Mosquito Ovitraps IoT Sensing System (MOISS): Internet of Things-based System for Continuous, Real-Time and Autonomous Environment Monitoring

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***Abstract*—The monitoring of environmental parameters is indispensable for controlling mosquito populations. The *abundance* of mosquitoes mainly depends on climate conditions, weather and water (i.e., physicochemical parameters). Traditional techniques for immature mosquito surveillance are based on remote sensing and weather stations as primary data sources for environmental variables, as well as water samples which are collected in the field by environmental health agents to characterize water quality impacts. Such tools may lead to misidentifications, especially when comprehensive surveillance is required. Innovative methods for timely and continuous monitoring are crucial for improving the mosquito surveillance system, thus, increasing the efficiency of mosquitoes' abundance models and providing real-time prediction of high-risk areas for mosquito infestation and breeding. Here, we illustrate the design, implementation, and deployment of a novel IoT-based environment monitoring system using a combination of weather and water sensors with a real-time connection to the cloud for data transmission in Madeira Island, Portugal. The study provides an approach to monitoring some environmental parameters, such as weather and water, that are related to mosquito infestation at a fine spatiotemporal scale. Our study demonstrates how a combination of sensor networks and clouds can be used to create a smart and fully autonomous system to support mosquito surveillance and enhance the decision-making of local environmental agents.**

Keywords—Internet of Things; IoT; Real-time Environmental Monitoring; Physicochemical Parameters; Water Quality; Mosquito Surveillance; Mosquito Breeding Sites; Ovitraps

I. Introduction

The emergence and successful applications of the Internet of Things (IoT) make it permeate several fields and industries. The movement towards IoT allowed automated methods of monitoring and automatic data collection. The data generated by IoT devices are considered heterogeneous and rapid; thus, it usually requires some processing tasks and specific analysis algorithms in order to detect situations of interest in real-time [1]. Advances in machine learning and cloud computing technologies make the analysis, storage, and management of big data achievable and easy to integrate [2].

Information on both: (1) exogenous climatic variables such as temperature and humidity and (2) ecological factors impacting mosquito biology, such as the physicochemical parameters of breeding water, could provide a better understanding of mosquito habitat. Therefore, a thorough knowledge of the drivers that influence mosquitoes' habitat on eggs, larvae production and development is of great importance in designing and formulating integrated vector control strategies and intervention tools by vector management programmes to combat vector-borne diseases.

Weather conditions are deemed to be a significant factor that impacts the presence and abundance of mosquitoes [3], [4], [5]. In addition, water quality parameters significantly influence mosquito breeding, especially the Potential of Hydrogen (pH) and Dissolved Oxygen (DO) [6], [7]. As such, having these parameters at high resolution, such as properties-level, breeding sites-level or ovitrap-level, might significantly impact the accuracy of the monitoring system.

However, methods currently rely on large-scale data sources, such as remote sensing and weather stations [8], where the fluctuation in weather variables is not precise for a specific distant location [9]. It also depends on equipment (i.e., portable multiparameter) which provides instant values and requires human input [10], [11], [12].

Considering that utilising automated sensor networks to monitor the mosquito population (i.e., adult mosquitos) and the surrounding environment, including weather and water, is a powerful mechanism as a prevention tool to control mosquito abundance, consequently, mosquito-borne diseases [13]. Acoustic sensors are valuable in detecting adult mosquitoes on the fly by tracking and recording the frequency of the mosquito's wing-beat rate [14], [15]. However, controlling mosquitoes in the early stages of their development cycle (i.e., immature stages) might help better understand mosquito habitat preferences.

The work presented here shows the development of MOISS (Mosquito Ovitrap IoT Sensing System), a novel environmental sensing system for continuous ecological monitoring of mosquito ovitraps which provides an ideal approach to evaluate the most suitable mosquito habitat. The primary purpose of this paper is to show the design, implementation and deployment of a real-time, robust, and automatic IoT-based system to monitor the changes and patterns of some environmental factors that relatively impact mosquito infestation. This research work is considered unique of its kind in utilising IoT technology in the field of weather and water quality monitoring with respect to the development of mosquito eggs and larvae on Madeira Island.

In this paper, we present the architecture of an autonomous weather and water monitoring system, which is designed based on Arduino, weather sensors and water sensors, as well as using mobile data networks to implement continuous data collection from the mosquito ovitrap in the field. The proposed system is an example of a generic platform that provides continuous monitoring from multiple sensors that could be deployed in any mosquito habitation. The system has been designed to operate under different circumstances, such as in areas without power or a Wi-Fi network (i.e., mountains).

The main contributions of this work include: (1) working with environmental agents to identify the requirements of the proposed system, (2) fully autonomous and unattended environment monitoring unit for capturing and remotely transmitting periodic data streams from mosquito ovitraps in the field sites over long deployment times, (3) full technical details on how the hardware has been designed and assembled, and (4) the architecture of a modular software framework for communication between sensors, devices, cloud services and databases.

II. Background and Related Work

A. *Mosquito Surveillance*

There are several approaches to control the proliferation of mosquitoes at different stages of their life cycle (1) eggs, (2) pupa and larvae, and (3) adult mosquitoes. One of the common and traditional approaches to control mosquitoes' eggs is the use of oviposition traps (ovitraps) or egg traps (i.e., where mosquitoes are laying their eggs), which have the advantage of being sensitive to mosquito presence. However, it is considered expensive to implement over a large scale owing to the laborious setup [16], as well as the need for practitioners with a considerable degree of training in using microscopy for accurate egg counting [17].

Another effective control measure is the surveillance of the mosquito in its immature stage (larvae and pupae), which is visually evaluated by community health workers (CHWs); through inspection of some mosquito ovitraps or sites that are likely to be breeding sites, such as stagnated water in properties, ponds, and so on. During these inspection visits, the health agents collected some water samples for laboratory analysis, eliminated these breeding habitats, and recorded all observations on paper-based forms. This task is potentially error-prone and time-consuming; at the same time, it does not provide remote, real-time, or highly precise data [18].

Other techniques solely focus on adult mosquitoes, such as trapping and mosquito sensors, which are critical in understanding the mosquito population, distribution, and dynamics across a specific geographic area. Mosquito adult traps provide the number of mosquitoes based on the trap's location. Still, this technique is considered expensive compared to ovitraps, as well as it might include some other challenges [19]. Acoustic [14], [15] and optical sensors [20] have been used as well to detect the adult mosquito by classifying the collected on-field wingbeat frequency (WBF) into corresponding species [20]. However, capturing a clear wingbeat sound is a challenge in itself. Moreover, the deployment of such devices has been found to be impractical and vulnerable to open field conditions [21].

This method of identifying mosquitoes using sensor devices also needs to be applied to a smarter scenario by considering technological solutions, such as the IoT, which results in real-time data collection, thus, timely analysis. Furthermore, incorporating such sensory data with other multiple data sources, such as environmental data (i.e., weather conditions and physicochemical parameters of water), field surveillance conducted by agents, and ovitraps into an effective data-driven model for predicting mosquito population density is the ideal mechanism for controlling the mosquitoes, and the diseases caused by them [16].

B. *The Impact of Climate on Mosquito Infestations*

Research has placed great emphasis on the direct impact of variation in climate variables on mosquito population dynamics. Yet, this impact varies based on species (species-dependent) [22]. Among several climatic variables, two major variables have been found to play a substantial role in the mosquito population: temperature and rainfall. However, in a study conducted in São Paulo, the temperature was linked to vector distributions of the mosquito population, whereas at a different site in the same region, rainfall was observed instead as the main influencer during the same period [22]. The nature of this variation is owed to either the species or the availability of the breeding sites [22].

Mosquitoes are one of the arthropods vectors, which are poikilothermic ectotherms (i.e., internal body temperature tends to fluctuate based on the temperature of the surrounding environment) [23]. Thus, many research studies consistently observe temperature as one of the most important abiotic factors affecting mosquitoes' survival, movement, feeding, reproduction and development. The temperature has been the focus of many developed models to forecast and map the distribution of mosquito species [22],[24].

The temperature significantly affects the viability of laid eggs and the hatching time. The impact on hatching time is species-dependent; for example, the eggs of *Ae. Albopictus* could tolerate a lower temperature compared to *Ae. Aegypti* [23]. Furthermore, the survival of immature mosquitos is subjected to temperature variations at breeding sites; the increase in temperature yields a decrease in the development time of immature stages [25]. Similarly, temperature also influences the mosquito adult stage, where some mosquitoes survive and fly at a specific temperature range; for example, the optimal temperature for *Ae. Aegypti* adult to fly is at 21ºC and *Ae. Albopictus* survives in a range of 15ºC to 35ºC [23].

Another climatic variable often used to determine mosquito population dynamics is humidity. High humidity is associated with low temperature, thus, low mosquito infestation. A notable decrease in mosquito abundance has been specified when air humidity is exceeds 79% [26]. The importance of humidity impact on adult mosquito survival and egg development is much the same as the significance of temperature [27]. For instance, in the same temperature settings, a significant reduction occurs in the number of larvae for those eggs laid at higher humidity

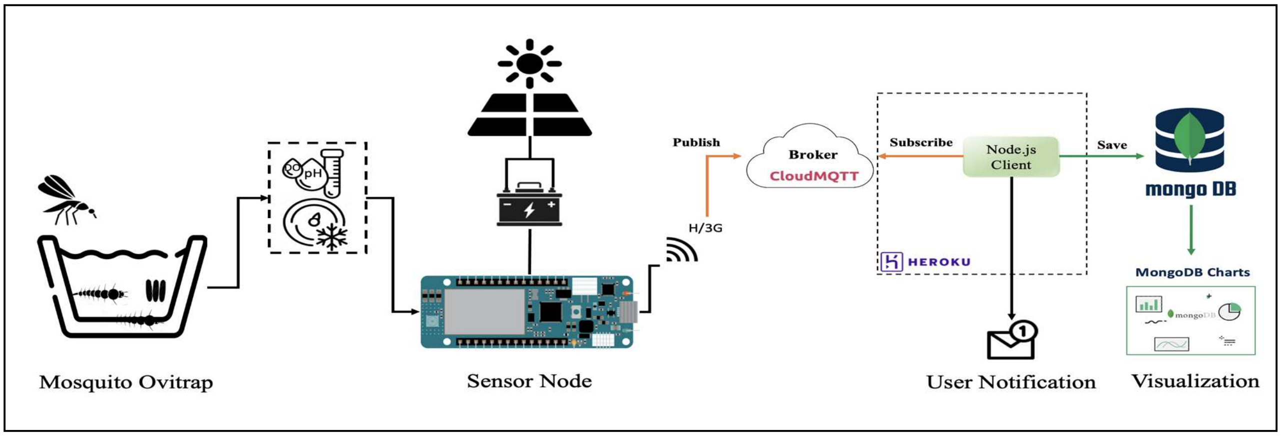

Fig. 1 MOISS architecture. It depicts how data is continuously captured from ovitraps in the field and automatically uploaded to the cloud server.

compared to lower humidity. Similarly, significant high rates of oviposition were observed at higher humidity [27], [28].

The overall results indicate that no consensus exists on the assumptions and findings on the impact of climatic conditions and breeding site characteristics on the development of mosquitoes at various stages of their lifecycle. Furthermore, some studies are conducted under controlled conditions (i.e., laboratory-based); thus, it is hard to assume the equivalent impact of the environment on mosquito presence and development in field settings [29]. The potential impact of seasonal and diurnal fluctuations on climate variables under various field settings requires consideration [26].

The inconsistency among studies is not limited to the climate association or experiment setting but also the used climate data sources. For example, some studies used direct surface measurement, remote sensing, or interpolated weather station datasets. The paucity and disparity of climate data, mosquito's immature development data and habitat characteristics, are likely to cause some challenges in understanding the species distribution as well as building robust relationship models. This equivocal conclusion reveals a need for further investigations into which studies are species-specific and context-specific [24].

C. *The Impact of Ecological Factors on Mosquito Biology*

Providing female mosquitoes with a suitable environment for breeding, including stored and stagnant water, as well as having a place to lay eggs (above the waterline) to grow and develop through their water stages (egg, larval and pupal) will support the abundance and prevalence of mosquito populations. Therefore, a call for a more precise and comprehensive understanding of mosquitoes' habitat conditions is crucial. Water characteristics are considered one of the principal factors of mosquito proliferation, where the survival of mosquito eggs, pupa and larvae depends on the chemical properties of the water. Research emphasises the direct impact of water's physicochemical parameters on mosquito immatures' presence or absence [29].

The temperature and the physicochemical parameters of the water, including pH, Dissolved Oxygen (DO, mg/L), Total Dissolved Solids (TDS, mg/L), and Electric Conductivity (EC, μS/cm), affect the oviposition behaviour of female mosquitoes. However, the influence of each variable varies based on the mosquito species and the site settings.

Studies have found that water temperature influences the rate of pathogen development (i.e., the extrinsic incubation period). The water temperature is within the range of 23°C to 32°C offers suitable habitat conditions for the developmental stages of the mosquito [30], [11]. Some studies have highlighted that water temperatures around 29°C provide the optimal conditions for egg, larval, pupal and mosquito development [10].

The physicochemical properties of breeding water have been identified as drivers that influence the density of mosquitoes. The impact of each parameter often varies; this variation is context-specific and species-specific. The pH and the DO have been determined to be correlate positively with the larva density [31]. However, a negative correlation has been observed between larvae density and other water parameters: salinity, TDS and turbidity [12]. Neutral pH ranging between 6.8 and 7.2 is a preferred breeding site by most mosquito species. Thus, outside this range, the growth of mosquitoes is reduced and will show higher mortality occurrence (i.e., pH below 4.5 or above 10) [11], [32]. Besides, the ideal DO level ranges from 5.02 to7.82 mg/L [30], [31].

Although pH and DO are the most critical parameters, some studies emphasise the influence of salinity and conductivity on some mosquito species. Some mosquitoes are salinity-tolerant species where they can develop different strategies to adapt to high salinity, such as *Ae. Albopictus* [32]. In the case of the *Anopheles* mosquito, a significant association was identified between the salinity and conductivity of the water and larvae density [11]. For *Ae. Aegypti*, pH, DO and salinity were determined to be the best predictors of abundance and presence [33]. However, another study conducted in Colombia found that Aedes aegypti immature infestation was negatively associated with DO whereases positively associated with the TDS [34].

Finding consistent findings among several studies on specific physicochemical parameters that significantly influence mosquito breeding is quite challenging. These parameters vary substantially in association with mosquito abundance and presence. The nature of this variation is subject to several factors, such as study areas, climate conditions, container characteristics, etc. Therefore, timely and continuous monitoring of these parameters in the field is crucial, as well as a microanalysis of the chemical composition of field sites in association with the specific context and species, which in turn yields a better

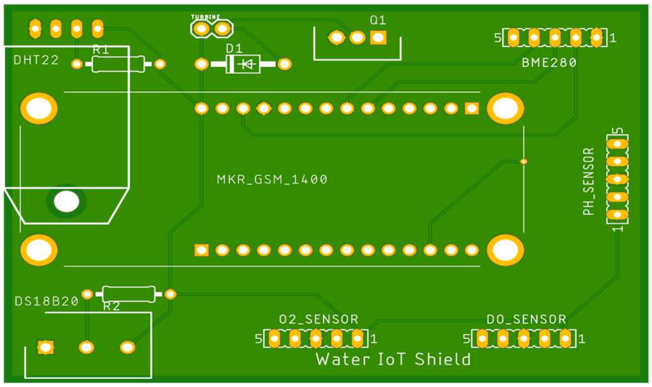

Fig. 2 Controller node shield

understanding of the biology, ecology and development of mosquitoes [29].

III. System Requirements

The primary goal of this project was to design and develop a novel environmental sensing system that could continuously monitor the habitat parameters that are highly related to the presence of mosquitoes across a large area by collecting and analysing weather and water physicochemical parameters. Accordingly, the system requirements have been determined as following.

The developed system needs to operate sufficiently (Roubust and Realiable) to allow epidemiologists and meteorologists to answer long-term questions about mosquito proliferation. This implies that the proposed MOISS has to operate and collect data continuously for at least several months to have adequate data for the analysis. In addition, the hardware component requires robust packaging to prevent any damage caused by overheating, humidity, water damage, curious animals or vandalism.

The system needs to provide real-time and continuous data gathering to provide sufficient data for building a near real-time prediction models to support the environmental agents in decision-making and determining the efficacy of mosquito control strategies. As such, the system needs to constantly monitor the environment and push the data when available to a cloud server. The system always needs to have access to the internet connection and power to realise autonomous monitoring.

Thus, a small and inexpensive Arduino-based controller with a built-in SIM card was chosen as a solution for the data gathering and connectivity. Plus, using the power supply at the deployment sites (when available) or a solar-powered system (with batteries) would guarantees uninterrupted power. However, accessing the mobile network can still be quite challenging in some locations, such as the mountains and forests with have less cellular coverage.

IV. Mosquito Ovitrap IoT Sensing System

The MOISS is comprised of various components, including the core data capturing electronics based around an Arduino MKR GSM 1400, two weather sensors, three water quality sensors, a solar power system, an electrical enclosure and a backend Node.js server that uses unstructured databases (MongoDB) hosted by a third-party cloud service (Heroku). The system uses a lightweight Message Queuing Telemetry Transport (MQTT) protocol to exchange messages between the embedded microcontroller and the cloud. Fig. 1 shows an overview of the current system architecture divided into three layers; the Perception layer includes five environmental sensors, the network layers involve the mobile network and MQTT protocol for communication, and the MongoDB Charts platform is the application layer.

A. Hardware Design

The system unit is the core building block of the developed system; it consists of (1) a small, embedded device (Arduino microcontroller) with software that determines the connected devices' behaviour, (2) an antenna for data communication and (3) five environmental sensors to monitor and collect environmental parameters (i.e., weather and water sensors). The Arduino MKR GSM 1400 board[1] has been selected as the main microcontroller board as it takes advantage of the cellular network as a means to communicate, as well as the low power consumption owing to the processor module (i.e., Arm Cortex M0 32- bit SAMD21).

Two weather sensors were used to measure the weather temperature, humidity, and air pressure. Three water sensors for capturing physicochemical water, including PH sensor, measures the acidity and alkalinity of the water, DO sensor, measures the amount of oxygen ($O2$) dissolved per unit volume of water; and the water temperature sensor. The pH and DO sensors interfaced with the microcontroller using their respective Atlas EZO circuit[2]. The remaining sensors were soldered to the PCB prototype board; the PCB board was designed based on the circuit architecture (Fig. 2). Weather sensors use serial communications to report the data, whereas pH and DO use the I2C communication protocol. Prior to deployment, the pH and DO sensors were calibrated at 25ºC to ensure correct and accurate readings as per the vendor instructions. The system's design is scalable to sustain the demand for additional sensors.

The system is designed to run using a solar-powered battery or the main power supply if available at the deployment sites. Like the work done here [35], we have used a similar schematic of the solar power system. The 12V/24V solar charger regulator controller is connected to a 20 W solar panel, a 12V 10Ah Absorbent Glass Mat deep-cycle battery, and a 12V to 5V DC converter, which powers the microcontroller (Arduino board). The charge controller is also responsible for controlling and regulating the voltage coming from the solar panel and battery terminals to provide a steady 12V DC.

The enclosure box was designed to house and protect internal electrical parts and components. The base and lid of the box are manufactured from 3mm Medium Density Fiberboard (MDF) using a CNC laser cutting machine which offers excellent protection and insulation for deployment in an indoor environment. Three holes were made in the side of the box to accommodate the three water props, and a custom-made holder was created using 3D printing to ensure a flexible movement of the water probe sensors while placing or removing them on and

[1] https://docs.arduino.cc/hardware/mkr-gsm-1400

[2] https://atlas-scientific.com

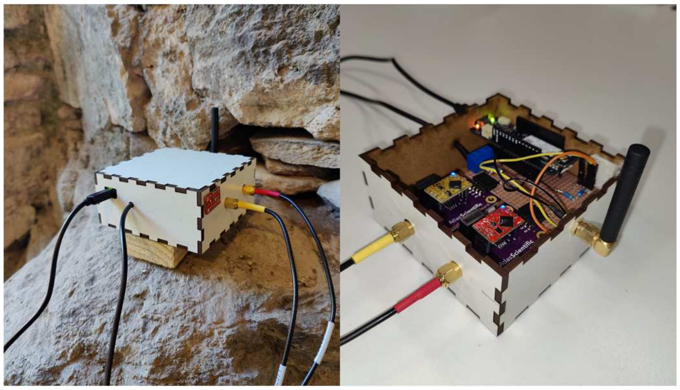

Fig. 3 Components inside the electrical enclosure (10x10x4.6 cm)

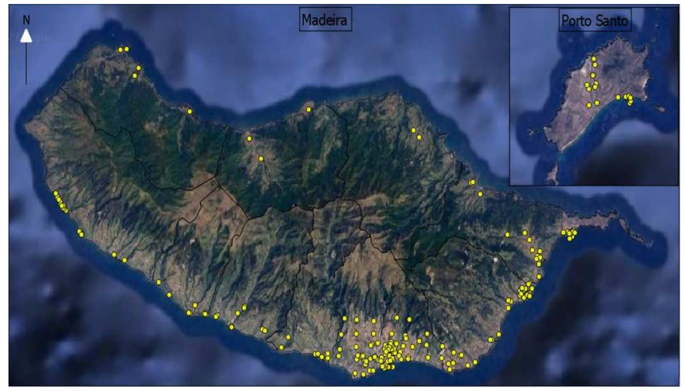

Fig. 4 The geographical distribution of ovitraps in Madeira Island

from the trap. Four additional holes were added for the antenna, a power supply and weather sensors. Fig. 3 shows the design of the enclosure box for housing hardware components.

Table I summarises the specifications and cost of each component. The total cost for one complete system is around £900, and a 3G data plan is about £20 per month. The proposed system is preferred over the other commercial options due to the ease of use, reduced inferred costs, and fidelity of the data it could provide. Unlike our system, most water sensors are portable, requiring frequent routine field visits and manual sensors providing instant readings. Other sensors are considered more expensive[3] (for example, RS Hydro water quality products); those sensors can store data into an embedded memory - which might end up losing the data due to some field conditions - and provide manual access to the data.

TABLE I. SYSTEM NODE COST ANALYSIS

Components	***Important Specs/ Ranges***	***Unit Cost (£)[a]***
Arduino MKR GSM 1400	MD21 Cortex®-M0+ 32bit low power ARM MCU	75
Temperature, Humidity (DHT22)	[-40°C - 80°C], 0-99.9% RH	8
Temperature, Humidity, Air pressure (BME280)	[-40°C - 85 °C], 0-100% RH, 300-1100 hPa	12
Atlas Scientific PH Sensor	0.001 − 14.000	280.60
Atlas Scientific Dissolved Oxygen Sensor	0.01 - 100+ mg/L	154.27
Solar Panel Kit	20 W solar panel, 12V/24V charge regulator	45
Lucas Absorbent Glass Mat deep-cycle battery	12V-10Ah	28

a. Prices are subject to change based on the suppliers.

The developed system here offers timely reading, remote data uploading and solar power. The system architecture is flexible for adopting extra sensors in the same node, such as an acoustic sensor for monitoring adult mosquitoes and large solar panels or parallel solar panels in case more power is needed. Another compatible and cost-effective solution for large-scale implementation is to reduce the cost by having better energy efficiency through Long Range (LoRa) technology that offers high performance, low power, and affordable connectivity to send data in remote areas [36].

B. Software Design

We developed an IoT-based environmental monitoring system for monitoring the weather conditions and the water quality in mosquito ovitrap. Our proposed system used a third-party message broker (CloudMQTT): it implements the Message Queuing Telemetry Transport (MQTT) protocol for remote monitoring and message exchanging between an embedded device, sensors, and the cloud. The broker supports data publications from the system unit into topics via a network such as 3G/4G networks; plus, it allows external clients to subscribe to a specific topic running on the broker.

A server-side, which is written in JavaScript, is hosted on the cloud (Heroku) to read the MQTT packet sent by the node, parse it, and then store it into a cloud-based database (MongoDB) in JSON (JavaScript Object Notation) format. The data packet includes timestamps, Ovitrap location coordinates, system ID, air temperature and humidity, and temperature, PH and DO of the water. The system is designed to gather all parameters in one message and in real-time periodically (every 15 minutes), especially that we are not expecting a significant fluctuation in the collected readings. The interval of logging data can be easily adjusted on the microcontroller based on the needs. Another cloud-based service, MongoDB Charts, is utilised for data aggregating, visualising, and real-time analysis.

An automated notification system is implemented on the server side to notify responsible clients each time the system fails using secure email (Fig. 1). Notification emails can alert the client of low battery voltage or failure in communication, data transmission and internet connection. Hence, we can take proper action by checking the availability of both the network and the power.

V. SYSTEM DEPLOYMENT AND EVUALTION

A. Study Area

Our study is conducted on the Portuguese Island of Madeira, located in the north-eastern Atlantic Ocean (32◦30′N and 16◦30′W), 900 km from mainland Portugal. A volcanic island,

[3] https://www.rshydro.ie/

and a large part of the island is inhabited. Madeira is known for its micro-climates and diverse ecology. The weather is always mild; the highest during summer is 24ºC, and the lower is 17ºC, while winter temperatures are lower by 4ºC [37].

The strong socio-economic relations between Portugal and South American countries, such as Brazil and Venezuela, have put Madeira Island at considerable risk of importing vectors and pathogens from these regions [38]. Moreover, studies found that *Ae. Aegypti* from Madeira[4] is potentially capable of transmitting viruses such as ZIKA, CHIKV and DENV. These findings indicate the implications of mosquito surveillance for Madeira Island [38]. The first reporting of *Ae. Aegypti* on Madeira was in 2005 in the island's capital, Funchal. Since then, this mosquito has been subsequently distributed throughout the island's southern coast [37].

Fig. 5 Deployment of the MOISS system at the Natural History Museum

Our study aims to provide real-time and continuous monitoring of weather conditions an d water quality around and in mosquito ovitraps distributed across Funchal to understand the potential impact of fluctuating in these variables on the distribution of *Ae. Aegypti* population. Sensory data obtained by the system will provide a solid basis for understanding mosquito habitat favouring, thus, supporting decision-making regarding disease prevention and control programs designed by the Madeira Health Authorities. Fig. 4 illustrates the location and distribution of mosquito ovitraps across the island.

B. System Deployment

A testing version of the MOISS has been configured and deployed in the field since November 2021 at the Natural History Museum of Funchal in Madeira Island, Portugal.

In this prototype version, three water sensors have been used DS18B20 Waterproof Digital Thermometer for water temperature and two sensors for pH and DO by Atlas Scientific. The system was powered by the main power sources at the museum. The three water probes were placed into the mosquito ovitrap, consisting of a ten-litre black plastic bucket filled with about 1.5 litres of tap water. The ovitrap has a red velvet-paper band fixed on a plastic ruler to catch the mosquito eggs, as shown in Fig. 5. The ovitrap has been placed at the entrance of the museum garden, which is considered to be partially shaded, and the system unit has been placed in a dry area to assure that the unit will not be exposed to any environmental conditions that could cause damage.

The ovitrap is inspected weekly by one of the environmental agents. During the routine inspection visit, the agent (i) changes the velvet-red band, (ii) records the number of eggs counted by using the binocular microscope and (ii) cleans and changes the bucket's water. However, for experimental purposes, we have asked the agent to follow the same strategy except for the weekly water change. Instead, they are changing the bucket's water biweekly for the sake of some variation in the data. The ground truth annotations recorded weekly by the agents on immature mosquitoes would be beneficial to understand the impact of physicochemical characteristics of habitats on the density and survival of mosquitoes' eggs and larvae.

A notable observation was that the pH and DO readings were structurally stable over that period, ranging from 6.75-8.12 and 3.01- 4.7 mg/L, respectively; we infer that this may be due to the water stagnation in the bucket (ovitrap). Thus, considering the effect of the water flow is crucial. Therefore, a slight change to the system's design is required to ensure the accuracy of the collected parameters. Finally, we haven't observed any change in the performance of the system unit or the sensors over this testing period (since November 2021), and there was no need to recalibrate the pH and DO sensors. The system was sufficiently able to record and transmit data every 15 minutes remotely and send a notification email in case of unexpected failures.

VI. Discussion and Future Work

In this work, we have introduced a continuous, independent mosquito ovitrap monitoring system. The system proved to be robust and versatile through successful pilot system deployment in Madeira Island over the previous six months. The smart ovitrap system has been designed for continuous environmental monitoring across large areas; however, the power supply and network are considered critical issues, particularly in the wild areas.

Using a battery (such as a Lithium or Lead Acid battery) would be the only viable method to power the system. Yet, batteries have a limited lifespan and cannot stand for a long time; plus, it is unlikely that researchers or environmental agents would be able to physically visit the installed devices regularly after deployment to replace the batteries. As such, solar panels are the optimal solution to recharge the battery and keep the sensors always powered. To this end, we designed our prototype of the system where a battery with a solar panel could be used as an alternative power source if required.

The mobile network could simply be unavailable at the site, which is still one of the ongoing challenges, or the signal could be poor or drop out for days for maintenance. As such, a micro-SD card can be used to store measurement data from the nodes when network connectivity is not available and then transmit the data whenever the system is reconnected.

A cloud-based broker was selected rather than a local server since it supports the setup of multiple broker instances, which provides high performance in terms of the number of subscribers

[4] https://www.iasaude.pt/Mosquito/

that a single broker can accommodate and the number of connections, as well as support for connecting different sensors deployed over a wide area. Furthermore, a cloud data platform has been used to store published data from the sensors. Although the volume of data collected through long-term continuous system monitoring requires consideration, we have not performed any remote analysis on the edge device (i.e.,edge-computing) at the point of data capturing due to several bases.

Our system is designed to be a general tool that could cooperate with other data, such as trap surveillance data collected by environmental agents and mosquito acoustic detection data; therefore, discarding some data could limit the analysis approaches. Moreover, performing any kind of remote analysis on the edge device would cause an increase in power consumption, creating an issue when a solar power system is in use.

According to the observations during the testing period, a mini micro water pump will be added to the water bucket to guarantee slight movements in the water, increasing the accuracy of the readings. Sensors will be expanded to include the water conductivity sensor, which reads the conductivity, total dissolved solids (TDS) and salinity based on the literature that emphasises the mosquito's species-specific behaviour. Lastly, a waterproof hardware enclosure needs to be adopted for outdoor deployment to offer excellent protection, insulation, and corrosion resistance.

A large-scale deployment is planned to be conducted in late July 2022 as a longitudinal study. This study will offer insights into the technical and logistical challenges of running and deploying such a system in the field and provide new insights into the relationship between fluctuating in weather and water variables and mosquito activity. The current plan is to select twenty mosquito ovitraps across Funchal, representing a quarter of the total number of ovitraps distributed in the capital (Fig. 4), to deploy the production version of the MOISS system presented here for running for at least six months period. Twenty ovitraps were picked based on certain criteria such as location, logistic challenges, and container characteristics. Environmental agents will collect ground truth data from all selected ovitraps.

The data and insights delivered by the IoT ovitrap monitoring system would be beneficial to many stakeholders, such as epidemiologists, meteorologists and public health authorities and will provide invaluable data for a mosquito's modelling tools and early warning systems. From a scientific perspective, the data gathered through the IoT-based system would help in building algorithms to predict the traps or areas of high risk of mosquito infestation, which could guide the environmental agents in their mosquito control efforts. It also contributes to our understanding of the possible impact of fluctuations in the environmental variables on mosquito presence and abundance.

The overarching goal of this work is to develop an early warning system by combing several data sources. This includes the involvement of more emergent technologies such as machine learning and mobile applications alongside the IoT. Deep machine learning algorithms will be developed to predict mosquito hotspot areas based on environmental conditions data (i.e., weather and water), adult mosquitoes' acoustic data [14] and data on immature mosquitoes. Currently, surveillance agents record immature mosquito data using traditional paper-based forms during routine surveillance visits. Therefore, a mobile application for mosquito surveillance is required to replace paper-based forms with real-time and digitised records in a central database. The mobile data will be used as ground truth data on immature mosquitoes and provide continuous iterative improvement and validation for the prediction system. The development of the Madeira surveillance app is a work in progress.

VII. Conclusion

Mosquito surveillance poses significant challenges and burdens on the inhabitants of tropical and subtropical regions. Currently, existing surveillance methods and techniques are characterized by substantial limitations. Data continuity, adequacy, quality, and frequency are not usually sufficient for the finest spatial analysis and modelling. In terms of applicability, it is considered time-consuming and requires specific expertise.

This work outlined the architecture design, implementation and deployment of an innovative ovitrap monitoring system that leverages state-of-the-art IoT technologies for continuous weather and water monitoring in mosquito ovitrap. The implemented system is highly reliable and scalable (i.e., it can be deployed at various site configurations), allowing large-scale field studies. The cost of the system is significantly reasonable when compared to existing alternatives.

The system has been successfully deployed and operated at the Natural History Museum in Funchal, Madeira Island providing the local surveillance agents with new means of monitoring environmental conditions in and around the ovitraps. The current plan for the system is to be expanded to cover twenty different sites across Funchal for a large-scale field study. Discussions and proposals have been concluded, and a further twenty systems will be deployed in late July 2022 for six months after some enhancements to be made based on the pilot observations.

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