Infrared Photoelectric Sensor Network Applied to Remote Arthropod Insects' Surveillance

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Abstract: This work presents a monitoring system trap to detect the presence of arthropod insects in a remote surveillance zone. Detections are made using sensor traps that are installed in twenty houses of an indigenous village of the Paraguayan Chaco in South America, where the insects that transmit Chagas disease are pressing to infest the area. Pheromone baits are used to ensure the attraction of *Triatoma infestans*. For detecting variations of the light due to insect intrusion, trap entrances have photoelectric infrared sensors. Once the insect is detected, the information is collected and transmitted to an Internet database storage server. More than 750 intrusions were detected during nine months, the highest number of detections occurred when the temperature ranged between 20 °C and 34 °C, relative humidity average less than 30% and the precipitation was less than 1.5 mm. This new result provides evidence of the *T. infestans* activity at different times of the day and month, and its relationship with certain environmental variables. These findings contribute to reorientate surveillance procedures, validate the monitoring system proposal and give important information on the vector's life activity.

1 INTRODUCTION

Chagas disease or American Trypanosomiasis is an important endemic parasitosis considered a public health problem in Latin American countries (Acosta et al., 2002; WHO, 2015). It is caused by a parasite named Trypanosoma cruzi and is transmitted mainly by an insect scientifically named Triatoma infestans (Hemiptera: Reduviidae), colloquially known as vinchuca in the Southern Cone of Latin American (Lent and Wygodzinsky, 1979; Clayton, 2010). Despite the substantial success of the Southern Cone Initiative to control the triatomine vector, persistent reinfestation in the Grand Chaco regions of Bolivia, Paraguay, and northern Argentina (Clayton, 2010; Gurtler et al., 2008; Brener et al., 2000), especially among indigenous villages, where prevalence rates are extraordinarily high and clinical Chagas disease is severe. In addition, these towns are threatened by the incursion of sylvatic triatomines which could establish the circulation of new strains in peridomestic and domestic areas (Ceballos et al. 2009).

The effectiveness of preventing and early attention of this disease relies on controlling its vector to interrupt the Trypanosoma cruzi transmission (Rojas de Arias and Villalba de Feltes, 2011). However, controlling the vector is difficult, especially in isolated regions, such as the Grand Chaco. This region has the characteristic of having very dispersed rural populations, and in most cases with limited accessibility (a typical dwelling is shown in Figure 1). Currently, this region still presents high levels and persistent infection by Trypanosoma cruzi (Marconcini, 2008).

T. infestans ("kissing bugs" or "barber bug") is a blood-feeding relatively large bug of about 35 mm in length (Ariel et al. 2014). Morphologically, it is divided in three major segments: head, thorax, and abdomen. The mouthparts are adapted for piercing and sucking. It lives in cracks and crevices houses, usually in rural areas. The feces of the insects can contain parasites that can enter the wound left after the blood meal, usually when it is scratched or rubbed. This situation normally happens at night. There are other modes of infection (contaminated

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food, transfusion of infected blood products, congenital infection and organs transplantation) and it can also infect several household animals or closely boarded livestock, and wild animals.

For controlling the T. infestans in Paraguay, the National Program for Chagas Disease Control works actively in its elimination in dwellings and neighborhoods using chemical insecticides. Once localities are sprayed, entomological surveillance is set, mainly by health-trained personal and throughout denounce, to detect new reinfestations. In the Chaco region, the reinfestation is considered fast, the human monitoring is costly and denounces is rare because inhabitants just perceive the presence of insects when they are already installed inside the dwellings. Moreover, the efficiency of this strategy is seriously compromised since the insects develop resistance to insecticides (Echeverria et al (2018). Pérez-Estigarribia et al. 2020) and prospecting visits at homes are made only every six months due to the high distance, displacement, with high costs of trained (Rojas de Arias et al., 2012). In addition, it should be considered that the detection of triatomines by manual capture has low efficiency and efficacy.

Figure 1: Study setting. The typical indigenous dwelling from the study area in the Paraguayan Chaco.

Box sensors were initially proposed by (Gómez and Nuñez, 1965) and even tested in villages (Rojas de Arias et al., 2012; Collim, 1987). Most of these methods provide shelter for the triatomines and facilitate their detection inside; however, to date, no sensor for surveillance has reached the stage of massive implementation for surveillance of intradomiciliary triatomines (Marsden and Penna, 1982; García et al., 1985). The most recently reported sensors concentrate their attention on attraction to the box by means of attractant pheromones (Rojas de Arias et al., 2012).

Although, the attraction and capture strategy has been demonstrated as the most convenient action to detect the presence of the insect (Bosa et al., 2008; Salas, 2008; Fontán, 2002), two crucial problems still remain: (1) the box and the pheromone release must adapt to the dry climate and working temperature; and (2) frequent monitoring by qualified persons are required to obtain information on reinfestation or repopulation of triatomines due to control failures. Problem (1) directly affects the efficiency in attracting the insect. The reinfestation process can be performed in a period relatively large. Hence the attractor can lose effectiveness. Problem (2) affects the decision-maker since the information about the new insect installation (an effective reinfestation) arrives with a considerable delay introducing high uncertainty in the effectiveness of the corrective actions.

The speed of pheromone release for increasing attractiveness efficiency was studied (Aquino, 2012, Monteiro et al., 2017), which proposes and proves the effectiveness in laboratory, using biomaterial pellets instead of polyethylene bags as a pheromone release mechanism. In parallel, to minimize the delay of having the information, during 2011 and 2012, a first model of an electronic device for automatically detecting the T. infestans intrusion in a box was presented (Montero and Serra, 2011). The Chaco is normally a hostile place for electronic devices. This is mainly due to the high temperatures with an abrupt change of them, the excess of very fine dust and the lack of constant electrical energy supplies. Therefore, a new model device was posteriorly designed for improving the electronic and adapting it to the working environment. Moreover, decision tree software was incorporated for identifying the T. infestans intrusion or eventually other species of secondary arthropod attracted (Gaona et al., 2014; Gaona et al., 2019).

The proposal of this work consists in using a remote sensing trap with pheromone as an attractor for detecting online the presence of triatomines and transmitting the information directly to the decision-makers. Since this is permanent monitoring, it improves the chances of obtaining information about a reinfestation in an early stage. This strategy will also minimize the cost of unnecessary human displacement and monitoring, optimizing the limited resources when having specific and well-localizing information about the reinfestation. Likewise, this work also proposes a system of environmental monitoring of some variables of interest, such as humidity and temperature, to obtain information about the life activity of the vector with respect to the climate.

The novelties of this article are: 1) the validation of an early detection system, through field implementation, detecting and obtaining real-time measurement values of intrusion (reinfestation) by the T. infestans of a sprayed region, and the contrast of results with experts in the area; 2) the finding of environmental variables and situations related to more activity of the arthropod. The latter is particularly important to develop surveillance procedures and to understand the life activity of the T. infestans.

The article is structured as follows. In Section 2, a description of the region of monitoring, as well as the description of the components of the trap. Section 3 presents the results of the intervention of monitoring; and the conclusion are presented in Section 4.

2 MATERIALS AND METHODS

2.1 Study Site and Trap Installations

Traps with a sensor network were installed in this village. Twenty dwellings were selected for this study. Each dwelling is separated from each other by approximately 100 meters. A sensor trap was installed in each chicken coop located in the peridomicile. In some houses, two traps were installed, one in the chicken coop and one inside the dwelling. In the center of the village was located the data hub and gateway. The farthest trap was 600 meters. Throughout the village, the total coverage range was about 1100 meters.

Figure 2 shows an example of the appearance and installation of the trap in a dwelling and its subsequent manual verification without sensors.

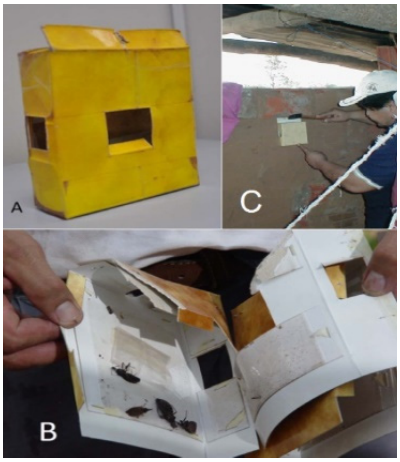

Figure 2: Chemically baited sticky trap used for Chagas disease vector surveillance. (A), outer aspect; (B), triatomines caught in the entomological glue inside a trap; (C), installing the trap.

2.2 System Description

Figure 3 shows the components of the arthropod remote monitoring system.

2.2.1 Trap with Sensors

In Figure 4, it is possible to observe the basic diagram of the trap with sensors. The four infrared photoelectric sensors are connected to a microcontroller based on a Microchip® PIC16F1825, chosen for being low power and accessible cost, compact and with the required functionalities, such as analog ports, internal oscillator, digital communication, among others. The reports on intrusions of an arthropod into the trap are sent through the RF module. At each specified and constant period, the Gateway report the information to the monitoring data center through the Internet. Each trap is prepared to work outdoors, anticipating aggressive weather conditions, using adapted 10-liter bottles to protect the trap without interfering with its functions.

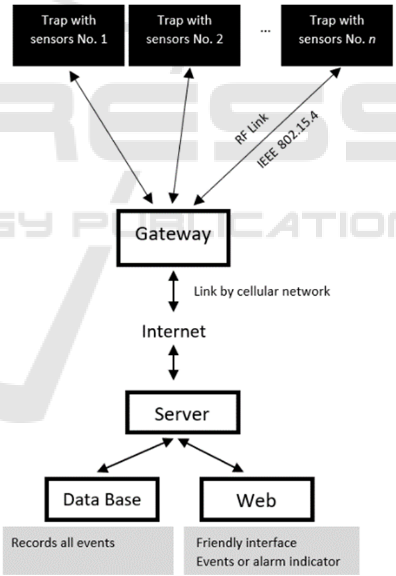

Figure 3: components of the arthropod remote monitoring system.

2.2.2 Adjusting

For calibration and tuning sensors, some T. infestans have been used in several stages of formation and several color tonalities. The color is important since the infrared photoelectric sensors detect intrusion by light reflection (Giron, 1998); hence it may affect detection efficiency (Gaona et al., 2014).

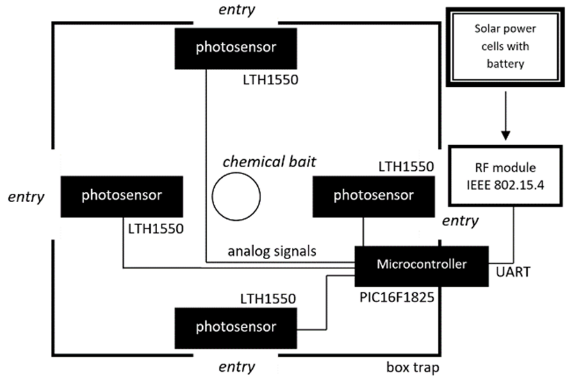

Figure 4: Basic scheme of the top view of a trap with sensors.

2.2.3 Bait

Pheromones are organic compounds emitted by insects, they are chemical messengers that provoke a response in other individuals of the same species, forcing them to opt for a certain type of behavior (Simon, 1994; Blanco, 2004). There are several types of pheromones including sexual, aggregation, tracer, alarm, dissuasive, etc., depending on the type of reaction they cause (Simon, 1994). These pheromones are used by insects to modify their behavior, either by the phenomenon of mating (sexual pheromone), search for food (pheromone tracer), the grouping of individuals in colonies (pheromone aggregation), for the stimulation of flight or defense (alarm pheromone), among others. For the specific case of the triatomines, where some species are vectors of Chagas disease, stridulation has been cited (action of producing sound by the friction of certain parts of the body) as a possible mechanism of communication between the sexes in T. infestans. Among other mechanisms of interest is the olfactory, which involves pheromones, a more intraspecific communication mechanism in insects, if we compare them with other alternatives such as vision and sound (Manrique, 2010).

According to studies made with different materials (hydroxyapatite, kaolin, Pyrex glass, and amber glass), porous granules of kaolin were used as slow-release systems of benzaldehyde for the traps attracting T. infestans, since this was the one that presented the best results during the liberation tests by weighing and assays in vivo with T. infestans in the laboratory (Aquino, 2012).

2.2.4 Gateway

It is located in the center of the village (study site) and consists of a cabinet for electrical and electronic components (basically schematized in Figure 5). It is composed of AC voltage input (220 Vac), two circuit breakers, uninterrupted power system (UPS), switching DC power supplies (for 5 and 12 Volts outputs), programmable communication module by radio frequency (IEEE 802.15.4 XBee-based), Arduino-based primary microcontroller (chosen for the ease of programming thanks to the free software and hardware community with modular functionalities required for this work), SD memory module, display LCD module + keypad, 4G-LTE module, sensors and interfaces for the portable weather station. It also has a special coolant system (using a compact 220 Vac fan), insect and dust filter, as well water.

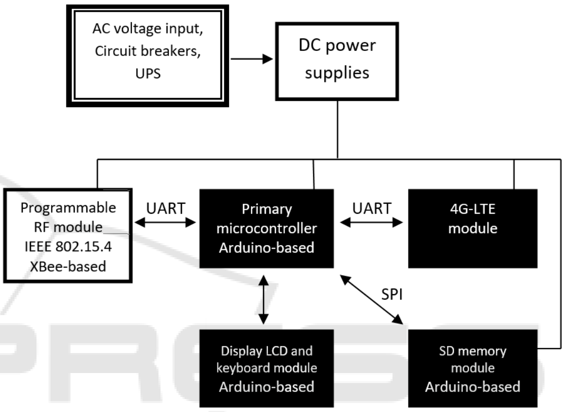

Figure 5: Basic scheme of Gateway.

The system must operate with the following characteristics: (1) User interface via display LCD-keypad module. (2) 4G-LTE and text message (SMS) communication with the servers on the Internet. (3) Record of events in SD memory. (4) Interaction with the UPS to determine the power supply. (5) Reading of indoor and outdoor temperature sensors, atmospheric pressure, humidity, direction and speed of the wind, amount of rain falling. (6) Wireless communication via RF with traps to be in the dwellings.

2.2.5 Monitoring Interface

It consists of a web application developed in PHP with PostgreSQL database hosted on a datacenter server accessible from the Internet. It allows online monitoring, as well as having an automatic histogram image related to the data recorded in a previously specified time range. Reports can have the following information from the traps: electrical supply problems, number of detections by day, and trap. From the meteorological station: wind direction and velocity, relative humidity, amount of rainfall, atmospheric pressure, internal and external temperature.

2.2.6 Networking

The RF module is the XBee-PRO 2.4 GHz of Digi® (IEEE 802.15.4 protocol) with Router mode settings for intermediate nodes and external nodes as End Device mode. In this way, a trap (node) that is located far from the center of the village can reach the Gateway throughout the routers in several ways forming a network of smart sensors. Since 128 bits of the address are used in the RF module, it is possible to have up to 2128 different nodes in one location.

2.2.7 Power Supply

Many indigenous villages in Paraguay do not have electricity. In the case of Tiberia (the study site), there is only one electrical power network in the center (a church) only. The Gateway is on this site. Sensor traps need a 3.3 V battery-powered supply system with solar recharge. Therefore, the topology used consists of an MPPT converter and charger module (CN3722) for lithium cells (shown in Figure 6). This module accepts an input voltage range of 7.5 to 28 Volts and operates at a frequency of 300 kHz. It has a load capacity of 5 Amps. The solar panel used is 20 Watts, in this way, the battery could run out after a couple of days without adequate sunlight, and when there is good sunlight again, the sensor traps will automatically restart.

When the Gateway detects the lack of network power, it reports via SMS to a predetermined telephone number. When its battery runs out and then the grid power returns, it automatically restarts and after 1 minute it is ready to receive and transmit detections from the sensor network again.

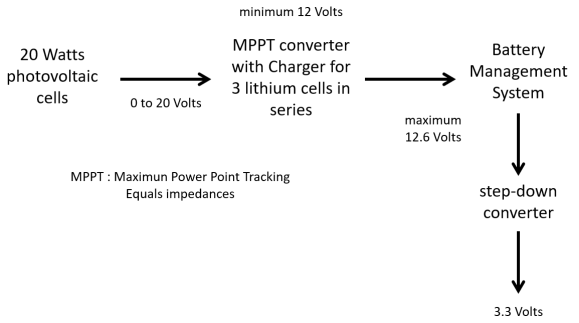

Figure 6: Basic scheme of the trap with sensors power supply.

3 RESULTS AND DISCUSSIONS

The system installed in the 20 indigenous dwellings for nine months worked robustly. Insect intrusions were efficiently detected by the infrared sensor system, as well as temperature, relative humidity and rainfall records.

The monitoring system allowed mainly knowing the level of activity of triatomines per dwelling, since the traps were identified physically and digitally. Therefore, the web interface of the computer system recorded the events in detail, such as date, time, trap identifier and variables of the portable weather station every 30 seconds, with date and time: wind direction, wind speed, amount of rainfall, ambient temperature, and relative humidity.

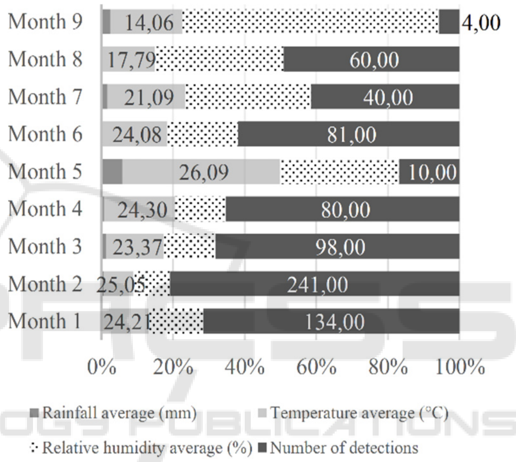

Figure 7: Percentage graph of the number of detections (values shown) versus relative humidity, ambient temperature (values shown) and the amount of rainfall for 9 months.

There were more than 600,000 records of meteorological information and more than 750 detections (filtering and eliminating successive counts) in 9 months of service. Since other insects can activate the alarms accidentally, detection follows criteria introduced in (Gaona et al., 2014). This is a caution flag that is alerted by software in case of detecting an intrusion that remains activated. Only after 30 minutes of inactivity, the flag is disabling. After this, the sensor passes to the position of "waiting" for the next detection (intrusion).

Figure 7 shows the behavior of the insect throughout the 9 months of field testing. Make a percentage comparison with some climatic variables. It is important to note that when precipitation was minimal, relative humidity was 30 % or less and temperature below 30 °C, higher triatomine activity was observed. Month 2 was the most prolific month in terms of detections (Figures 7-8). In this period, the control field personnel performed an on-site corroboration when the detection alarm occurred. The most important results in this analysis period are the verification that the detections have a strong correlation with T. infestans or other triatomine species activity in or around the sensor traps. However, in a normal monitoring situation (without expert personal verification), if multiple traps are activated, this means high triatomine activity, therefore there would be a high probability that there is intense pressure to install a new process of infestation. It is important to note that the number of T. infestans detections during the months was decreasing. Some of this may be due to the summer heat with high average rainfall, where the number of detections decreased abruptly, or it could be due to the decreased attractiveness of the pheromone attractor.

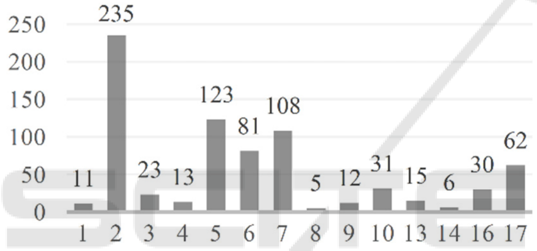

Figure 8: Number of arthropod *T. infestans* detected during 9 months for each trap. Traps with zero detections are not displayed.

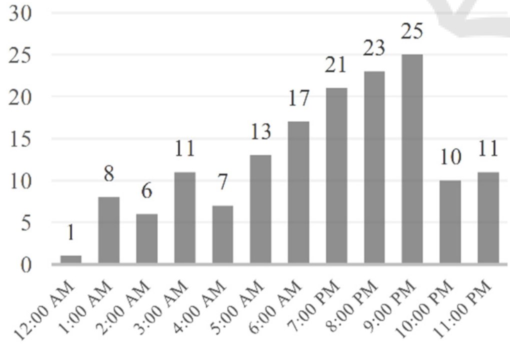

Figure 9: Activity of *T. infestans* per hour for 9 months.

Computational records also allow us to determine which trap has the highest of T. infestans activity, as can be seen in Figure 8, trap number 2 that is fully identified with an indigenous home and family, therefore, that dwelling is the one that has a higher presence of T. infestans activity.

Figure 9 shows the time when the T. infestans had the highest activity. It can be seen as from 07:00 p.m. the presence of T. infestans begins to increase until 09:00 p.m. This is because the chickens begin to sleep at that time. Only night hours are considered due to the characteristics of the insect.

Multiple entrances of an insect can be detected by the sensors. It is important to remark that in laboratory observations this behavior does not exceed in 10 % of the cases (Gaona et al., 2014). Multiple entrances will affect the density accounting. However, since this work is interested in the early detection of the insect, hence multiple entrances will not significantly affect the results. By contrast, it denotes a high level of vector activity, and in consequence, a higher probability to identify them in an early process of reinfestation to control it, avoiding a new potential set up of the parasite transmission inside the dwellings.

4 CONCLUSIONS

After nine months operating properly in an aggressive arid environmental, the autonomous trap (conformed in a wireless mesh network sensor monitoring system) has demonstrated a robust behavior. The system allows identifying rapidly the presence of arthropod insects inside the trap, and the temporal-geographical distribution. It is important to remark that this is the first time it is collected meteorological data and insect behavior in its attempt to invade places previously sprayed by an insecticide. The results show an increase in vital activity of T. infestans under certain environmental circumstances. This evidence could contribute to reorient surveillance procedures to detect reinfestation early and minimize the probability of installing Chagas disease transmission cycles in the intervened localities.

The system presented has the possibility of being regionally scalable in Latin America countries where Chagas disease vector surveillance is a priority in endemic areas (18 of 21 countries of America). The system is affordable in terms of cost and is a tool for early detection of infestation or reinfestation of the main vectors of Chagas disease in the region, either inside dwellings or in the peridomestic areas, during the entomological surveillance phase.

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