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RhinoCam IoT- a Distributed Trap-Surveillance System for Coconut Rhinoceros Beetle Connected to Cellular Network

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ABSTRACT. *A biological invasion of the Coconut Rhinoceros Beetle (CRB; Oryctes rhinoceros) to the island of Oahu was discovered in late 2013, posing a major threat to iconic palm trees on the island and potential for accidental export to other Hawaiian Islands or to commercial palm plantations in California. Surveillance and physical trapping of CRB in remote, undeveloped areas is a critical part of the program for containment and eradication efforts, and continuous surveillance near ports of entry is especially important to rapidly eliminate incipient populations. Here we report on the deployment of autonomously powered custom electronic surveillance systems with a camera and digital microphone, mounted in arrays of panel traps for CRB and communicating data through cellular network. The system enables continuous or high-frequency monitoring of traps, reducing personnel and transportation costs for manual trap checking, allowing faster response to new infestations, and better understanding of the diurnal behavior patterns of CRB. As we more widely deploy the system the accumulated images can also be used to train improved machine vision models for automated classification of trap contents and alert systems for new trap catches.*

Keywords. *Insect Pest monitoring, Low-Cost Surveillance, Remote Pest Control, Trap Camera Boards*

Introduction

In the Pacific region, Palms are one of the most important trees. They are cultivated as a cash crop for nuts, oil, and timber and also serve aesthetic purposes, cherished by islanders and tourists. Coconut Palms are known as the tree of life on small islands, providing income, food security, and resources for oil, soup, baskets, garments, and habitation. (Marshall et al., 2016). However, currently, the Coconut Rhinoceros Beetle (CRB), Oryctes rhinoceros, poses a significant threat to coconut and oil palms in the Pacific region (Marshall et al., 2016). CRB was first discovered near Pearl Harbor, Oahu, by the Hawaii Department of Agriculture (HDOA) in late 2013 ("Coconut rhinoceros beetle," 2016). Adults of this invasive beetle feed on a variety of host plants, including palms, bananas, and sugar cane. As the name of the beetle implies, the preferred host is the coconut palm (Cocos nucifera). CRB feeding results in large boreholes near the crown, introducing a route for infection by a variety of pathogens. CRB damage can easily be recognized by characteristic cuts and notches on fronds as they grow out, and in cases of severe damage, the tree can be completely defoliated and die.

Integrated Pest Management (IPM) is an environmentally sustainable framework that utilizes a data-driven, eco-conscious approached, and incorporates action thresholds to enact targeted pest control (Radcliffe et al., 2009). It is deemed as a mitigation tool for the growing invasive species impact worldwide (Diagne et al., 2021). Moreover, IPM is used for the early detection of pest outbreaks through utilizing effective monitoring techniques (Barzman et al., 2015). Utilizing pheromone-based trapping is one of the pillars of IPM, and it is used to monitor and estimate targeted pest populations.

Pheromone-based traps are also used as a monitoring method for CRB in different Pacific islands (Paudel et al., 2023).

To identify the beetle presence and inspect the infestation status, more than three thousand pheromone bait CRB panel traps are installed throughout the island of Oahu by the CRB Response team, each visually inspected at regular intervals (approximately once or twice per month, depending on location) by human operators. However, visual inspection is laborious, expensive, and time-consuming. Also, after field visits, manual data logging and processing are done to estimate the pest population density, which is tedious and might delay timely decisions for pest control. This problem is not specific to CRB. Traditional pest monitoring methods rely on manual, periodic visual inspection of isolated traps, and according to a study by (Preti et al., 2021), classic pest monitoring methods suffer from limited temporal and spatial resolution due to its manual monitoring nature. They are cumbersome, slow, have elevated cost implications as the invasive pest grows its territory, and do not provide real-time information on the distant traps, which is a crucial part of IPM early detection and control strategies.

There is a growing research interest in automating pest monitoring technologies, especially using camera-equipped traps. This is due to camera sensors and off-the-shelf camera boards becoming more affordable (Preti et al., 2021). To transmit the captured trap images to the server, a camera board uses communication network gateways. For indoor pest monitoring purposes, especially the greenhouses, researchers typically use the onboard Wi-Fi modules of the popular off-the-shelf camera boards, like Raspberry Pi single-board computers, and connect them with a local Wi-Fi access point inside the greenhouse in order to send the data to the server (Chou et al., 2023).

However, for outdoor invasive pest monitoring, Wi-Fi is less reliable, and solutions relying on Wi-Fi for connectivity have a short range, especially in outdoor environments. Additionally, single-board computers, like Raspberry Pi, generally consume energy continuously; hence, large batteries (Bjerge et al., 2021) or local energy generation (i.e., PV panels) is required if these boards are deployed "off-grid". The size of these systems can also require more cumbersome and expensive mounting hardware. In implementations that do not use a solar panel, battery swap becomes necessary after a few days (Droissart et al., 2021), which for remote monitoring purposes can add to labor costs and defeat the purpose of being remote cameras.

To address these challenges, in this study, we propose an energy-efficient automated remote camera board (RhinoCam) using a low-power, low-cost microcontroller unit (MCU) and a data management ecosystem for continuous or high-frequency monitoring of CRB (or any migratory invasive pest) to facilitate IPM control operations.

Materials and Methods

RhinoCam Hardware design

Our first iteration of the camera board used a low-cost, commercially available embedded camera system (ESP32-CAM) mounted onto a custom PCB designed for power/battery management and to enable system programming and debugging. We used this microcontroller system as it is robust, reliably cycling through the code, including intermittently waking up from low-power deep sleep mode to record and share images of the scene. Our first prototype with ESP32-CAM transmitted images intermittently from a restricted area on the UH Manoa campus (a fenced-in area behind the AEI building at the UH Manoa campus) to a static image gallery website for many weeks. When not actively recording and transmitting images, the microcontroller was programmed to stay in a low-power deep sleep mode.

However, after deploying two of these early prototypes outdoors, at a site at Iroquois Point operating through a nearby Wi-Fi access point, the boards stopped sending images after a few days. On further investigation, we discovered that the Wi-Fi connection was not reliable, and the battery was getting drained by continuously trying to make a connection to the mentioned access point. To address this issue and increase the coverage area of our remote systems without the need for a nearby access point for each camera board, we developed an alternative approach through a different internet gateway, namely, a low-cost, low-power cellular modem that connects to the cellular networks. New versions of the camera board, RhinoCam, incorporated this cellular modem.

Our RhinoCam board consists of several modules: power regulation, the camera, microphone, file storage, and cellular modem modules. The system uses the most recent generation of the ESP32 microcontroller (Espressif Systems, Shanghai, PRC), ESP32-S3, on a module (ESP32-S3-WROOM-1U-N16R8) with embedded flash memory and pseudo-static RAM (PSRAM). The ESP32-S3 has a large number of highly versatile general-purpose input/output (GPIO) pins to support data acquisition (from the OV2640 camera module and digital microphone), peripheral memory storage and access, data transmission (through the SARA-R422M8S cellular modem module) and peripheral control (i.e., for a white LED).

Figure 1. RhinoCam view

For the power regulation module, we use an efficient buck-boost regulator and a lipo battery tracking charger chip to charge lipo with solar panels. For the Camera module, we use the OV2640 (OmniVision Technologies, Santa Clara, CA, USA) Camera system, a low-cost camera module with configurable sensor image resolution in the software based on the required resolution. Moreover, we added a White LED for illumination of the scene at night (and potentially for enhanced attraction of CRB into the trap cup). The microphone module is ICS 43432, a 24-bit I2C microphone with a MEMS sensor ("ICS-43432 Datasheet | TDK," n.d.).

The SARA R4 series of modems (u-blox, Thalwil, Switzerland) are multi-band LTE-M / NB-IoT / EGPRS cellular modules with multi-regional (around the globe) coverage frequency bands("SARA-R4_DataSheet_UBX-16024152.pdf," n.d.). LTE-M is a low-power wide-area (LPWA) air interface that connects IoT devices with medium data rate communication. The SARA-R422M8S module, a member of the SARA-R4 cellular modem family, can communicate with both LTE-M and NB IoT technology standards and includes an integrated GNSS chip("SARA-R42-Application-Development_AppNote_UBX-20050829.pdf," n.d.). We opted to use LTE-M for communication, which connected quickly using a Cat-M sim card (AT&T, Dallas, TX, USA) and efficiently shared images through the network even up to the 2 MB resolution available on our imaging sensor.

For energy Management, a battery charging system and an energy-efficient buck-boost regulator is used to operate the 3.3 V microcontroller and cell modem from a compact 2000 mA-hr LIPO battery and additional regulation for peripheral low voltage sensor systems (imaging system and digital microphone).

The power consumption on the board varies depending on which hardware is powered and what tasks are being performed. To make the board as efficient as possible, we have programmed the system to turn off power to the cell modem and, disable the voltage regulator for peripheral sensors, and put the microcontroller into deep sleep mode whenever active surveillance and communication is not required. This is an advantage of using an MCU compared to a single-board computer like Raspberry Pi for remote locations, making our MCU-based camera board energy sustainable.

RhinoCam Software Design

We have programmed the RhinoCam camera Board to retrieve the time from the cellular tower after it connects to the cellular network. If it's after sunset, the White LED turns ON, an image is captured, and the GPS antenna searches for geolocation. RhinoCam sends this data to the cloud server and goes to a one or two-hour deep sleep.

Results and Discussion

We have installed several dozen commercially assembled RhinoCam boards on CRB panel traps at different locations across the island of Oahu to evaluate the energy sustainability of the RhinoCam trap camera boards. The RhinoCam board is compact and uses a lightweight Lipo battery and Solar panel, as shown in Figure 2. This means the trapping system does not require any additional mounting gear, and its functionality is not affected. The camera boards have been sending images reliably for the past few months to our server, demonstrating their effectiveness for remote pest monitoring, eliminating the need for battery swap or running out of energy.

Figure 2. RhinoCam installed at trap cup of CRB Panel trap connects to a cellular network at programmed time intervals.

After we deploy the camera boards, the recorded images are sent to our cloud server. We use the Flask web server framework ("Welcome to Flask — Flask Documentation (2.2.x)," n.d.) to implement a dynamic website using a cloud-based Linux server (Linode). A Linux server and programming with a functional TCP server ("Socket Programming HOWTO — Python 3.11.0 documentation," n.d.) to accept incoming images and a Web server using Flask to implement a dynamic user-facing website are necessary components to monitor CRB from remote trap images on our remote server. The TCP server constantly listens on a certain port of the server for a new camera board TCP client connection and then shows the saved images to the human users through a Flask HTTP/HTTPS web server.

Using the Flask web server framework, we now have a dynamic website controlled by a custom Python script we modified for our application. Also, we were able to process the image data and sort the captured images by date. Also, use Nginx("Advanced Load Balancer, Web Server, & Reverse Proxy," n.d.), a fast, modern web server with more functionalities, like being a load balancer, if we need more servers to capture the client camera board images.

Currently, in our Flask Image gallery, Figure 3, the images are sorted in reverse chronological order and displayed on the web page, with trap number, date, time, and geographical coordinates (latitude/longitude).

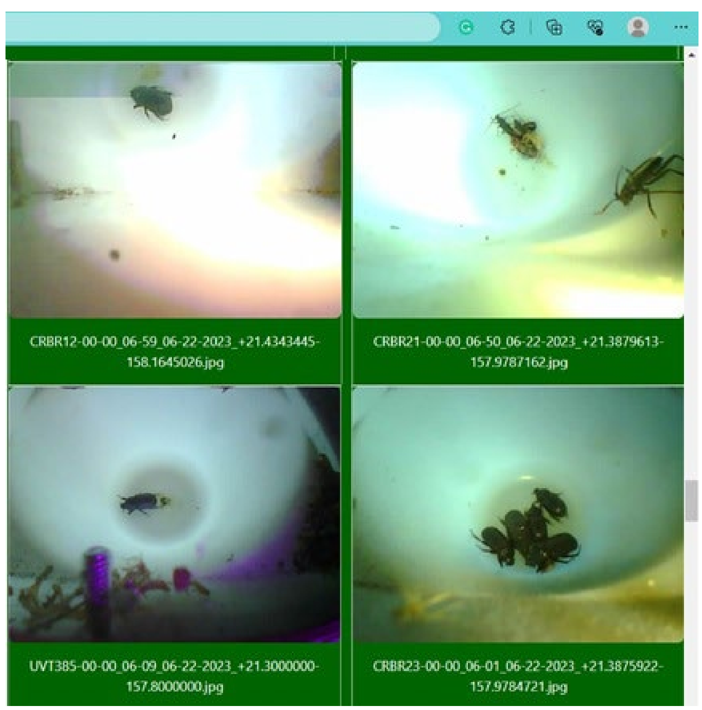

Figure 3. Image gallery showing each image with its file name (shows the date, time, trap number, latitude, and longitude). All recently captured images are sorted by the most recent capture time on the Flask web server.

Conclusion and future work

Over the first six months of 2023, up to the July 2023 ASABE presentation, we have successfully deployed several dozen RhinoCam boards, which have transmitted more than twenty thousand images to our cloud server, where images were observed daily on the Image gallery of the web server. These boards cover distant locations on Oahu and have recently captured and transmitted images from Kauai Island, where a new invasion was discovered in June 2023. The images were observed daily on the Image Gallery of the web server, providing hourly or custom time trap image data to the headquarters of the CRB response team at Oahu, hundreds of miles away. By monitoring our web server daily for the most recently captured images, the CRB Response team was able to achieve early detection of a few CRBs on Kauai Island, which assists with rapid and effective pest control decisions.

In this study, we demonstrate the durability and energy-sustainability of using a low-power modem and low-cost, low-power microcontroller in designing a remote camera board for remote monitoring of migratory invasive pests like CRB.

Future Work

On the server, we have preliminary results for running a CRB identification computer vision model, which can automatically identify beetles on the captured images, count the number of beetles in each image, and generate an Excel sheet report for the CRB response team. Our goal is to label more trap data for a precise CRB identification model, automate the reports (catch numbers and distribution maps), and design an enhanced RhinoCam v2 (5G modem, IMU to detect fallen trap, UV LED).

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