the period of 1 June 2006 to 31 December 2006. It clearly shows that the oriental fruit fly's daily peak activity is between 06:00 and 10:00 a.m. This result matches the previous hourly physically observations by Jiang (1986), indicating that our system is capable of providing high temporal resolution for field information using an economical recording technology.

3.4. Statistical analysis of the fly counting accuracy provided by the proposed monitoring system

To demonstrate and confirm the reliability and accuracy of our system, the data collected from both RMPs (#1 and #2) for more than 1 year (RMP #1: 20 July 2006 to 31 July 2007; RMP #2: 1 June 2006 to 31 July 2007) was statistically analyzed. Faulty data due to system maintenance and zero trapped flies were eliminated, resulting in 222 and 313 data points being used in this analysis for RMP #1 and RMP #2, respectively. Fig. 22 shows the linear regression of the counting results from RMP #1 (a) and RMP #2 (b). Each data point in the figures indicates the numbers being counted manually and automatically with reference to the abscissa and the ordinate, respectively. The slope of the regression line indicates the average accuracy of the fly counting of the RMP, and R^2 represents the reliability of the fly counting accuracy. The average accuracy of RMP #1 is 81.42% and that of RMP #2 is 73.71%, both with very high reliability, i.e., $R^2 = 0.951$ for RMP #1 and 0.952 for RMP #2, respectively. While the selected data in this statistical analysis is in a period different from that mentioned in Section 3.3, the average counting accuracy of RMP #1 is quite similar to previous one (i.e., 84%). This fact once again demonstrates the stability and the reliability of performance of our system.

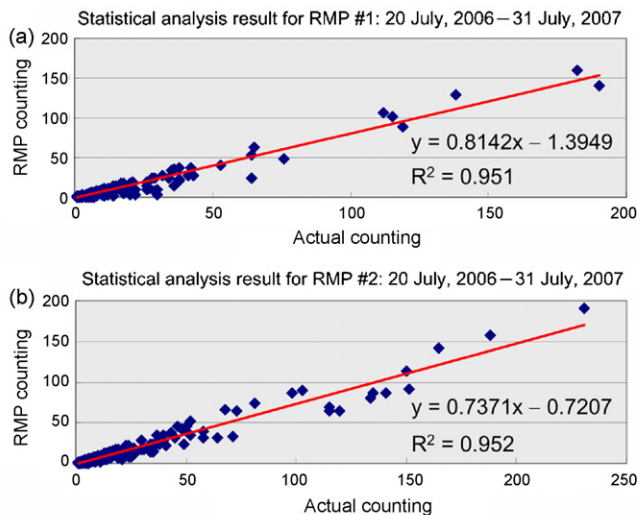


Fig. 22 – The linear regression analysis of the counting accuracy resulting from both RMPs: (a) RMP #1 and (b) RMP #2.

4. Conclusions

This study developed a complete and automatic monitoring system for remote field information. The purpose of developing this monitoring system was to achieve the remote wireless measurements of environmental parameters and population dynamics of the oriental fruit fly in real-time. The monitoring system is designed in a modular fashion and consists of two parts, i.e., RMPs and an HCP. The RMP is equipped with a MSP430F449 core-processing chip. This chip can package the sensory data of temperature, humidity, wind speed, and the number of trapped flies into a short message, and then send that message to the HCP at a pre-set time interval by GSM module. The HCP then writes the sensory data into the MySQL database under the control of a program written in LabVIEW. By using the PHP website development software, users can search the remote ecological information of the oriental fruit fly on the Internet. In addition, any researcher or farmer can search the historical data on the website, and use the website to analyze the data. The environmental variations can be monitored in real-time by our system. The long-term monitoring accuracies for the oriental fruit fly achieved by the two RMP we designed in this study, RMPs #1 and #2, were 81.42% and 73.71%, respectively. According to our results, the reliability of our automatic fly trapping system is about 95%. Moreover, since the RMPs automatically sent the field information back to the HCP every 30 min as scheduled, the daily activity model of the oriental fruit fly was available and the model matched the previous study, indicating that our proposed system provides reliable data.

The major contribution of this study is that it makes large scale, long distance, and long-term monitoring for agricultural information achievable. High spatial and temporal resolutions for monitoring the data of the oriental fruit flies with respect to environmental changes can also be achieved. Via our system one can easily gather field information in real-time, suggesting a possible application for a pest alarm system in the field of

agricultural management. Also, using our system will be very helpful for monitoring invading species. In addition, when combined with a biological identification model and/or ecological theories, the ability to collect field data and have access to the long-term recording database of this system will be one of the most useful references and tools for integrative pest management. For example, through the long-term information collected in the field, including temperature, humidity and wind speed, and the population dynamics of the pest, one can create a dynamic population model in a particular application area. This is very useful when making decisions on a pest control strategy—which depends on applying the right method at the right time in the right place. Therefore, compared to the traditional monitoring methods, our system can effectively reduce the cost and increase the effectiveness of pest control.

Acknowledgements

This work was supported in part by the Council of Agriculture of the Executive Yuan, Taiwan, under contracts: 92AS-1.1.6-FD-Z1, 93AS-1.1.6-FD-Z1, and 94AS-1.3.6-FD-Z1. The authors would also like to thank the National Science Council of Taiwan, for their financial supporting under contract no.: NSC 95-2218-E-002-073.

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