ICT-based Remote Agro-Ecological Monitoring System – A Case Study in Taiwan

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Abstract

In recent years, information and communication technologies have opened many opportunities to modern agriculture systems. Monitoring the fruit farm is one of the potential applications that may help improving fruit farm profitability through observing the fluctuation of the oriental fruit fly population and environmental conditions in the field. These data can be used to provide knowledge or warning for the farmers and government officials to accurately respond to the variations in the field. In this study, a remote agro-ecological monitoring system is presented to be a context-aware sensor platform to analyse the relations between population dynamics of the flies in the field. The system consists of three major layers, i.e., the front-end sensing layer, the telecommunication layer, and the data collection and analysis layer. A Global System of Mobile Communication (GSM) module is used to enhance the ubiquitous monitoring capability of the system. The monitoring system has been deployed to investigate the population dynamics of *B. dorsalis* since August 2008. Historical sensing data is available through a web-based decision support program built upon a database and a pest population forecast model, so that farmers and government officials are able to receive real-time farm status, as well as to carry out pest control program. Compared

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with the previously version of the system, various useful functions have been added into the proposed system, and its accuracy has been improved when measuring different parameters in the field. We believe that the proposed system provides a valuable framework for farmers and pest control officials to analyse the relation between population dynamics of the fruit fly and meteorological events. Based on the analysis, a better insect pest risk assessment and decision supporting system can be made as an aid to IPM programs against *B. dorsalis*.

Keywords: ICT, remote monitoring, pest control, agro-ecological monitoring, wireless sensor networks.

1 Introduction

The oriental fruit fly, *Bactrocera dorsalis* (Hendel), is one of the most economically important phytophagous insects around the globe [1–3]. There are nearly 5000 documented species of the fruit flies (family Tephritidae) distributed around the world, of which 148 species pose potential threats to the agricultural systems in Taiwan [4]. A female oriental fruit fly may lay about 1200 to 1500 eggs during her lifetime. It takes 14 to 24 days for the fruit fly to develop from egg to adult and it lives for up to 3 months. Such a growth rate allows the oriental fruit fly to complete about 8 to 9 generations per year. More than 150 species of fruit and vegetables, including those economic important ones, such as guava, peach, mango, and citrus, have been recorded as the host plants of the oriental fruit fly. The fruit is rotten and dropped if getting attacked, so the quality and quantity of infested fruit are declined. Thus, in Taiwan, the economic turmoil caused by the oriental fruit fly reaches up to 130 million U.S. dollars per year [5–9].

The oriental fruit fly was firstly recorded in 1912, and it mainly originated from Taiwan and Ryukyu Islands [10]. Due to quarantine failure, the fruit fly has spread to most of the countries or regions around the Asia-Pacific areas because of increasing activities in national/international trading since the past century [11–14]. Such problems further enhance the dispersal capability of the oriental fruit fly, and also result in more successive biological invasions by the pest [15]. For the protection of agricultural products, as well as for the protection of human health and the environment from misused pesticides, the government of Taiwan annually sets a budget of 5 million U.S. dollars to carry out Integrated Pest Management (IPM) programs in order to reduce the economic loss caused by the oriental fruit fly [16, 17]. The IPM is an integrated

approach that consists of a series of actions, including pest identification, risk assessment, threat prevention, and agro-ecological problem solving, without using a large quantity of chemical pesticide when agricultural systems are deployed. Attempts have also been made to investigate more favourable approaches to control the population of the oriental fruit fly, such as physical, biological [18, 19], integrated [19] and chemical [20] controls, sterile-insect [21, 22], male annihilation [23, 24], RNAi [25], and bait application [26, 27] techniques. Some studies also suggest that early resistance management programs should be initiated in order to restore the efficiency of pesticides and to reduce the growth of resistant strains [28, 29]. In some control programs, an additional investment in labour to count and record pest numbers may be worthy in surveying major pests in high value crop sites. As in Taiwan, a large number of monitoring stations have been set up [30, 31]. However, such a surveillance approach relies on manual measurement at a 10-day scale, and the data is often incomplete and inaccurate without dense temporal resolution and ambient data. Using such data to determine whether the oriental fruit flies are normally present or in an outbreak status may lead to a wrong conclusion. Nor can the data be used to analyse the factors that involved population dynamics of the oriental fruit fly, because the life cycle of the oriental fruit fly might be shorter than the survey interval in the summer. Furthermore, past studies have demonstrated that the ecology of the oriental fruit fly is influenced by the factors like temperature, solar illumination, rainfall, and different kinds of crops [32–38]. In order to have greater knowledge regarding the connection between these factors and the population dynamics of the oriental fruit fly, it is necessary to develop an automatic surveillance technique which can provide accurate, long-term, and up-to-the-minute data (e.g. meteorological data, population dynamics of pests, etc.) when monitoring a fruit farm. This new precision agriculture technique makes it possible to assess the risk of insect pest outbreaks in the fruit farm and arrange better pest control activities. Hence, the IPM programs can be greatly improved by the technique [39, 40].

1.1 Programs for Oriental Fruit Fly Control in Taiwan

Taiwan is an island with 36,000 square kilometres and a wide range of terrain. With warm climate and abundant rainfall, many types of fruit and vegetables grow profusely on the island, and several are indigenous to other countries. Unfortunately, up to 89 types of fruit and vegetables in Taiwan are the potential hosts of the oriental fruit fly. Female oriental fruit flies deposit their eggs in the pericarps, and then the larvae feed and grow inside the fruit. Pest

infestation not only causes severe economic damage by reducing both the production and quality of the fruit, but also impedes exports of fresh fruit due to quarantine restrictions imposed by other countries [5–9]. In the past decades, the male annihilation with poisoned attractant (i.e., methyl eugenol) was widely adopted by the government of Taiwan for its large-area control strategies against the oriental fruit fly. However, it is very difficult to achieve satisfactory control, since the oriental fruit fly is already widely distributed throughout the island with an extremely broad host range, including 29 non-economically important plants [3]. These plants are unworthy for growers but the government has to initiate costly pest control programs for them to prevent further spread of the oriental fruit fly to non-infested areas. Many protective strategies, including fruit bagging, net-house cultivation, and pesticide sprays, have been widely used by growers to protect their agricultural products against the oriental fruit fly. However, these methods are costly and require much manpower, and pesticide sprays could seriously affect the environment and human health.

Since 1994, the Taiwan Agricultural Research Institute (TARI) has published a pest information bulletin every 10 days regarding the population size and distribution of the oriental fruit fly in Taiwan, and the bulletins, serving as reference tools, are sent to fruit growers to take necessary action to control the population of the pest. The monitoring data and analysis reports in the bulletins come from more than 77 monitoring stations, each of which includes 9 spots equipped with fly traps that contain the attractant mixed with insecticides, and thus a total of 613 monitoring traps have been assembled and placed at major farm production regions where soils, climate, and environmental parameters vary [30, 31]. Such information is proven useful in identifying locations with high-density of the oriental fruit fly. However, without the aid of the automatic recording technology, the monitoring system relies on manual measurement at a 10-day scale without meteorological information. The data collection is often incomplete and requires much manpower and high management costs [7]. In addition, the long sampling interval makes the monitoring system not fully capable of assessing insect pest risks. Nor does the system send out warning messages regarding instant pest breakouts.

Recently, the Bureau of Animal and Plant Health Inspection and Quarantine (BAPHIQ) of Taiwan has launched a series of research projects to overcome the shortcomings of the manual pest surveillance methods. These projects focus on assisting IPM programs against the oriental fruit fly by (1) developing a remote sensing technique to monitor pest migration in selected areas; (2) avoiding unnecessary pesticide spraying to reduce the harm brought

to the environment and human health; and (3) improving the competitiveness and the economic diversification of locally grown fruits (Chang et al., 2010). Since 2000, the BAPHIQ and TARI have successfully organized 155 farmer associations to collaboratively participate in IPM programs to control the population of the oriental fruit fly. Furthermore, modern technologies developed in recent years have also been incorporated into pest control programs [19]. For example, the geographic information system (GIS) was used to visualize the acquired data and to assess the damage caused by the oriental fruit fly [41, 42]. In addition, a new type of protein bait, GF-120 [23, 43, 44], has been introduced to Taiwan since 2003 for female fruit fly density control from spring to summer [45]. Spraying GF-120 on the crops inside and outside orchards decreased the fruit damage ratio from 70% in 2005 to 15% in 2006, and the GF-120 spray also reduced the environmental hazard caused by chemical pesticides. These successful results have drawn much attention from foreign research groups that would like to learn from the Taiwan experience in pest control [46].

An IPM system is generally designed with three major components: inspection, identification, and control. In precision agriculture, the most important task of the program is to perform pest inspection and identification. A successful IPM program relies on frequently visual inspection and accurate pest identification. When the population of the pest reaches an unacceptable level, mechanical control methods are the first options to disrupt the breeding of the pest. The surveillance and control methods described above are still insufficient to guarantee a successful IPM program for two reasons. Firstly, monitoring the population of the oriental fruit fly at a 10-day scale provides very limited information to model the population dynamics of the pest. Secondly, applying biological bait and chemical pesticides should be considered as a last resort for pest control, since the method might affect local environments.

1.2 Historical Background on WSN-based Monitoring Systems in Taiwan

To yield solutions to the problems mentioned above, the National Science Council (NSC), TARI and BAPHIQ have cooperated with our research team at National Taiwan University (NTU) to develop a remote pest monitoring system targeted at the oriental fruit fly since 2006, 2009 and 2011, respectively. In 2008, the authors presented a prototype of the system that is able to provide precision agriculture services. It is able to automatically report the environmental conditions and the number of trapped pests in real-time [7].

The acquired data was stored in a database for further analysis. The prototype system has been deployed and tested in an experimental farm at the NTU campus, and the experimental results show that the system can effectively reduce the cost of labour and increase the effectiveness of IPM programs.

2 Overall System Architecture

Monitoring of the population dynamics of the oriental fruit fly was conducted by deploying the proposed agro-ecological monitoring system to the crop sites of interest. To increase the applicability of the monitoring system, since 2008 the prototype system has been extended to a large-scale, long-term and real-time agro-ecological monitoring system designed to monitor various types of pests. The monitoring system has been deployed to 20 crop sites that cover different terrain in Taiwan, and the system consists of 12 WSN-based monitoring stations (currently assembled by 163 sensor nodes) and 3 standalone monitoring stations. Detailed information regarding these monitoring stations is shown in Fig. 1.

The overall configuration of the proposed remote agro-ecological monitoring system is depicted in Fig. 1. The fundamental architecture of the monitoring system can be divided into three major layers: the front-end sensing layer, the telecommunication layer, and the data collection and analysis layer. The purpose of the front-end sensing layer is to acquire field data from the area

Figure 1 Conceptual architecture of the remote agro-ecological monitoring system presented in this study.

of interest. Two monitoring systems – a standalone monitoring station and a WSN-based monitoring station – are deployed in this study, and the detailed information regarding their configurations will be addressed in the following section. In the telecommunication layer, the sensing data measured by the sensors in the front-end sensing layer is organized into text messages for data transmission using the short message service (SMS) via GSM [47] which is virtually accessible to people from any populated areas in the world. Finally, in the data collection and analysis layer, the server built upon LabVIEW [48] receives the sensing data acquired from all monitoring stations via GSM. All historical data is stored in a MySQL [49] database for information retrieval and analysis by specialists via web services programmed by PHP [50]. The technologies used by the components in the infrastructure of the latter two layers are well-known commercialized technologies. Due to limited space, further discussion on these components is omitted, and the following discussion will mainly focus on the devices used in the front-end sensing layer, which make major contributions to agro-ecological monitoring. Designed for different field conditions and to meet farmers' demands, two types of sensing approaches are available to monitor the crop sites of interest. One is a standalone monitoring station, and the other is a WSN-based monitoring station.

2.1 Standalone Monitoring Station

The standalone monitoring station is an evolutionary version of the remote monitoring platform presented in our previous study [7]. Different from the preceding version, the standalone monitoring station is designed on the basis of an MSP430 microcontroller (MSP430FG4619 made by Texas Instruments, Inc.). It works alone in the monitoring area, and is equipped with a set of meteorological sensors, including temperature and humidity sensors (SHT71 with high measurement accuracies $\pm 0.4^{\circ}\text{C}$ for temperature and $\pm 2\%$ for relative humidity, made by Sensirion, Inc.). Moreover, it is also coupled with an automatic pest counting trap designed for the oriental fruit fly, a GSM module (Fastrack Supreme 10, produced by Wavecom Co., Ltd.), a GPS receiver (GM44, made by San Jose Navigation, Inc.), as well as a solar photovoltaic panel (its power rating is 20 W) and a battery (the battery voltage is 12 V with the energy storage capacity equal to 100 Ah). The design for the automatic pest counting trap will be discussed in detail later. Fig. 2 shows the external configuration and internal architecture of a standalone monitoring station deployed in Chiayi. The standalone monitoring station aims at capturing the event of the fruit fly crawling into the trap. The number of the fruit flies and

Figure 2 External configuration and internal architecture of a standalone monitoring station deployed in Chiayi.

real-time readings acquired from all meteorological sensors are sent to the back-end servers via GSM every 30 minutes.

2.2 WSN-based Monitoring Station

In addition to relying on single-point sampling using the standalone monitoring station, a WSN-based monitoring station is employed in this study to provide a unique, wireless, and easy solution to tackle distributive and multiple-point agro-ecological monitoring tasks over an area of interest with better spatial and temporal resolutions. Each WSN-based monitoring station is composed of a number of wireless sensor nodes and a gateway. The design and implementation of the wireless sensor nodes are addressed in the following section.

2.2.1 Wireless Sensor Node

In a WSN-based monitoring station, each wireless sensor node is made upon the foundation of a ZigBee transmission module (Octopus II, developed by NTHU). The ZigBee transmission module is coupled with an automatic pest counting trap, an 8051 microprocessor-based pest counting controller, an

infrared interrupter controller, a luminance sensor, temperature and humidity sensors, as well as a solar photovoltaic panel (its power rating is 20 W) and a small package battery (battery voltage is 12 V with energy storage capacity equal to 36 Ah). Fig. 3 shows the external configuration and internal architecture of a wireless sensor node and its peripheral devices located at the campus of the National Taiwan University. The wireless sensor nodes are deployed in the crop field of interest to measure the environmental conditions and the population density of the oriental fruit fly. Average distance between any paired sensor nodes is around 20 meters due to the limitation of low-power wireless transmission. All readings are sent to the gateway of the network via an ad-hoc mechanism. In addition, all measurements, including temperature, humidity, light intensity, rainfall, wind direction and pest numbers are used to analyse the correlation between ambient factors to the pest population dynamics.

Figure 3 External configuration and internal architecture of a wireless sensor node and its peripheral devices deployed at the campus of the National Taiwan University.

2.2.2 Wireless Gateway

Based on different power consumption requirements, two types of gateways are designed – MSP-based gateways and PC-based gateways. The MSP-based gateway is similar to the standalone monitoring station but without the automatic pest counting trap. The MSP-based gateway is equipped with a ZigBee transmission module (Octopus II, developed by NTHU) [51] such that it can collect all sensing data measured by the wireless sensor nodes in the agro-ecological monitoring network. Fig. 4 shows the external configuration and internal architecture of an MSP-based gateway in the network (No. 21) deployed in Pingtung. In contrast, the PC-based gateway is built upon the basis of a mini-laptop personal computer (PC), and it offers a broad range of functions designed and optimized for agro-ecological field surveillance applications. A PC-based gateway consumes more power than an MSP-based gateway, so the power for the former is supplied by commercial electricity. Each PC-based gateway is equipped with a professional weather station (WS-2308, made by La Crosse Technology, Ltd., which provides readings of an anemometer, a wind vane, a pluviometer, indoor/outdoor temperature/humidity sensors, and an atmosphere pressure meter), a ZigBee transmission module (Octopus II, developed by NTHU), as well as a GSM module (Fastrack Supreme 10, produced by Wavecom Co., Ltd.) and a GPS receiver (GM44, made by San Jose Navigation, Inc.). Fig. 5 shows the external

Figure 4 External configuration and internal architecture of a MSP-based gateway in the network (No. 21) deployed in Pingtung.

Figure 5 External configuration and internal architecture of a PC-based gateway in the network (No. 19) deployed in Changhua.

configuration and internal architecture of a PC-based gateway in a network (No. 19) deployed in Changhua. The purpose of a gateway is to manage wireless sensor nodes in a network, and to collect information measured by the nodes. The gateway also measures local environmental conditions using its own high precision meteorological sensors, and then periodically sends the readings acquired from the entire network to the back-end servers via GSM every 30 minutes. Detailed information regarding the sensor validation and system-level experimental results, please refer to [52].

3 User Survey Results

Currently, the proposed agro-ecological monitoring system has 24 registered users, and they are either the owners of the orchards or pest control officials from the experimental farms listed in Table 1 of the original paper. Among these users, 14 of them (58.3%) are senior fruit growers, and the rest (41.7%) are pest control officials with the government. A closer review of the registered

user profiles revealed that 25%, 58.3% and 16.7% of the users have participated in this project for at least 2, 3, and 4 years, respectively. In addition, the user age profile showed that increasing use of the system is associated with user's age, to the point where 58.3% of the users were older than 50 years old (Fig. 6). The educational background of the registered users reveals that 45.8% of the user received bachelor degrees or higher, which is similar to the proportion of the users who serve as pest control officials (Fig. 7). Furthermore, 29.1% of the registered users are female, and the rest 71.9% are male.

In September, 2011, all registered users – including fruit growers and pest control officers – are required to complete a survey in order to evaluate the satisfaction of using the proposed system. In the proposed system, the monitoring data collected by each monitoring station was sent back to the back-end servers for storage and analysis. The analytical results of hot-spot analysis [7, 53–55] and pest density forecasting are provided by the web-based decision support program of the proposed system. First of all, the authors were wondering if the deployment of the wireless sensor nodes in the farms may cause inconvenience to the daily operations of the fruit growers in the ordinary farms (not experimental farms). However, the survey results show that 57.1% of the fruit growers stated that the deployment of the system did more good than obstructing the daily farm operations, and that the rest thought that the wireless sensor nodes did not disturb their daily operations.

Figure 6 Age class distribution of the registered users in the user survey.

Figure 7 Education background of the registered users in the user survey.

Furthermore, 91.6% of the users found that the results of hotspot analysis is helpful for the farmers to identify potential breeding location of oriental fruit flies, and 95.8% of the users agreed that the pest density forecasting service provides a great help to prevent pest outbreaks (Fig. 8).

Additionally, the proposed system allows users to access to the sensing data via three different ways: short-message service (SMS), smartphone application, and computer web browser. Users' familiarity with the Internet-capable devices and interface convenience are two primary factors to attract farmers and pest control officers to make the best use of the proposed system. Among the users, 47.1% preferred to receive real-time sensing data and alert messages via SMS since more than 70% of them were familiar with ordinary cell phone, and they also thought that using ordinary cell phone was a less complex way to acquire information from the proposed system. Computer was the second preferred platform (41.2%) because about 57.1% of the users reported that they were familiar to personal computers, while 64.3% claimed that they felt comfortable to access to the web-based decision support program via personal computers. Surprisingly, only 11.8% of the users were willing to use smartphone as the medium to access to the monitoring data provided by the

Figure 8 User feedback to the question of what function provided by the system changes users' management strategy.

proposed system, because there was a significant portion of the users (71.4%) who did not have a mobile smartphone yet, no wonder why using a smartphone to acquire pest-related information was not a preferred way for the users (Figs. 9–11).

With the data and information provided by the web-based decision support program, the ways through which the proposed system supports farm management practices were – avoiding unnecessary pesticide sprays (85.7%), using pesticide at the right moment (78.6%), providing a clarified IPM schedule (64.3%) and strategy (50%), and offering a low-cost monitoring platform (21.4%) (Fig. 12). In terms of who should pay for the proposed system after the development grants have expired, 58.3% of the users suggested that the central government should continue to sponsor the project, 25% and 16.7% indicated that local authorities and farmers' association should support the project, and 16.7% felt that part of the funding should be supported through user fees (Fig. 13). The survey result indicated that the reasonable installation fee would be around 1550 USD per station if the users had to pay for the installation of a monitoring station (with 6 to 8 wireless sensor nodes), and the average user fees suggested in this survey was around 25 USD per user/month. However, all of the farmers clearly stated that the installation fee should be covered by the government.

Figure 9 User feedback to the question of what device is preferred by users to access to the sensing data.

Figure 10 User feedback to the question of how much familiarity users have with Internet-capable devices.

Figure 11 User feedback to the question of how convenient the interface provided to users is.

Figure 12 User feedback to the question of the different ways in which the proposed system have helped users manage their orchards.

Figure 13 User feedback to the question of who should financially support the proposed system after the development grants have expired.

4 Conclusions

In this study, an agro-ecological monitoring system deployed in 20 different fruit orchards to monitor local meteorological and pest information is presented. Different from the prototype system in our previous paper [7], wireless sensor networks are integrated into the system to provide large-area monitoring capability. The proposed system contains three major layers: front-end sensing layer, telecommunication layer, and data collection and analysis layer. In the front-end sensing layer, there are two types of monitoring stations that were deployed, one is standalone monitoring station formed by an MSP-based sensing device, and the other is WSN-based monitoring station constructed by a number of wireless sensor nodes and a gateway. Both types of the stations are able to provide periodical measurement of meteorological conditions and pest information every 30 minutes. Meteorological and pest information is transmitted to the servers in the data collection and analysis layer via the telecommunication layer. All sensing data is open for public access via the Internet.

Comparing with our previous system [7], several improvements have been made to the proposed system. The previous system was a MSP-based monitoring device that is able to transmit the sensing data to a remote database via GSM platform. In this paper, a novel system is presented. Wireless sensor network technology is integrated to allow the farmers to investigate the behaviour of the oriental fruit fly using high temporal and spatial resolution data obtained by the system. The automatic pest counting trap is redesigned in order to improve the pest counting accuracy, and the evaluation results have been summarized in [55]. These improvements guarantee the practicability of the proposed system that can be deployed for long-term agro-ecological monitoring tasks in wild fields.

In order to achieve real-time system management, a remote control interface has been implemented to allow system administrators to remotely reconfigure the parameters of the proposed system via the Internet. Furthermore, a web-based decision support program is available for farmers and pest control officials to perform data inquiry, analysis, and receiving newly announced pest control tactics using any Internet-connected devices (e.g. computers, laptops, or smart phones) virtually from anywhere. Based on the feedbacks obtained from the user survey, the proposed system poses a great potential for the farmers and pest control officers to take proper precautionary actions to prevent possible pest outbreaks from getting out of control.

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