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A RESEARCH VISION

Intelligent System for Integrated Pest Management in Agriculture: An electronic approach to Sustainable Farming

Sistema inteligente para el manejo integrado de plagas en cultivos: Un enfoque electrónico para una Agricultura Sostenible

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ABSTRACT

Pest management is an essential activity in agriculture to ensure optimal crop yield and avoid threats. In this context, integrated pest management is presented as a strategy to effectively manage the crop, turf or indoor space, preventing the proliferation of pests. This paper introduces a novel approach to integrated automatic pest management by combining the rational behavior of intelligent agents and Internet of Things (IoT) technologies. The design and implementation of a cyber-physical system based on the concept of an Intelligent Agent for integrated pest management in crops is presented. The system allows the acquisition of real-time information through electronic traps connected to a wireless sensor network based on LoRaWAN™, a low-power wide area network protocol built on the LoRa™ radio modulation technique.

The developments of the communication systems, hardware and software are detailed, and monitoring is addressed both on-site or on-farm remotely from other locations through a central station connected to the Internet. The developed system enables efficient spatiotemporal monitoring of pests and insects to identify and locate infestation hotspots in the field. This precise and focused detection capability reduces the need to apply treatments across the entire area, optimizing the use of resources and minimizing environmental impact. The implementation of this cyber-physical system represents a significant advance in integrated pest management, offering a technological and sustainable solution to improve agricultural productivity and contribute to more efficient and responsible agriculture.

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RESUMEN

El manejo de plagas es una actividad esencial en la agricultura para garantizar el óptimo rendimiento de los cultivos y evitar amenazas. En este contexto, el manejo integrado de plagas se presenta como una estrategia para administrar de manera efectiva el cultivo, el césped o el espacio interior, previniendo la proliferación de plagas. Este artículo introduce un enfoque novedoso para el manejo automático integrado de plagas mediante la combinación del comportamiento racional de agentes inteligentes y las tecnologías de Internet de las Cosas (IoT). Se presenta el diseño e implementación de un sistema ciberfísico basado en el concepto de Agente Inteligente para el manejo integrado de plagas en cultivos. El sistema permite la adquisición de información en tiempo real mediante trampas electrónicas conectadas a una red de sensores inalámbricos basada en LoRaWAN™, un protocolo de red de área amplia y baja potencia construido sobre la técnica de modulación de radio LoRa™.

Se detallan los desarrollos de los sistemas de comunicación, hardware y software, y se aborda el monitoreo tanto en sitio o en granja de forma remota desde otras ubicaciones a través de una estación central conectada a Internet. El sistema desarrollado, posibilita un monitoreo espacio-temporal eficiente de plagas e insectos para la identificación y localización de focos de infestación en el campo. Esta capacidad de detección precisa y focalizada reduce la necesidad de aplicar tratamientos en toda el área, optimizando el uso de recursos y minimizando el impacto ambiental. La implementación de este sistema ciber-físico representa un avance significativo en el manejo integrado de plagas, ofreciendo una solución tecnológica y sostenible para mejorar la productividad agrícola y contribuir a una agricultura más eficiente y responsable.

1. Introduction

Integrated Pest Management (IPM) involves the application of several methods to control insects, pathogens, and weeds, combined with monitoring to reduce unnecessary pesticide applications and ensure optimal crop yields by preventing threats that could affect agricultural production [1]. The purpose of IPM in agriculture is to reduce pest levels below the threshold at which they would cause economic damage to crops through an ecological approach that combines diverse strategies and management practices to minimize pesticide use [2]. Although IPM can include the use of pesticides, its main components clearly distinguish it from typical pest control practices that rely solely on trapping and poisoning [3]. These key components include inspection and monitoring, identification, threshold level establishment, implementation of two or more control measures, measurement and evaluation [4].

The increase in pesticide resistance, pest adaptation, and climate change are just some external challenges IPM faces. A strategy to address these challenges and move towards a more sustainable and effective crop protection system is the use of emerging technologies with innovative perspectives [5, 6]. This paper introduces automated integrated pest management with electronic traps that combine the rational behavior of intelligent agents [7, 8, 9] with Internet of Things (IoT) technologies using Wireless Sensor Networks (WSN) [10-17].

IoT technologies is currently one of the most popular topics, where sensors and smart devices enable the collection and data communication. In IoT, one of the main concepts is wireless sensor networks, in which information is collected from all sensors in a network characterized by low energy consumption and a wide communication range [18-21].

Agriculture plays a fundamental role in providing food for the growing global population. However, it faces several challenges, including effectively managing pests that can decimate entire crops and threaten food security. Traditional agriculture has relied on the massive application of pesticides, which is not only costly but also hurts the environment and human health. Moreover, the lack of real-time information on field conditions and pest presence further complicates decision-making. Therefore, the primary motivation of this study is to provide reliable information to farmers for decision-making through insect counting and to reduce pesticide consumption while increasing productivity in agricultural plantations.

The objective of this work is to address this issue by introducing an integrated pest management system based on intelligent agents and IoT technology. To this end, an architecture is proposed to monitor the presence and count of the fall armyworm (*Spodoptera frugiperda*), which primarily affects maize and cereal crops in the eastern plains of Colombia [22]. This approach will allow farmers to monitor and manage pests more efficiently, minimizing pesticide use and maximizing crop productivity. The study focused on combining two key elements: the behavior of intelligent agents and IoT connectivity through a wireless sensor network [19, 20].

This system collects real-time pest information in a crop field through electronic traps connected to a wireless sensor network based on LoRaWAN™, a low-power, wide-area network protocol that uses the LoRa™ radio modulation technique [23-27]. Considering these factors, the typical architecture of an IPM system can include a system that monitors insects in the crop using wireless sensor networks and the IoT to finally send an inspection report to the end user. With the reported information, the end user (farmer) can more efficiently schedule pesticide applications on the crops.

Currently, agriculture 4.0 is a strategy that uses information technology to improve agricultural quality and production. It has been demonstrated that wireless sensor networks play a significant role in applying digital technologies in the agricultural sector [12]. These networks enable real-time data collection on various agricultural parameters and variables, such as environmental and climatic conditions, and in this case, pest presence, providing critical information for data-driven decision-making [14].

Thus, the WSN use in agriculture has proven effective for monitoring environmental conditions, preventing unnecessary pesticide use, and improving productivity [15]. However, challenges have been identified in implementing these networks in agricultural environments, such as energy optimization, efficient communication protocol choice, transmission distances, and network scalability [16, 17].

This article is structured as follows: Section 2 examines the experimental crop characteristics where the IPM system is implemented. Additionally, it introduces the proposed architecture of the intelligent IPM system, the electronic traps structure, and the features of the LoRaWAN™ wireless sensor network [25, 26]. Section 3 outlines the experimental setup of the IPM system, detailing the configuration and installation of electronic traps and LoRaWAN™ sensors for real-time data collection. The processing performed for insect recognition and counting is discussed, and the results obtained from the data collected throughout the study are presented. Finally, based on the analysis of the results, it is concluded how the intelligent agent has contributed to decision-making related to pest control and the effectiveness of LoRaWAN™ as a communication platform in agricultural environments.

2. Materials and Methods

This study was conducted at the facilities of the Universidad de los Llanos and the Libertad Research Center of the Colombian Corporation for Agricultural Research – AGROSAVIA, located at kilometers 12 and 17 of the Villavicencio - Puerto López road, Meta Department, Colombia. The climatic characteristics of the region include an average temperature of 26°C and an annual average precipitation of 2,933 mm.

The IPM system was tested on a pilot corn crop infested with the fall armyworm (*Spodoptera Frugiperda*), a severe pest that damages key cereal crops like maize, rice, sorghum, and cotton, as well as various vegetables, affecting food security. The fall armyworm feeds on leaves, stems, and reproductive parts of plants and originates from tropical and subtropical regions of the Americas [22].

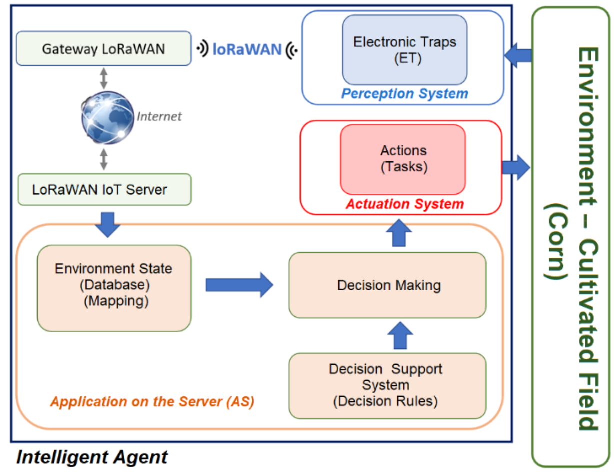
2.1. Intelligent System for Integrated Pest Management (IPM) in Crops

The developed system in this project consists of a network of smart electronic traps designed to count fall armyworms (*Spodoptera Frugiperda*) at specific locations in the field and transmit reports to a central station, which are then forwarded to an IoT web service. This study refers to the data acquisition, processing, and transmission system to the central station for visualizing pest counts. Future work will address decision-making and field actions. The perception system utilizes a network of electronic traps (ET). These traps can determine the insects population attracted by a pheromone and trapped on weather-resistant sticky paper.

At user-defined intervals, images of the trapped insects are captured and processed using image processing techniques to determine the number of moths trapped. The insect count data from each trap is sent to a LoRaWAN™ Gateway, which then forwards it to a LoRaWAN™ IoT Server. The information is collected via a web application, mapped, and displayed on internet-connected devices (Figure 1). With this data, managers, agronomists, or researchers can analyze pest behavior and establish decision rules for field actions.

The intelligent agent development integrates several subsystems, which will be described in terms of their software and hardware requirements. Initially, the hardware specifications for implementing the electronic traps are presented. Next, the software used for data acquisition and processing is discussed. Finally, the requirements for the data transmission system and web services are outlined.

Figure 1. Intelligent Agent Architecture for IPM.



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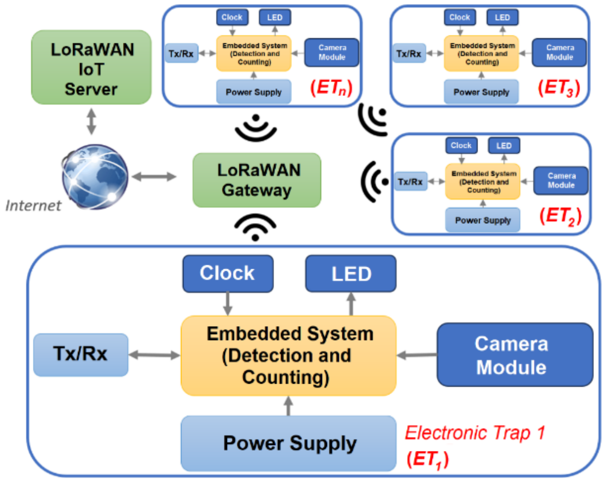
2.2. Electronic Traps (ET)

To ensure the scalability, modularity, and reproducibility of the electronic traps (perception system), low-cost electronic components readily available in the Colombian market were used. Each electronic trap is made up of a 12V rechargeable battery, a 10W solar panel, and a power regulator to ensure energy supply in an open field. The processing unit is a Raspberry Pi® Zero W (*Raspberry Pi Foundation*). For wireless communication, LA66 LoRaWAN™ modules (*Dragino Technology Development Co. LTD*) are used. The LA66 modules can cover distances of up to 20 km, depending on the antenna type used, with an operating voltage between 1.8V and 3.7V and a frequency range from 150 MHz to 960 MHz.

Each ET includes a second-generation Raspberry Pi® camera (Version 2) equipped with the Sony Exmor IMX219 sensor capable of capturing 8MP images (*Spectrum Technologies, Inc., Aurora, IL, USA*). For field operation, a clock for the Raspberry Pi® and an LED for illuminating the area where moths and worms are trapped are required (Figure 2).

Figure 2. Electronic Traps Architecture.



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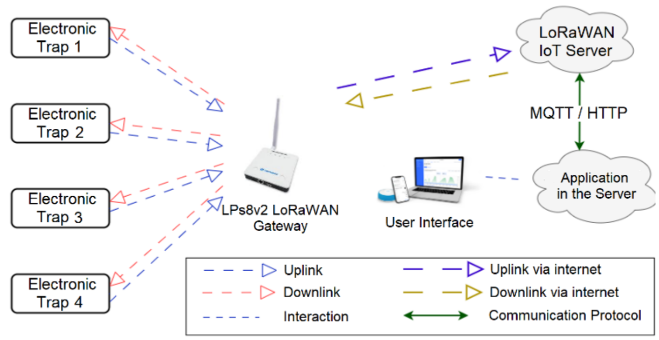
Two techniques were implemented for insect counting using image processing. The first technique involved acquisition, enhancement, restoration, color processing, morphological processing, segmentation, representation, and concluding with object description and recognition. The second technique employed convolutional neural networks (CNN) to detect and count the insects. This study presents the results of the first strategy, while the comparison and performance evaluation of the methods will be discussed in other publications

2.3. LoraWAN™ Network

As shown in Figure 3, the electronic traps transmit their data to a LoRaWAN™ Gateway - LPS8-v2 (*Dragino Technology Development Co. LTD*), which, along with the electronic traps, forms the wireless LoRaWAN™ system. This Gateway receives the data from the traps and sends it to *The Things Network* console, which is a LoRaWAN™ IoT server. Information from this server can be accessed through a web application that allows for the visualization and download of the collected data. The IoT server, the server application, and the user interaction system correspond to the IP Network Base in WAN/WiFi™ or 4G/5G.

Figure 3. LoRaWAN™ network architecture.



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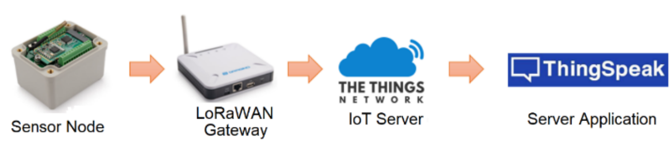
3. Results Analysis

The experimental setup for pest monitoring in the proposed IPM system was configured according to the requirements, and the electronic traps (ETs) were installed in the pilot crop. The ETs (Sensor Modules) send the measured data to be transmitted wirelessly by the LoRaWAN™ Gateway using the LoRa™ modulation scheme to the server application, as illustrated in Figure 4.

Figure 4. WSN and IoT System Implementation.



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The performance of the electronic trap for detecting the fall armyworm (*Spodoptera Frugiperda*) in maize was installed and configured as required. The acquisition and wireless transmission of insect count information and its web visualization were satisfactory.

Figure 5. Components of the electronic trap.

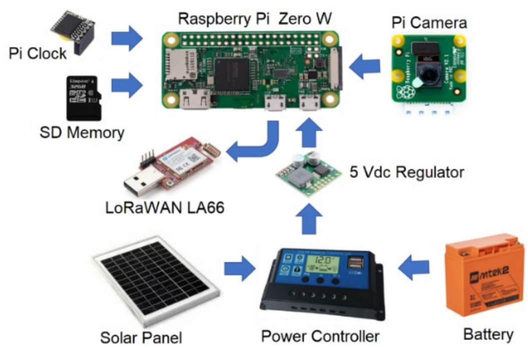

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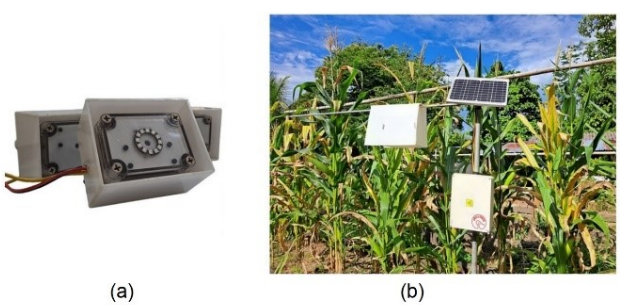
Figure 5 shows the schematic diagram of the electronic trap's components arrangement implemented in the field, as explained in section 2.2. Figure 6 shows the field implementation of the ETs for data acquisition. As observed in Figure 6a, the trap components were integrated into a single device with environmental protection against rain, humidity, dust, and temperature. Figure 6b presents the trap implementation with the photovoltaic power supply system.

Figure 6. Implementation of insect traps in the maize crop.



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The detection and counting algorithms were developed in Python™ 3. The OpenCV library was used for image acquisition and processing. Figure 7a illustrates an example of fall armyworms trapped on the adhesive paper of the electronic trap, and Figure 7b details the results of image processing for detection and counting using Python™'s OpenCV, employing morphological and segmentation operators. It shows how the detection of contours representing insects leads to the recognition and counting of the trapped moths.

Figure 7. Recognition and counting of moths and worms in the electronic trap.

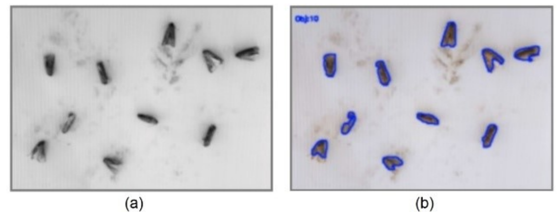

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Figure 8 shows the configuration screenshot of the LPS8-V2 Gateway modem in the frequency bands of the AU915Mhz plan: AU915, FSB2 (915~928 Mhz), via WiFi™. This modem is responsible for acquiring data from the sensor nodes or traps installed in the field.

Figure 8. Configuration of the LPS8-V2 Gateway.

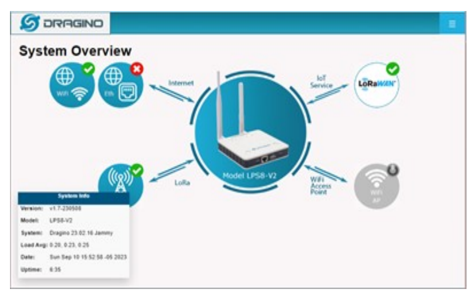

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Figure 9 describes the creation of the Gateway within *The Things Network*, named *FarmTechnology-Unillanos*. Several applications can be created for this Gateway. For this project, the *Spodoptera* Traps application was created and linked to the four ET nodes, as shown in Figure 10. The Gateway functions as a bridge between the end nodes and the LoRaWAN™ network core. The registration and creation of the Gateway and nodes were carried out manually using *The Things Network* (TTN) console, a free, decentralized, open global IoT network, by entering the configuration parameters: Gateway ID, Gateway EUI, and frequency plan, among others.

Figure 9. Creation of the Gateway in The Things Network.

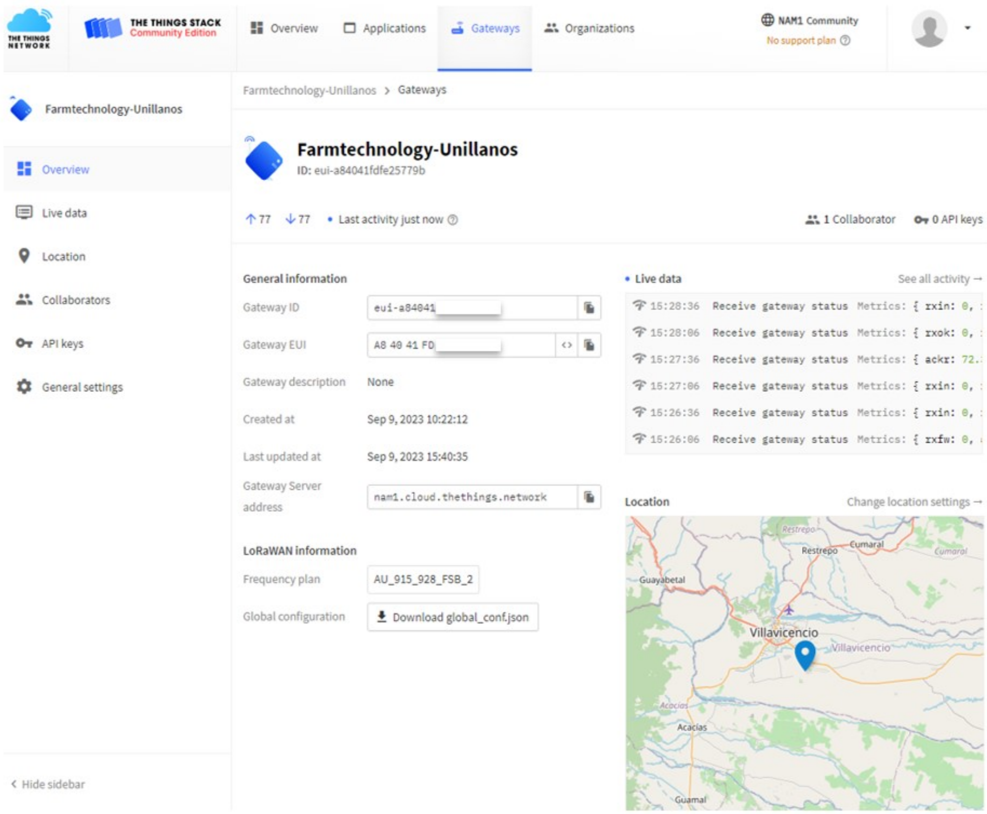

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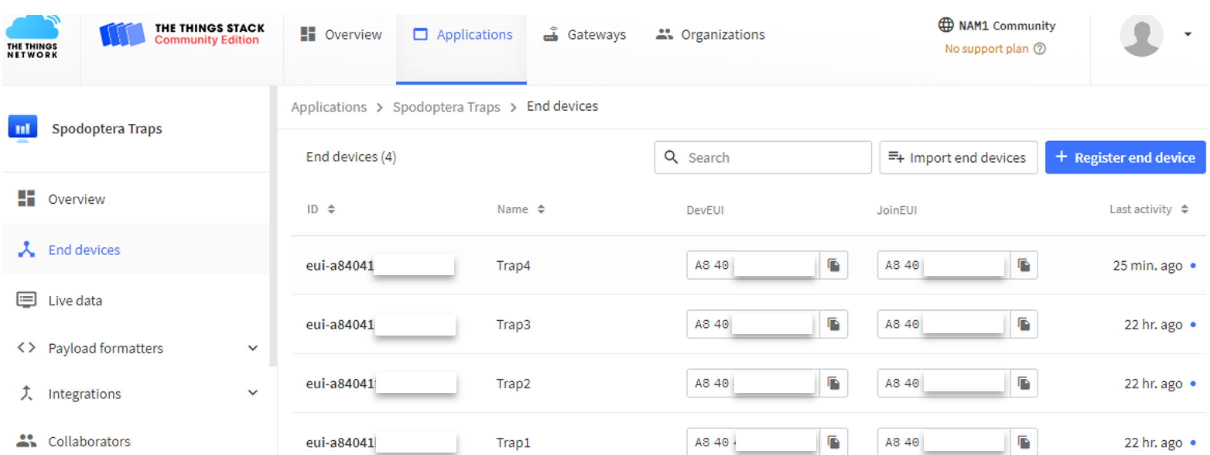
Figure 10. Nodes Creation in The Things Network.



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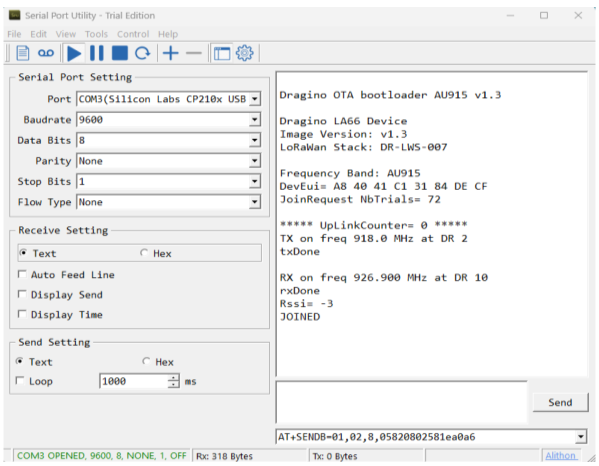
Subsequently, a connectivity desktop verification between each node and the Gateway was performed, as shown in the screenshot in Figure 11, where the correct creation and configuration of the devices are verified.

Figure 11. **Desktop verification of Node and Gateway connection.**



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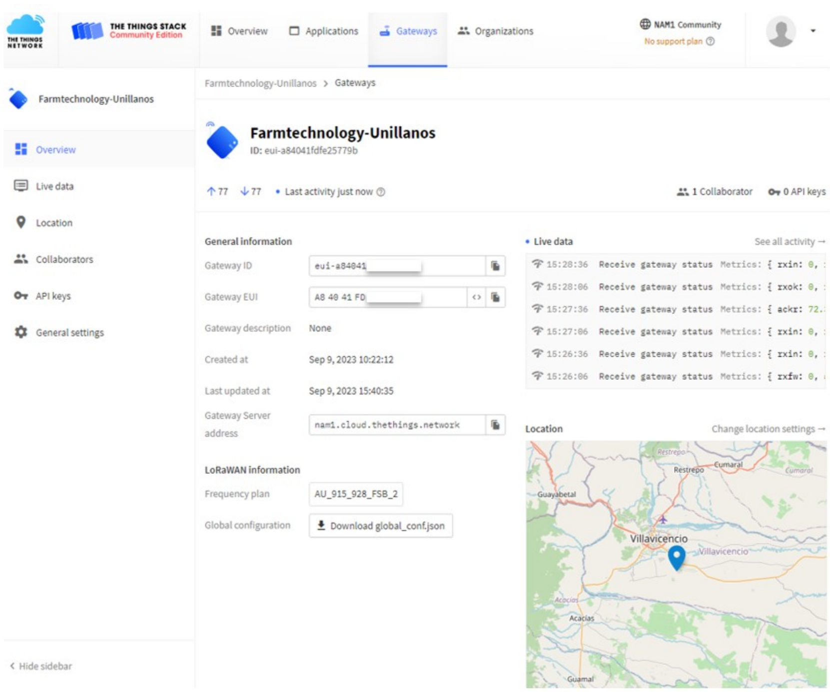
Finally, the ThingSpeak IoT platform was used to collect and store data from the electronic traps (sensor nodes in the cloud) to analyze and visualize pest count data previously transmitted from the Raspberry Pi® (Figure 12).

4. Discussion

The LoRaWAN™ network met the operational requirements of the IPM system designed for the IoT application, making it an appropriate technology for the detection and counting of fall armyworm moths in maize crops. LoRa™ can enhance the scalability of implementing IoT devices in agricultural fields. LoRa™-based end devices are cost-effective, energy-efficient, and also overcome bandwidth limitations, outperforming other wireless communication technologies like Wi-Fi™, Bluetooth®, or ZigBee®. LoRaWAN™ demonstrated greater interference tolerance, better signal propagation, and broader coverage in the presented IoT application.

Figure 12. **Visualization of electronic trap data on ThingSpeak.**



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While the results in pest detection, counting, wireless transmission, and data visualization were accurate, the research project aims to establish criteria, methodologies, and lighting management in the trap for proper image acquisition, as well as to determine the number of trapped insects using deep learning strategies.

Define abbreviations and acronyms the first time they are used in the text. Avoid using abbreviations in the title, unless it is essential.

5. Conclusions

Agriculture is undergoing a digital revolution. Specifically, there is an abundance of data sources available, presenting an incredible opportunity for exploitation. Moreover, the implementation of wireless sensor networks, artificial intelligence, machine learning, and computer vision techniques can reduce human interventions and efforts in pest management, optimizing inputs and maximizing crop yields.

The use of technology, electronic and software knowledge, and data analysis to monitor the *Spodoptera frugiperda*, along with the design and installation of automatic traps developed in this research, equipped with camera devices and wireless communication, will enable the implementation of pest management programs. These programs provide accurate insect identification and up-to-date counts by remote location in maize crops.

This work proposes an intelligent pest monitoring model in a pilot maize crop based on LoRa™ technology. The end nodes enabled for the electronic traps can be implemented on a large scale in agricultural fields. These nodes transmit data to the receiving node, and the received data on fall armyworm moth counts are monitored on the ThingSpeak IoT platform and stored in the cloud database for analysis and decision-making.

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