MIRMS: A Case Study on Smart, Responsive IoT Solution for Mosquito Habitat Monitoring

Aisha Aldosery‡∗ , Dinarte Vasconcelos†, Miguel Ribeiro†, Ella Browning∗, Anwar Musah∗, Bruna Gouveia§, Nuno Nunes† and Patty Kostkova∗
Email: {aaldosery@kacst.gov.sa} {dinarte.vasconcelos, jose.miguel.ribeiro, nunojnunes}@tecnico.ulisboa.pt
{ella.browning.14@alumni.ucl.ac.uk} {bruna.gouveia@madeira.gov.pt} {a.musah, p.kostkova@ucl.ac.uk}
∗UCL IRDR Centre for Digital Public Health in Emergencies, University College London, London, United Kingdom.
†ITI/LARSyS, Instituto Superior Técnico, Lisbon, Portugal.
§Regional Directorate of Health, Secretary of Health of the Autonomous Region of Madeira, Funchal, Madeira Island
‡ King Abdulaziz City for Science and Technology (KACST), Riyadh, Saudi Arabia

***Abstract*—The integration of cloud computing and Internet of Things (IoT) technologies has significantly advanced environmental monitoring, yet its application in critical public health domain such as mosquito surveillance, remains limited. This paper introduces an innovation solution, the Mosquito IoT Responsive Monitoring System (MIRMS), which boosts mosquito surveillance by employing real-time monitoring of key environmental variables critical for mosquito breeding. By integrating a combination of weather and water sensors with cloud technology, it provides continuous and precise monitoring, moving beyond traditional portable multiparameter meter methods. However, implementing such systems in real-world environments poses challenges, particularly in system design and testing across diverse field settings and scenarios. We describe the stages of design, development, and practical use of MIRMS, highlighting the selection criteria that led to the hardware and software architecture design. We also demonstrate how the system's design has evolved in response to the challenges encountered during real-world deployment, contrasting these experiences with controlled settings. This study validates MIRMS as a robust mosquito surveillance tool that not only improves the data collection process but also supports real-time decision-making and efficient resource management, providing key lessons for future IoT deployments in public health.**

Keywords—Habitat Monitoring, Mosquito Surveillance, Internet of Things, IoT Architecture, Real-World Deployment, Digital Health.

I. Introduction

In an era where Internet of Things (IoT) technology is applied across an increasingly diverse range of fields and settings, its use in public health, specifically for combating mosquito-borne diseases, is both revolutionary and imperative. Traditional methods of mosquito surveillance, which rely heavily on manual efforts and generalised data, are in stark contrast to the precise, real-time monitoring potential that IoT provides.

Mosquito surveillance is crucial for controlling the spread of mosquitoes in regions vulnerable to vector-borne diseases. Monitoring breeding sites is essential for preventing infestations and outbreaks, as it supports understanding of mosquito oviposition, which significantly enhances predictions of population dynamics and responses to control measures. However, precisely identifying and monitoring these sites continues to pose a significant challenge [1]. To address this, environmental health agents perform routine ground surveillance activities, such as monitoring mosquito oviposition traps (ovitraps) and collecting water samples. These tasks necessitate effective resource management to strategically direct agents to areas most likely impacted by mosquitoes, thus emphasising the importance of identifying potential hotspots in advance.

Weather conditions [2] and water physicochemical parameters, such as Potential of Hydrogen (pH), Dissolved Oxygen (DO), and Electric Conductivity (EC) [3][4], are critical indicators that influence mosquito breeding and lifecycle. Monitoring these parameters at high resolution, such as at the ovitrap-level, can significantly enhance the accuracy of surveillance systems.

By leveraging cutting-edge IoT technology to directly measure key environmental determinants, we developed the Mosquito IoT Responsive Monitoring System (MIRMS). This system marks a paradigm shift towards automated, high-resolution monitoring of mosquito habitats, a critical advancement in vector control strategies. MIRMS represents a significant breakthrough in mosquito surveillance, collecting real-time and high-resolution environmental data at the ovitrap-level. This precision significantly enhances the accuracy and efficiency of mosquito surveillance systems and provides data for modelling and early warning of mosquito breeding addressing the urgent need for more effective vector control methods. Moreover, it developed in collaboration with Brazilian and Madeiran environmental agencies, leverages local expertise to enhance its design and effectiveness in real-world surveillance.

MIRMS significantly advances existing mosquito surveillance technologies, which typically depend on sporadic and low-resolution data (i.e., remote sensing, weather station). By automating the integration of climatic and aquatic data, MIRMS enhances data collection precision, resolution, and efficiency, substantially reducing the need for manual interventions and frequent field visits. Developed with substantial input from key stakeholders, it is the first system to implement real-time, IoT-based high-resolution monitoring directly at mosquito breeding sites. This innovation fills crucial gaps in earlier systems, boosting predictive accuracy and operational efficiency for more effective public health interventions.

The main contributions of this work are: (1) the establishment of a modular software architecture enabling seamless communication between sensors, devices, cloud services, and databases; (2) a comprehensive account of the system's iterative design and evolution, underscoring the technical adaptations and innovations in hardware and software essential for successful field deployment; and (3) valuable insights into navigating the challenges encountered during real-world deployment, contributing to the broader discourse on IoT applications in public health surveillance.

II. Related Work

The management of mosquito populations presents distinct challenges that critically distinguish it from broader environmental monitoring practices, such as wildlife [5] or forest health tracking [6]. This differentiation is crucial in deploying IoT technologies for mosquito surveillance, highlighted by the development and application of MIRMS. Mosquito surveillance necessitates addressing specific life cycle stages; egg, larva, pupa, and adult - each requiring tailored detection and management strategies. Unlike wildlife [5] [or forest monitoring [6], which utilise IoT technologies to track broader ecological indicators such as animal movements or general forest health, mosquito surveillance requires a more targeted approach. This involves precise, real-time monitoring of specific micro-environmental factors [2][3][4]. While wildlife and forest monitoring are crucial for ecological research, the granularity and immediacy required for mosquito surveillance are particularly challenging. The need for high-resolution data to effectively prevent disease outbreaks underscores the unique technical demands and critical importance of targeted vector surveillance.

Furthermore, scaling traditional methods, such as ovitraps and manual water inspections, pose significant challenges due to labour-intensive processes and high costs, limiting existing environmental monitoring systems for effective mosquito management [7]. These methods also suffer from environmental constraints that can impair data quality, an issue less prevalent in other forms of monitoring. Environmental monitoring systems, such as those used for wildlife monitoring, typically rely on broad geographical data (i.e., macro-scale), and do not typically require the high-resolution observations, contrasting sharply with the micro-environmental focus necessary for mosquito lifecycle management [8]. Mosquito surveillance requires detailed monitoring of factors crucial to mosquito breeding cycles and population dynamics. Given that each mosquito species adapts to its local environment, a granular approach is essential for accurately understanding and managing their populations. Moreover, the direct public health implications of mosquito-borne diseases necessitate a more dynamic and responsive monitoring system, capable of integrating diverse data types for predictive modelling and immediate vector control interventions [7].

MIRMS represents a pioneering step in leveraging IoT technologies to offer a comprehensive solution tailored to the nuanced demands of mosquito surveillance [7][9]. Its design philosophy, focusing on non-intrusive monitoring and minimising ecological impact, sets it apart from traditional approaches. By integrating data from mosquito trap sensors with environmental condition metrics, MIRMS provides a real-time understanding of mosquito population dynamics, a capability not afforded by generic environmental monitoring systems [9]. This specialised system is uniquely engineered to address the intricacies of mosquito population management, underscoring the importance of bespoke vector control strategies. Such targeted interventions significantly contribute to public health by aiming to mitigate the transmission of mosquito-borne diseases, highlighting the critical role of precise and focused surveillance in controlling mosquito lifecycles.

III. System Design and Architecture

A. IoT Architecture

The MIRMS system follows a five-layer IoT architecture, ensuring effective operation within the established layers [10]. This modularity is crucial, as it allows the system to easily integrate additional sensors and communication methods, thereby expanding its functionality without the need for extensive redesign. Such adaptability is a hallmark of a well-structured IoT system, designed for progressive evolution and expansion in adherence to layered architectural principles. To enhance scalability, particularly for large-scale deployment, the system's design accommodates the potential inclusion of long-range communication technologies like LoRa and solar panel, addressing limitations of GSM, WiFi and main power. Moreover, it supports the various sensors additions, such as cameras or acoustic sensors, expanding its functional range and application potential. The following points describe how MIRMS layers aligned with the IoT architecture.

Perception Layer: this layer (aka Physical layer), equipped with a suite of sensors weather and water quality sensors, and an Arduino microcontroller acts as the nerve centre at this layer, collecting and preparing environmental data for transmission. Its modularity enables integrating sensors tailored to specific conditions, ensuring adaptability.

Transport Layer: this manages communication protocols and networks, which together facilitate the efficient movement of data from the perception layer through to the processing systems. The MIRMS system is designed to include the use of either GSM or WiFi based on the deployment requirements.

Processing Layer: the backbone of data management, this layer uses Heroku's[1] cloud computing resources for scalability, accommodating varying data rates and potential real-time collection needs.

[1] https://www.heroku.com/platform

Middleware layer: this layer manages the integration and intermediate processing of sensor data, ensuring efficient data flow between layers. CloudMQTT [2] manages message brokering, and MongoDB provides robust data storage and analysis capabilities, facilitating the transition of processed data to the application layer.

Application Layer: MongoDB Atlas Charts [3] serves as the visualisation tool, presenting the data in an interactive format that enables end users to make informed decisions based on real-time environmental information.

IV. Hardwre Componennts and Setup

This section outlines the components used across all three iterations of MIRMS's, including a review of the hardware components, weather and water sensors, and the water pump. Details specific to the design and usage of these components in each iteration will be deferred to the subsequent sections.

A. Hardware Components

In the architectural design of the MIRMS system, the selection of a core microcontroller was influenced by various factors: data processing type, power efficiency, computational requirements, network connectivity, and sensor compatibility. The Arduino series, known for its 5V logic compatibility and lower power consumption, was identified as the most suitable choice. Initially, the Arduino MKR GSM 1400 was selected for its integrated GSM connectivity in the first two iterations. However, due to its discontinuation and the specific technical requirements of the Atlas sensors, the Arduino UNO was chosen for the third iteration.

B. Sensors and Water Pump

A range of "off-the-shelf" sensors, employed for weather and water quality monitoring, along with a water pump, were integral to the system's functionality to monitor the essential environmental variables for mosquito breeding.

Weather Sensors: the system employs two low power consumption weather sensors the DHT22 and the BME280 for meteorological data collection, selected for their low power consumption and precise measurement. The DHT22 measures temperature (±0.5°C precision) and humidity (±2-5% RH accuracy), while the BME280 offers similar accuracy for humidity and temperature, adding atmospheric pressure readings for more comprehensive analysis. This dual-sensor setup ensures robust and precise data collection, guarding against potential data discrepancies.

Water Sensors: the system employs Atlas Scientific EZO series sensors to monitor water quality parameters such as, pH, DO, EC, TDS, and salinity, complemented by the DS18B20 water temperature probe, renowned for its accuracy and one-wire communication. The choice of Atlas Scientific's water quality sensors was primarily motivated by their affordability, availability, and compatibility with Arduino-based systems, crucial for integration. Atlas Scientific, is renowned for its extensive experience in producing high-performance sensors, widely recognised in scientific research. This reputation, coupled with the proven reliability of its sensors in numerous projects, affirmed their suitability for our precise aquatic environment monitoring needs [11]. Calibration of the Atlas sensors, essential for data integrity, was performed in a controlled environment at ±1° from 25° C in UART mode, following the manufacturer's instructions, using the Arduino UNO microcontroller.

Submersible Pump Motor: the integration of the DC Mini Submersible Water Pump is a significant enhancement, designed to improve sensor reading accuracy by promoting consistent water movement and reducing stagnation, particularly affecting DO levels. Chosen for its quiet operation to minimise noise and turbulence, which could affect sensor precision or disturb mosquitoes, the pump operates at a low voltage of 3-6V. It efficiently processes up to 120 litres per hour with minimal power consumption, maintaining a low current consumption of 220mA. This novel combination of the water and weather sensors with the water pump is the first hardware architecture of its kind.

V. Software Development and Behaviour

The software architecture of the MIRMS system comprises two primary components: an Arduino-based client functioning as the publisher, and a Node.js server-side application that subscribes to and processes the data.

A. Client-Side

The Arduino client initiates sensor communication protocols and establishes a network connection, GSM or WiFi, based on the microcontroller used. The water pump, activated intermittently, agitates the water for five second to enhance sensor reading accuracy. Subsequently, water temperature is measured, aiding the system in intelligently compensating for temperature-related variations in sensor readings, especially for DO sensor. Following this, data from all sensors is collected, compiled into JSON format, and published to the MQTT broker using client credentials. The process, governed by the **delay()** Arduino function, ensures regular data collection from all six sensors, with the system idling until the next interval, continuously monitoring for errors. The software exemplifies a high standard of programming proficiency, evidenced by strategies such as modular function design, the judicious selection of efficient data types, meticulous handling of sensor reading failures, and proactive power management through timed activation of the water pump.

B. Server-Side

The Node.js server-side application in the MIRMS system, serves as a data handler, tasked primary with processing and storing environmental data received from the Arduino client. It serves as the intermediary layer, facilitating data transfer from Arduino's collection to the end-user's visualisation. The application is hosted on Heroku server. This server-side setup comprises Express.js for HTTP request management, Mongoose for MongoDB interfacing, and MQTT client libraries for subscribing to data topic, selected for their publish-subscribe model, which offers unparalleled efficiency in handling sporadic network connectivity and low-power requirements, making it

[2] https://www.cloudmqtt.com/

[3] https://www.mongodb.com/docs/charts/

inherently superior for real-time, distributed IoT environments like MIRMS compared to the traditional client-server protocol.

Upon connecting to the MQTT broker, the Node.js server subscribes to relevant topics, anticipating incoming JSON-formatted messages with the environmental parameters that are parsed for data extraction and validation. The integration of the system with MongoDB features a crucial data validation function. This function scrutinises the JSON payload received from the MQTT broker, comparing sensor readings with predefined error indicators from their datasheets. This ensures database integrity by storing only valid data, enhancing monitoring system reliability and accuracy. Validated data is stored in MongoDB within a schema-specific collection.

The system is enhanced by a bespoke notification mechanism within its server architecture. This feature sends email alerts to system administrators or designated users under certain conditions, such as when data from a specific device is not received as per predefined intervals, or when discrepancies in environmental data are detected. Integrating the email notification system ensures prompt and efficient communication in response to potential environmental issues, improving the overall monitoring and management process. This critical component keeps stakeholders well-informed, enabling swift action in response to any system failures or sensor data issues.This software architecture, with its focus on error-handling and data validation, ensures consistent monitoring, fulfilling the system's aim of providing precise, reliable, and timely environmental data.

VI. Iterative Solutions and Deployment

This section traces the evolution of the MIRMS system across three iterations, each signifying a development and refinement phase that enhance precision, robustness and reliability as well as introducing novelty in terms of the hardware architecture. Each iteration will be examined in terms of five aspects: system components, circuit design, hardware housing, field deployment, and observations.

A. Iteration 1: Prototype and Pilot Deployment

This initial iteration, serving as the pilot of the system, laid the foundation for all subsequent iterations.

System Design: The MIRMS system's initial design utilised the Arduino MKR GSM 1400 microcontroller for environmental monitoring, employing DHT22 and BME280 sensors for atmospheric data, complemented by Atlas Scientific components for aquatic measurements (pH and DO), and the DS18B20 for water temperature. In its testing phase, rapid six-second data sampling intervals were employed to evaluate system stability and sensor responsiveness, prioritising technical assessment over sustainable data transmission. Network connectivity was facilitated by the system's built-in GSM feature along with an Arduino-compatible antenna and standard SIM card. While the system's power supply was successfully implemented and tested using a solar panel in a lab setting, it was not deployed in the field as a stable power socket was always available, making it the preferred choice for consistent power during deployment.

Circuit Design: the circuit design of the prototype centers around the Arduino MKR GSM 1400 microcontroller, incorporating a multi-protocol approach for sensor communication. The DHT22 sensor communicates via a signal-wirw protocol, transmitting digital signals that encode temperature and humidity readings. While the DS18B20 water temperature sensor employs the OneWire protocol, and the Atlas Scientific sensors utilise the I2C protocol. This setup enables efficient handling of diverse sensors. The Arduino board is programmed and powered via a micro-USB connection, highlighting the prototype's design focus on simplicity and ease of use. This prototype, a custom, hand-assembled unit, reflects the early-stage development and iterative nature of the design process.

Enclosure: The prototype's housing, constructed from 3 mm medium-density fibreboard (MDF), was precision-cut using a CNC laser to accommodate sensor interfaces and water inlets, providing adequate protection for indoor deployment. However, it necessitated a more robust solution for use in external environments.

Field Deployment: The initial deployment was at the Madeira Natural History Museum, where it was integrated into a mosquito ovitrap. It comprised a ten-litre black plastic bucket containing approximately 1.5 litres of tap water. A red velvet-paper band was affixed to a plastic ruler for collecting mosquito eggs (Fig.1). The ovitrap was strategically positioned at the entrance of the museum's partially shaded garden, while the system unit was placed in a dry area to ensure protection from environmental conditions. The ovitrap was inspected weekly by an environmental agent. During these routine inspections, the agent (i) replaced the red velvet band, (ii) counted and recorded the number of eggs using a binocular microscope, and (iii) cleaned and changed the water in the bucket. However, for experimental purposes, we instructed the agent to retain the same strategy except for the frequency of water changes. Instead of weekly, the water in the bucket was changed biweekly to introduce variation in the data. The weekly ground-truthed data annotations made by the agents on immature mosquitoes are invaluable in understanding the impact of weather and physicochemical characteristics of habitats on the density and survival of mosquito eggs and larvae.

Observations: During testing, pH and DO levels showed remarkable consistency, suggesting a non-dynamic environment, likely due to water stagnation. This underscored the need to integrate a water movement mechanism for more accurate readings. Furthermore, the necessity for sustainable, robust housing, possibly using 3D printing or specially designed outdoor boxes, became evident. The temporary use of a standard SIM card highlighted the need for a permanent networking solution in future iterations. Impressively, the sensors-maintained accuracy for over a year without recalibration, consistently transmitting data at set intervals and successfully

B. Iteration 2: Enhancements and Modifications

The second version of the system, building on the initial iteration, featured key enhancements in design and deployment, to improve robustness, reliability, and accuracy, informed by insights from the pilot study.

System Design: In this enhanced iteration, while retaining the core Arduino board and existing sensors, the sensor array for water quality monitoring was augmented by introducing the electric conductivity sensor to measure EC, TDS, and salinity. This addition is pivotal for understanding species-specific mosquito behaviour [3]. To address the critical issue of water stagnation and its impact on sensor reliability, a submersible mini-micro water pump was integrated, thereby improving the accuracy of sensor readings by creating subtle water movements. In parallel, network connectivity was upgraded with the introduction of a dedicated IoT SIM cards from Things Mobile[4]. This development not only facilitates comprehensive SIM card usage monitoring but also provides a scalable and reliable solution for global IoT deployments.

Complementing hardware enhancements, software improvements now include temperature compensation for DO and EC measurements. The system uses water temperature sensor readings to adjust DO and EC outputs, ensuring accuracy despite environmental temperature fluctuations. Furthermore, the data collection interval was optimised to five minutes, striking a balance between effective monitoring and conservation of data usage.

Circuit Design: this iteration's circuitry, building on the initial design, added an extra Atlas sensor via the I2C protocol and integrated a submersible micro water pump. The pump is operating within a 3-6V range and was connected to the Arduino's 5V output, controlled by a TIP41C NPN transistor acting as a digital switch. A resistor was included to align with Arduino specifications and regulate the pump's base current. Additionally, an IN4007 diode was installed in parallel with the motor as a flyback diode, essential for dissipating energy and protecting the circuit from reverse currents when the transistor turns off. Furthermore, the system's circuitry was transposed onto a professionally fabricated printed circuit board (PCB), ensuring a neat assembly and robust connections for all components. Terminal blocks and connectors were utilised to securely integrate the sensors and water pump into the system.

Enclosure: The initial MDF housing was replaced with a commercially procured electrical box, selected for its durability and suitability for outdoor environments. This enclosure was custom-modified with precision-drilled apertures for the sensors and water pump. Furthermore, a net-like pattern of holes was created on one side, overlaid with a protective shield, to facilitate air exchange while preventing water ingress (Fig. 1).

Field Deployment: Thirteen devices were strategically deployed across the city of Funchal, Madeira Island, encompassing schools, ports, hospitals, a university residence area, a museum, and governmental offices. This deployment aimed to gather a comprehensive dataset on the local mosquito population. The specifications of the ovitraps and the data collection strategy regarding mosquito eggs and larvae remained consistent with those used in the first iteration (Fig.1).

Observations: The second iteration featured significant enhancements such as an expanded sensor array, temperature compensation, and a micro water pump. These improvements generally yielded positive results, but also revealed challenges, pointing towards further development needs.

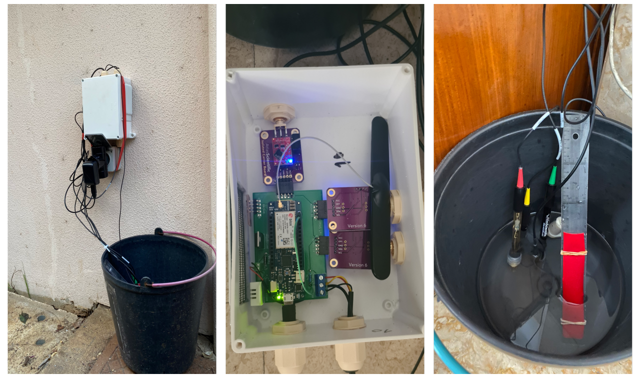

Fig. 1 Iteration 2 - Deployment of the Second Version on Madeira Island.

A key addition was the micro water pump, introduced to mitigate the impact of static water on sensor precision. Although it enhanced environmental sampling by stimulating water movement, its long-term operation was impeded due to its 180mA electrical demand, surpassing the Arduino's 5V pin capacity of 40mA. Furthermore, the pump's high start-up current exerted strain on the microcontroller's circuitry. Although initially a TIP41C transistor as a digital switch effectively managed the pump, the Arduino's digital pin's current limit soon became evident. This highlighted the need for an intermediary in motor control for handling higher currents or voltages, underlining the importance of a specialised power solution and thorough testing to resolve such issues.

The choice of standard electrical boxes for hardware housing, while robust, introduced practical constraints. The absence of transparency required frequent manual checks to confirm the system's functionality, a time-consuming and inefficient process. In response, the housing design will be revised for enhanced access and monitoring.

Conversely, employing professionally manufactured printed circuit boards (PCBs) significantly enhanced the reliability of component assembly, aiding effective deployment across various locations. Moreover, transitioning to a dedicated IoT SIM card from Things Mobile greatly improved network reliability and management with the cost remained effective, with a pay-per-use plan priced at €0.10/MB. The platform's advanced features for overseeing SIM cards and remote control, including credit top-up capabilities, were crucial for uninterrupted data transmission from the units.

Despite these advancements, the water pump operational challenges underscore the necessity for thorough, extended component testing, especially when integrating mechanical and

[4] https://www.thingsmobile.com

electronic components. These insights and experience were crucial for developing a robust system in future iterations.

C. *Iteration 3: Final Refinements*

A key change in this version was the switch to the Arduino UNO board, resulting in considerable alterations in circuit design and a shift to a new study area (Recife, Brazil).

System Design: This iteration integrates an Arduino UNO microcontroller, enhanced with a WiFi module and dongle to bolster connectivity and data handling. Yet, the sensor array and water pump configuration have been retained from the previous design. The networking was specifically tailored to suit the field area in Brazil. The reliance on standard SIM cards with a data plan emerged due to the limitation of Things Mobile IoT services for SIM cards in the region. However, the frequent instability of SIM card connections has prompted considerations for alternatives, such as WiFi routers or potentially LoRa technology, to ensure reliable data transmission. Additionally, the system's reliance on mains power, rather than solar panels, was dictated by logistical challenges in the field, although the local environmental conditions suggest that exploring solar-powered options could be beneficial in future deployments.

In terms of software, the primary change was extending the data collection interval to 60 minutes, focusing more on the breadth of data collection.

Circuit Design: The transition to the Arduino UNO board marks a significant shift in the circuit architecture, introducing advanced components, a key change is the integration of the ESP8266 WiFi module, chosen for its wireless capabilities. However, this necessitated complex wiring solutions to harmonise its 3.3V logic with the UNO's 5V system. Moreover, this iteration has addressed previous power management issues with the water pump. Through meticulous re-engineering, the pump's functionality has been optimised, significantly boosting the system's reliability and longevity.

The following paragraphs detail the critical modifications made to the circuit design, illustrating how these enhancements synergistically improve its performance. From power regulation to communication protocols, every element has been refined to meet system requirements.

The power supply strategy has undergone significant optimisation to improve functionality and reliability. The Atlas Scientific sensors and DHT22 continue to be powered directly from the Arduino UNO's 5V pin. The BME280 sensor and ESP8266 module, requiring a 3.3V supply, are now powered via a dedicated voltage regulator, ensuring they receive the correct voltage for optimal performance. This careful voltage management is crucial to prevent damage and ensure accurate data measurement and communication.

The water pump's power supply has been notably revised. Instead of drawing power from the Arduino, it is now connected to an independent external power supply, chosen for its adaptability and safety. The selected universal AC/DC adapter offers an adjustable DC output from 3V to 12V, up to 2A, and a USB output, accommodating the pump's requirements. With safety features like overvoltage, overcurrent, short-circuit, and overheating protection, this change rectifies the previous iteration's power issues, ensuring the pump's uninterrupted and stable operation. These power supply enhancements mark a strategic step towards greater system autonomy and resilience, for delivering reliable data.

To facilitate communication between the 5V Arduino UNO and the 3.3V sensors and modules, the circuit design incorporates voltage regulation and logic level shifting components. This integration safeguards sensitive parts from potential high-voltage damage by maintaining safe voltage levels during interactions. The LD1117V33 voltage regulator provides a stable 3.3V supply to the ESP8266 module and the BME280 sensor. Complementing the voltage regulation, the BOB-12009 bi-directional logic level shifter enables effective communication between devices with different voltage requirements. It converts the 5V I2C signals from the Arduino to 3.3V, facilitating bidirectional compatibility. The converter's HV side connects to the Arduino's 5V output, while its LV side interfaces with the 3.3V line, ensuring the safe operation of components across varied logic levels. Together, the voltage regulator and the logic level shifter perform harmonious functions: the former ensures the right operating voltage for each component, while the latter modifies signal voltages for precise data exchange within the system's mixed-voltage environment.

The circuit incorporates a complex wiring scheme to support the various communication protocols needed by its components. The I2C protocol is employed for the Atlas and BME280 sensors, while serial communication via SoftwareSerial is established with the ESP8266. Additionally, the DHT22 sensor utilises a digital signal, and the DS18B20 water temperature sensor employs the OneWire protocol. This integration ensures synchronised operation of all system components for optimal performance.

To summarise, this advanced circuit design skilfully integrates voltage regulation and logic level adaptation, significantly enhancing the MIRMS system's reliability. The meticulous planning inherent in each design decision is thoroughly documented in detailed schematic.

Enclosure: The enclosure design continues to utilise standard electrical boxes, customised to meet our specific needs and closely resembling the design used in the second iteration. A notable enhancement in this version is the addition of a transparent LED and clear numbering on the top, streamlining issue reporting, debugging, and maintenance processes.

Field Deployment: in September 2023, the updated version was deployed in the Nova Descoberta neighbourhood of the city of Recife, Brazil. Three out of seven devices installed were connected to household routers, while the others used dongles with local SIM cards. The ovitraps used differed from those in Madeira. The ovitraps were smaller and made from halved 1.75-litre soda bottles painted black and filled over halfway with water. They also featured a wood fibre strip for egg attraction and were suspended one metre above ground (Fig. 2). Unlike Madeira's weekly maintenance, the environmental agents in Brazil visit these traps once a month for data collection and water refilling, without cleaning the bottles. This homemade nature and the ovitraps' smaller size necessitate creative solutions for sensor and pump placement, presenting unique challenges and raising concerns about the impact of ovitrap characteristics on reading accuracy.

Observations: from a technical perspective, a notable observation in this iteration was the memory limitations of the Arduino UNO. This issue became increasingly prominent as system complexity grew, especially with the introduction of more advanced code. It highlights the necessity for either software optimisation or the adoption of alternative microcontrollers with larger memory capacities to improve system stability and functionality. Additionally, the network availability and power stability were significant challenges in this study area. Concurrently, the implementation of an independent power supply for the water pump marked a significant improvement. It effectively resolved the power delivery issues encountered previously, emphasising the critical role of bespoke power management strategies for components with high power demands within the system.

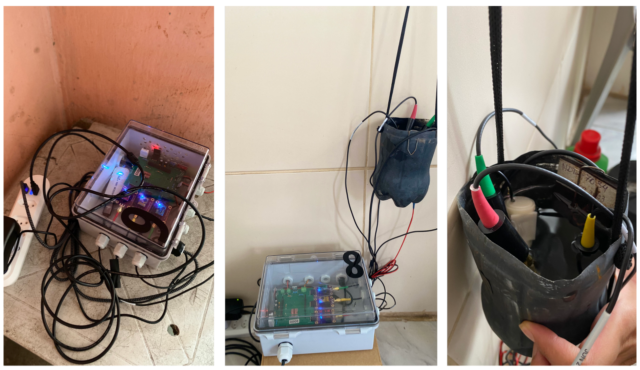

Fig. 2 Deployment of the last version of MIRMS in Recife, Brazil.

VII. Discussion and Future Work

The development and deployment of MIRMS across three phases have provided substantial insights, rich in both technical aspects and real-world deployment. The final iteration showcases a comprehensive understanding of the complexities involved in developing such a system, marking significant advancements over previous versions. However, further challenges remain.

In our investigation of sensor technology and board design, we encountered challenges, especially with the DHT22 sensor in humidity measurement. The sensor often provided inaccurate readings after prolonged exposure to high humidity environments, a phenomenon known as sensor saturation. This issue causes the sensor to struggle with accurately measuring humidity, often erroneously reporting 90-100% humidity. Recovery time for the sensor varied from a week to no recovery at all. This led us to re-evaluate our sensor selection, considering the adoption of high-quality weather sensors. Consequently, we increasingly relied on the BME280 sensor, which consistently outperformed the DHT22 under these challenging conditions.

A noteworthy technical consideration is the effect of sensor proximity within the system. The conductivity sensor's proximity to other water sensors disrupted their readings, underscoring the importance of strategic sensor placement and the timing of data collection, especially in compact settings. Introducing time intervals between water sensor readings and enlarging the 3D printed probe holder served as interim solution This approach, while effective, emphasised the need for a more integrated design that includes spatial considerations in future iterations. Sensor interference became particularly pronounced in the constrained environment of the ovitrap setup, contrasting with the large ovitrap used in Madeira.

The selection of the core board for the MIRMS system required balancing power consumption, memory capacity, and compatibility with diverse components. The complexities of managing these components, each with unique voltage and communication requirements, suggested the advantages of a custom-designed circuit board. Such a bespoke board would streamline the architecture and enhance stability and efficiency, optimising both hardware and software integration. Our exploration highlighted the limitations of standard boards like the Arduino UNO, particularly in terms of memory for complex code and the need for extensive additional components such as transistors, resistors, and diodes. Even boards like the MKR GSM 1400, while suitable for GSM, faced challenges in Wi-Fi integration. Furthermore, the Arduino's limited current output necessitated separate power supplies for components like the water pump. A custom circuit board, with larger memory and higher current outputs, could eliminate the need for external power sources and support both GSM and Wi-Fi connectivity. The inclusion of adjustable voltage regulators and modular slots for component integration would further enhance flexibility and scalability, meeting evolving project requirements.

Cellular network unreliability necessitated exploring GSM, WiFi, and LoRa for connectivity, with local conditions guiding the choice. The MKR GSM 1400 board equipped with GSM and Things Mobile SIM cards, proved effective on Madeira Island due to stable networks and a supportive platform for usage monitoring and recharging. However, in Brazil, network coverage was spotty, LoRa infrastructure was impractical and consistent household WiFi access was limited. Therefore, local SIM cards and dongles were used instead, due to regional limitations with Things Mobile. This experience underscored the value of local data storage solutions, like memory cards, for data collection, despite their limitations for real-time monitoring. Nevertheless, they are useful for developing predictive models. LoRa, despite its infrastructural demands, emerged as a potential reliable data transmission solution, outperforming GSM, and WiFi.

Unlike in Madeira, where power stability was not an issue, the location of domestic power sockets in Brazilian households posed a challenge. These sockets, often handcrafted by extending existing cables, lacked structural soundness, and posed safety concerns due to the risk of device malfunction from unstable electrical supply. Consequently, solar panels were considered as a potential solution; however, the establishment of solar panel infrastructure in Brazil faced logistical, financial, and potential theft challenges.

Additionally, the standard one-meter length of water sensor cables, like those used with the Atlas EZO circuit, were often insufficient, necessitating longer cables. However, extended cables might act as antennas, picking up environmental electrical noise, particularly for pH probes. This underscores the need for a balanced approach to cable length and signal interference, highlighting the importance of considering local environmental and infrastructural factors in system deployment.

The software architecture presents several avenues for enhancement, capitalising on the robust foundation of programming proficiency already established. Key areas for improvement include integrating dynamic power management techniques beyond timed water pump activation and implementing event-driven or sensor-based activation to further optimise energy usage. Additionally, refining sensor communication protocols to adapt data collection frequency and granularity based on environmental changes could enhance data relevance and reduce overhead. Adopting advanced data compression techniques and adjusting data collection frequencies before transmitting to the MQTT broker can significantly alleviate network bandwidth constraints, ensuring the system's efficiency and viability across large-scale deployments, even within the bandwidth limitations of long-range communications like LoRa. Thus, efficient handling of real-time data underscores the system's adaptability to dynamic environmental monitoring requirements. Finally, advancing error monitoring to incorporate predictive maintenance could minimise downtime and enhance reliability. Each enhancement would leverage the system's existing strengths, pushing the boundaries of environmental monitoring with IoT technologies.

These insights underscore the critical role of iterative design in IoT systems, particularly in diverse and complex environments. Each challenge we addressed led to a more robust solution. However, real-world deployment presented significant challenges beyond system architecture, involving the practicalities of technology deployment in unpredictable field conditions. This highlights the importance of adapting to local environments for effective implementation of such innovation. The contrasting conditions in our study areas showed how real-world deployment impacts system design, emphasising the need for a thorough evaluation of local settings before implementing digital innovations, to ensure both technical soundness and practical feasibility.

VIII. Conclusion

This paper presents the evolutionary journey of the MIRMS, representing a pivotal advancement in combatting mosquito-borne diseases through heightened surveillance. Developed through iterative design phases, MIRMS has undergone meticulous refinement, drawing upon field deployment data to enhance its architecture, hardware, and software significantly. The system's inherent modularity and adaptability underscore its suitability for deployment in diverse environmental contexts, effectively addressing concerns regarding sensor accuracy and reliability. The MIRMS system marks a significant leap in mosquito surveillance, introducing a more efficient, data-driven methodology.

Future efforts will focus on addressing sensor accuracy and reliability across diverse conditions while also exploring the system's operational parameters to enhance energy efficiency and reduce duty cycles. This includes optimising sampling rates, processing speeds, and data transmission rates to balance data fidelity with energy conservation. The overarching aim of our research is to collect spatially and temporally relevant data for an advanced predictive model. This model will leverage data from MIRMS sensors and integrate it with a mobile application designed for field observations of mosquito eggs and larvae, aiming to accurately pinpoint potential mosquito breeding hotspots. Ultimately, this enables proactive mosquito control by predicting the location of breeding sites in advance and displaying these spots on a dashboard. This comprehensive approach enhances the effectiveness of vector management strategies by facilitating timely interventions.

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