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IOT-BASED SOLUTION FOR DISEASE VECTOR MOSQUITO MONITORING

DIEGO AUGUSTO AMORIM SANTOS

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To my family.
Especially to my mother, Maria de Jesus Alves de Amorim,
and my life partner, Marcos Rodrigues Camurri.

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Contents

List of Figures

List of Tables

Abbreviations

BI	Breteau Index
DC	Direct Current
FFT	Fast Fourier Transform
FoV	Field of View
GPRS	General Packet Radio Services
HF	High Frequency
HTTP	HyperText Transfer Protocol
ICT	Information and Communication Technology
IoT	Internet of Thnigs
JSON	JavaScript Object Notation
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MBD	Mosquito-Borne Diseases
MDF	Medium-Density Fiberboard
MQTT	Message Queuing Telemetry Transport
PCB	Printed Circuit Board
PF	Photonic Fence
PWM	Pulse Width Modulated
RGB	Red Green Blue
SNR	Signal-to-Noise Ratio
WHO	World Health Organization

Abstract

The study of acoustic properties of flying insects wingbeats allowed advances of sensing mosquitoes in free flight. The determination of particular wingbeats frequencies and respective harmonics of each species is the basis of frequency spectrum analysis approach in acoustic and optical traps for mosquitoes detection in the field. Studies based on acoustic devices, microphones, amplifiers, and recorders have generated great contributions and database. However, it was only when optical approaches were deployed in the detection of flying insects that sensor devices became smaller, faster, self-triggered, and more reliable and energy efficient. These benefits enable the State of the Art to move towards smarter mosquito traps that automatically process data and have greater autonomy in inaccessible locations. In this context, the Internet of Things is a promising new paradigm for the development of solutions in the monitoring of mosquito swarms. This work consists, at first, of a deeply literature review on automated electronic sensors for mosquito detection and proposes open issues and opportunities for the State of the Art in expanding scenarios considering new emerging technologies, as the Internet of Things. Another objective of the research is the selection of adequate sensing technologies, for energy consumption and data processing optimization. In this way, it proposes a new solution for mosquitoes monitoring based on Internet of Things, from the design of the sensor hardware to the most appropriate communication protocol.

Keywords

Internet of things, optoelectonic sensors, acoustic sensors, electronic insect traps, mosquitoes.

Resumo

O estudo das propriedades acústicas das batidas de asas dos insetos voadores permitiu avanços na detecção automática de mosquitos em vôo livre. A determinação de frequências de batidas específicas de cada espécie e suas respectivas harmônicas é a base da abordagem de análise de espectro de frequência em armadilhas acústicas e ópticas para a detecção de mosquitos. Estudos baseados em dispositivos acústicos como microfones, amplificadores e gravadores foram responsáveis por grandes contribuições e banco de dados da pesquisa. No entanto, somente quando as abordagens ópticas foram implementadas na detecção de insetos voadores, os dispositivos sensores ficaram menores, mais rápidos, auto-disparados, mais confiáveis e eficientes em termos energéticos. Esses benefícios permitiram que o Estado da Arte se caminhasse na direção de armadilhas para mosquito mais inteligentes que processam dados automaticamente e têm maior autonomia em locais inacessíveis. Neste contexto, a Internet das Coisas é um novo paradigma promissor para o desenvolvimento de soluções no monitoramento de enxames de mosquitos. Este trabalho consiste, em um primeiro momento, em uma revisão profunda da literatura sobre sensores eletrônicos automatizados para detecção de mosquitos e propõe questões abertas e oportunidades para o Estado da Arte em cenários de expansão considerando novas tecnologias emergentes, como a Internet das Coisas. Outro objetivo da pesquisa é a seleção de tecnologias de sensoriamento adequadas, considerando o consumo de energia e otimização do processamento de dados. Desta forma, este estudo propõe uma nova solução para o monitoramento de mosquitos baseada na Internet das Coisas, desde a concepção do hardware do sensor até o protocolo de comunicação mais adequado.

Palavras-chave

Internet das Coisas, sensores optoeletrônicos, sensores acústicos, armadilhas eletrônicas de insetos, mosquitos.

Chapter 1

Introduction

The fight against Dengue and all other diseases transmitted by *Aedes aegypti* mosquito is a huge challenge in public health context. Adequate deployment of mobile health teams in a given coverage area is an important achieving success factor in mosquito breeding control [1]. Considering that, automated mosquito sensor networks can be combined with traditional prevention measures and extend the area where mosquito prevalence and its consequent diseases progression can be monitored. The fundamentals of many available solutions for sensing flying insects based on frequency spectrum analysis comes from studies in the Biology field. Male mosquitoes have mechanisms at their antennas base that make them able to detect conspecific females through vibrations induced by flight sounds [2].

Investigation of acoustic signals for the insect species classification is not a recent practice. The first research records about the analysis of acoustical signals from insects flight tones date back to 1868. Researchers employed tools such as the kymograph or chronophotographic method and, by the time of 1952, they began to use stroboscopes and oscillographs in the classification of flying insects [3]. The use of such equipment made it possible to study the insects' wingbeat in free flight, whereas previous methods required to attach insects to an observation surface. In this way, it became possible to establish the association between the insects' flight tone and some properties of their species, such as the body mass and the wing-stroke angle. In general, the variation of WBF (Wing-beat Frequency) between different insect species is inversely proportional to their dimensions. These frequencies can range in values from 10Hz to 1MHz.

Mosquito population control as a preventive measure is a powerful mechanism in combating diseases epidemics such as Dengue, Zika, Chikungunya, and Yellow Fever. Although these diseases affect mainly the public health in tropical countries, they produce social and economic consequences at a global scale. It is estimated that only Dengue fever is capable of infecting 50-100 million people worldwide per year. Asia accounts for about 70% of these infections. In the Americas, where approximately 18 million people are infected with Dengue every year, it is noteworthy that more than half of these infections occur only in Mexico and Brazil [4]. The main reasons for this infections concentration in particular regions are the vast urban conglomerations in climatic and environmental conditions favorable to the Dengue's spread.

Sundry attempts to eradicate the *Aedes aegypti* mosquito were attempt along the years without effectiveness. This mosquito is the major disease vector of Dengue, Zika, Chikungunya, and Yellow Fever, causing concerns worldwide because there are no adequate vaccines. Within all of these pathologies, the Dengue Hemorrhagic Fever is the most worrying just because of its lethality [5, 6]. An infected female *Aedes aegypti* mosquito bite is responsible by the transmission of Yellow Fever, Dengue Fever, Zika, and Chikungunya. This insect lives mostly in warm and wet weather regions. The ideal temperature for *Aedes aegypti* is between 20^{o} Celsius and 29^{o} Celsius [7]. Thus, tropical and subtropical countries are more susceptible to MBD (Mosquito-Borne Diseases) . Moreover, the elevation of the global temperature is one critical attention point as well, since it can contribute to the mosquito's spread around the world. Soon, mild temperature countries will present high Dengue Fever vectors rates, increasing the diseases cases number in the world [8].

Globally, about 2.5 billion people live in MBD' high incidence areas. Socio-economic situations aggravate this datum in tropical and subtropical countries [9]. The favorable environment to the mosquitoes proliferation is a consequence of the fast population growth, disordered urbanization, inadequate urban infrastructure, urban livelihoods, weak public health services and campaigns, and lack of monetary resources for preventive actions. Dengue Fever is a disease already reported in 128 countries. The disease presents approximately 50 to 100 million incidents per year, and 20,000 of them result in the patient's death [10].

In Brazil, the fight against Dengue began in the twentieth century. From 1950 to 1960, the country intensified methods to eliminate the *Aedes aegypti* mosquito, including military campaigns characterized by discipline. However, since neighboring countries have not achieved success in their mosquito-control strategies, new infestations have repeatedly occurred showing that combating MBD should be a global concern [11]. Since Brazil has hot temperatures and wet weather most of the year, the tropical climate conditions are favorable for the *Aedes aegypti*'s fast reproduction and dissemination. According to the WHO (World Health Organization) , Brazil is the country who most suffer against to Dengue worldwide [12]. In this century's first decade, there was a massive increase in the Dengue cases, leaping from 63.2 in 2004 to 429.9 cases per 10.000 inhabitants in 2010. This information evidences the need for more preventive actions and *Aedes aegypti* mosquito-population control [13].

There are varied ways to prevent the *Aedes aegypti* mosquito spread. In Brazil, the central actions focus on prevention policies promoted by municipalities. These strategies are based on training and hiring specialized human resources, investment in sanitation, and population information and education. Moreover, the use of insecticides spraying equipment is frequent. The use of pesticide as a method to eliminate the disease vector is an excellent technique, but its effectiveness tends to decrease over time. This trend is due to these organisms' accelerated evolutionary and adaptive process. Likewise, the *Aedes aegypti* mosquito has already presented biologic resistance to cypermethrin, deltamethrin, fenitrothion, and other insecticides, making evidence to the lack of mitigation strategies alternatives [11] [14].

The *Aedes aegypti* detecting approaches are diverse, and they can be split into two principal strategies: larvae/eggs and adult mosquitoes' detection. One of the most common mosquito eggs detection is the ovitraps use. This technique consists of the *Aedes aegypti* eggs capture using a standing water dark container. After, an automatic or manual system count the eggs' number. Moreover, once the adult mosquitoes develop, they are incapable of escaping from the trap. Therefore, this mechanism can identify which regions have higher mosquitoes incidents. Ovitraps can assist cities that need preventive and corrective public health actions on MBD issue [15].

The methods that identify adult flying insects use the WBF identification by acoustic sensors, photosensors, or flight dynamics analysis [16]. The flying insects' WBF is a unique characteristic of each species or genus and can range from 10 to 1000 Hertz. The frequency scale of the female *Aedes aegypti* is around 400 Hertz, and the male's frequency scale is about 600 Hertz. Acoustic and optical sensors take advantage of this data to identify the Dengue Fever vector mosquitoes automatically [17].

1.1 Motivation

The spread of MBD is a concern not only in Brazil but also in the world. It is estimated that over 700,000 people die each year from MBD [18]. In Brazil, the Ministry of Health indicates that, in 2016, more than 475,000 people have been infected by Dengue, the central MBD that affects this country [19]. Technology can play a crucial role in preventing these diseases by monitoring, recording and analyzing data using appropriate automated sensors. Automated sensing of biological field data is a difficult task. In particular, the lack of instrumentation for measuring insect flight activity is an essential limitation for progress in monitoring studies of flying insect species [20].

A recent study shows the spread of Dengue through human mobility, specifically in Sri Lanka [21]. It is a fact that human mobility is much higher than mosquitoes', making it difficult to model systems capable of predicting MBD propagation in a given territory. Therefore, the implementation of new solutions for mosquito swarm monitoring can be a powerful tool not only in insect prevalence studies but also in MBD control.

Dengue is the most important viral MBD in the world. The increase in cases recorded during the last 20 years is alarming, and the disease has become potentially epidemic worldwide. However, the numbers previously presented represent infections officially detected and recorded by public health surveillance systems. The number of inapparent Dengue fever infections exceeds the total number of annually worldwide registered cases [22]. The high number of inapparent infections is due to diagnosis difficulties and asymptomatic infections cases. Besides, in some circumstances, people infected with Dengue fever do not even seek formal public health services. Therefore, the impacts caused by Dengue are even more impressive than has been estimated. The technology may enhance the screening process of possible undetected mosquitoes foci and, consequently, of Dengue fever.

The *Aedes aegypti* mosquitoes population has doubled between 2006 and 2015. Consequently, the related MBD have shown significant growth in different regions of the world. Beyond Dengue, which has been considered a public health issue for decades, Zika and Chikungunya Fever have shown recent outbreaks of alarming growth across the globe. Even Yellow Fever re-emerged recently causing severe health consequences for the world's population [6]. This progression makes it clear that current methods for controlling *Aedes aegypti*, such as larvicides, insecticides, and preventive measures for the emergence of new outbreaks, have not been sufficient to contain the mosquito population growth and its consequences. Therefore, the development of new technologies for mosquitoes detection is fundamental for the advancement in diseases control and significant improvements in public health.

1.2 Problem Definition

Diseases associated with the *Aedes aegypti* mosquito are considered a public health problem in Brazil and the world. Currently, there are no practical solutions in the mosquito fight, especially in the technological scenario. The establishment of metrics for geographical mapping of mosquito prevalence is other of major challenges for MBD control. The traditional methods make use of BI (Breteau Index) , which establishes the ratio between the number of positive mosquito larvae containers found per inspected sites [23]. Besides being inefficient, this method depends entirely on the action of health teams that cross the territory in search of possible outbreaks of mosquito larvae.

Techniques available in the literature for automatic detection of possible mosquito larvae outbreaks are still very incipient and ineffective. New studies show relevant advances in analysis of thermal and RGB (Red Green Blue) images for possible MBD outbreak detection [24].

However, frequency spectrum analysis of insect wingbeat patterns for adult mosquitoes detection are still the most efficient, inexpensive and pervasive tool for implementing new electronic approaches to disease control and public health preservation.

Many studies are presented in several approaches, such as electronic traps by suction, laser as well as acoustic and optical approaches to sensing mosquitoes. However, it is perceived that most of these solutions are restricted to the laboratory environment. Besides, many field studies still need to be conducted to validate these new solutions and their integration with emerging new technologies.

The development of IoT (Internet of Thnigs) fits into this scenario. Through IoT, it may be possible to integrate mosquito monitoring solutions to the Internet. The data collected can be contextualized for optimization in the control of diseases such as Dengue. Also, remote regions can be monitored without the need for a constant presence of human resources. The benefits generated can have a significant impact not only technological but also social and economic.

1.3 Research Objectives

The main objective of this dissertation is the proposal of an IoT-based solution for mosquitoes monitoring. It includes the evaluation of main approaches for mosquito-detection through the WBF and the sensors noise sensitivity evaluation. Thus, it is possible to concept the best solution for mosquito-monitoring considering data and energy processing into an IoT scenario. To achieve this main objective, the following partial objectives were identified:

- Deep review of the state of the art on approaches for mosquito-detection through the WBF;
- Optical sensors sensitivity and noise evaluation;
- Proposal, development and evaluation of a new solution for mosquitoes monitoring based on IoT.

1.4 Main Contributions

The first contribution of this dissertation is the state of the art review of the main approaches for mosquito-detection through the WBF. This review thoroughly analyzed the acoustical and optical sensors as main electronic approaches for mosquito detection. This study is described in detail in Chapter 2. The review was published in the Journal of cleaner production.

The second contribution is focused on the evaluation of optical sensors noise sensitivity. This study identifies the main noise sources for optical sensors and determinates the main noise-free frequency bands. This contribution is described, in detail, in Chapter 3, and it was published in a paper presented in the 3rd International Conference on Smart and Sustainable Technologies (SpliTech).

Finally, the last contribution of this dissertation proposes an fan-based actuator for mitigate mosquitoes in automated electronic traps. This contribution is detailed described in Chapter 4 and it was published in IEEE 10th Latin-American Conference on Communications (LATINCOM).

1.5 Publications

During this research work, several research papers were published and another one was submitted to an international journal. They are listed below.

- **Diego A. A. Santos**, Joel J. P. C. Rodrigues, Vasco Furtado, Kashif Saleem, Valery Korotaev, "Automated Electronic Approaches for Detecting Disease Vectors Mosquitoes Through the Wing-beat Frequency", in *Journal of Cleaner Production*, Elsevier, Vol. 217, April 2019, pp. 767-775, DOI: 10.1016/j.jclepro.2019.01.187.
- **Diego A. A. Santos**, Luiz E. Teixeira, Antonio M. Alberti, Vasco Furtado, Joel J. P. C. Rodrigues, "Sensitivity and Noise Evaluation of an Optoelectronic Sensor for Mosquitoes Monitoring", *International Multidisciplinary Conference on Computer and Energy Science* (SpliTech 2018), Split, Croatia, June 26-29, 2018.
- **Diego A. A. Santos**, Renann F. Brandão, Gabriela A. C. Duarte, Débora R. Totti, Vasco Furtado, Joel J. P. C. Rodrigues, "A Fan-Based Smart Selective Trap for Flying Insects", *IEEE Latin-American Conference on Communications* (IEEE LATINCOM 2018), Guadalajara, Mexico, November 14-16, 2018.
- **Diego A. A. Santos**, Joel J. P. C. Rodrigues, Mauro A. A. Cruz, Pascal Lorenz, Ricardo A. L. Rabêlo, Petar Solic, "An IoT-based Solution for Disease Vectors Mosquitoes Monitoring". Article submitted to an international scientific journal.

1.6 Thesis Statement

The proposal of a new IoT-based solution for mosquito monitoring is based in a survey focusing on a deep review of the main electronic approaches for flying insects based on the WBF analysis, especially optical sensors.

1.7 Document Organization

This remaining chapters of this document are organized as follows. Chapter 2 surveys the state of the art focusing the main approaches for mosquito-detection through the WBF: acoustical and optical sensors. Open research issues on the topic are identified. Chapter 3 describes the optical sensors sensitivity and noise evaluation. This study allowed the project of a new optical-modulated signal photodiode sensor. Chapter 4 proposes an IoT-based solution for mosquitoes monitoring. This solution is based on optical photodiode sensor and is integrated to In.IoT middleware. Chapter 5 concludes the dissertation, showing the lessons learned, final considerations, and suggestions for further studies.

Chapter 2

Approaches for Mosquito-Detection Through the Wing-beat Frequency

2.1 Introduction

The knowledge of flying insects wing-beat acoustical properties supported the progress of sensing disease vectors mosquitoes in free flight. The classification of individual flying insects species' through WBFs and respective harmonics is the principle of frequency spectrum analysis method both in acoustical and optical sensors approaches for disease vectors mosquitoes. Investigations based on acoustic devices, microphones, amplifiers, and recorders have produced extensive scientific contributions to behavioral and biological insects' knowledge. Moreover, the researches based on acoustical approach are accountable for the massive available database on flying insects species and gender classification. However, it was the advent of the optical sensing approach for flying insects detection that allowed sensor devices to become smaller, cheaper, faster, self-triggered, and further reliable and energy efficient. These benefits enabled the state of the art on mosquitoes monitoring to move towards smarter devices that automatically process data and have greater autonomy in inaccessible locations. Consequently, it becomes plausible to break geographic, economic and social boundaries for the flying insects sensing, allowing the ubiquitous monitoring of disease-vector mosquito populations. This chapter reviews the related literature on automated electronic approaches for disease vectors mosquitoes monitoring and identifies open issues and opportunities for further researches in expanding scenarios considering new data processing and emerging transmission technologies.

2.2 Background

The spread of MBD is a global concern considering over 700,000 people die each year from diseases that have mosquitoes as main vector [18]. The bite of female *Aedes* mosquitoes are responsible for the transmission of Yellow Fever, Zika, Chikungunya, and Dengue. Dengue is the MBD that has the potential to spread more quickly around the world. WHO reports more than 2 million Dengue cases annually and estimates that more than 40% of the world population live at infection risk [22]. Automated sensing of biological information is a challenging task. In particular, the instrumentation shortage for measuring insect flight motion is a deterrent limitation for progress in monitoring studies of flying insect species. Technology can play a crucial role in preventing these diseases by monitoring, recording and analyzing data using appropriate automated sensors.

Current models for predicting potential Dengue outbreaks are based primarily on historical disease cases data. However, with transport technology development, human mobility has increased and become more agile [21]. Historical data and traditional monitoring methods are no longer able to predict new Dengue outbreaks accurately. Also, the monitoring of Dengue cases through mobile health teams has limited resources, access, and coverage [1]. Health teams have difficulty reaching ubiquitously and at the required speed the most remote locations. In general, these are the neediest places for surveillance and health care.

As a result, it is not possible to obtain accurate and up-to-date information on the prevalence of disease-transmitting mosquitoes as well as their geographical spread. The inaccuracy of the data available and collected decreases the effectiveness of the health teams work in the field and, consequently, the monitoring of Dengue and mosquitoes prevalence in the surveyed sites. It is crucial to mediate the efforts of significant society actors to combat the spread of MBD [25]. In this sense, epidemiological studies should be combined with advances in the biological mosquitoes characterization, and the climatic and socioeconomic data collected contextualization through a more precise and efficient sensor network.

Dengue infections are occasionally not clinically diagnosed, even if the patient has several characteristic symptoms of the disease. These undiagnosed Dengue cases are called inapparent infections. Inapparent Dengue infections occur for a variety of reasons, including the symptoms similarity to other diseases and the patients' lack of access to the health system in poorer regions. Estimates indicate that, when both apparent and inapparent infections are accounted, the total number of Dengue cases in the world may be up to three times higher than that reported by the WHO [4]. Besides, these data gathering reinforces the prevalence of MBD in countries located under the tropics, correlating Dengue incidence with social and climatic data of temperature and precipitation. These results indicate the importance of mosquito detection systems and their proper contextualization of geographic, climatic, and socioeconomic data.

The development of effective vaccines against MBD is still incipient. Among the most advanced vaccine research to date, the effectiveness of disease protection is still below 70 % [26]. At the same time, countries with higher Dengue and other MBD rates have used sterilization methods for male *Aedes aegypti* mosquitoes' dispersion in the environment, whereas females reproduce only once during the life cycle. However, despite the advances obtained in Dengue control, there is a diversification effect of MBD, especially in Latin America [22]. Chikungunya Fever has presented new outbreaks in diverse countries in recent years, causing substantial socioeconomic and public health impacts due to its possible sequelae and even lethality.

Infestations by *Aedes aegypti* mosquitoes show great heterogeneity and spatial variation, which hampers the use of traditional entomological monitoring techniques [21]. These techniques depend directly on human action for checking and counting *larvae foci*. The current difficulty of monitoring and controlling the true prevalence of *Aedes aegypti* mosquito indicate the need for more reliable and accurate autonomous technologies for mosquitoes detection and classification. Therefore, the development of techniques capable of identifying and counting the number of adult mosquitoes in the environment is significant for advances in the control, prevention, and prediction of MBD.

Research into MBD has advanced in many fields, such as medicine, immunology, and the biological and agricultural sciences. Several countries have shown significant increases in the scientific publications' number on MBD controlling and monitoring methods [6]. At the same time, ICTs (Information and Communication Technologies) have performed an essential role in supporting and providing an extensive database for these researches. In this context, this chapter performs a deep review of the available literature on electronic approaches for detecting and classifying diseases vectors insects. Acoustical and optical sensing approaches are the most widespread and will be compared according to established criteria of performance, functionality and noise immunity. Finally, the main scenarios of the sensing techniques inclusion in autonomous data processing and IoT oriented environments will be presented, aiming data collection and contextualization in real time, considering energy consumption and computational processing factors.

2.3 Methods

The literature review on automated electronic approaches for detecting disease vectors mosquitoes through the WBF adopted articles published in scientific journals and international conferences as the database. Altogether, a total of 62 papers were reviewed, dating from 1939 to 2018. The earliest references were used to substantiate the optical and acoustic principles that are the basis for the most current low-energy optoelectronic approaches for the flying insects' detection. Also, these references are essential for the insects' WBF database consolidation presented throughout the chapter.

The research is divided into two main approaches: Acoustic and optical sensors for the detection of flying insects through the WBF. As the acoustic approach is the basis for the optical approach development, it is presented before in the chapter so that the research's temporal linearity is respected and facilitate the text's understanding. In this sense, there are addressed 11 references particularly dedicated to the development of the acoustical approach and 14 references that discuss the advances of the optical approach to the state of the art.

The two approaches are then qualitatively compared in their main features as well as the advantages and disadvantages of each of the two lines. The main aspects addressed were efficiency, applicability, energy consumption, processing power required, and the possibility of integrating new emerging technologies, such as the IoT.

2.4 Related Work

The earliest research records aimed to identify and classify flying insects through the WBF date back to the beginning of the 20th-century. The first experiments were performed using Kymographs, oscillographs, and stroboscopes [3, 27–29]. Researchers in the musical and acoustical field have dedicated their studies to recognize direct connections between the flying insects' morphology and their WBF. For the parameterization of the WBFs collected in several scientific literature sources and presented at this section, the measured frequency of *Aedes aegypti* females will always be used as the reference value throughout this chapter.

By the end of the 1980s, studies in the biological field had already proven that the flying insects' WBFs are inversely proportional to their body size, reaching values between 10Hz and 1,000Hz [30]. At this point, the challenge was to perform the automated acquisition of frequency values. The developed system used two main outputs. The analog output was recorded on a tape and treated by a frequency analyzer. The converted digital signal was processed by a computer that performed the collected signal FFT (Fast Fourier Transform) . The research analyzed the signals coming from two mosquitoes species, *Aedes aegypti* and *Aedes triseriatus*. Recordings of 512 samples were performed, and the mean WBF measured value for the female *Aedes aegypti* mosquitoes was 508 Hz.

Researches carried out in the late 1980s still have focused on correlating a more considerable amount of morphological data from flying insects to their WBFs. The parameters used to verify correlation were body mass, wing area, and wing loading. The measured results were cross-referenced with the already broad literature on the WBF of several flying insects species.

As the female *Aedes aegypti* WBF reference, the research considered the 480 Hz value measured in a previous survey [31]. The results show that due to differences in flight mechanisms between species, the data that contain the most direct correlation are the WBF and the wing loading [32]. Nevertheless, this correlation of data can vary significantly from one species to another.

More recent studies, already after the 2010s, have focused on increasing accuracy in the flying insects' WBF signals through the implementation of probabilistic models. Experiments carried out using a sequence of 500 recordings performed using five different species of flying insects, implementing different probabilistic models. The results indicate that the Complex Gaussian Models presented the best performance in increasing the accuracy of insect classification through the decision mechanisms usage [33]. The automatic decision-making process is an important aspect to be taken into account since the measured results usually present a considerable variation that can lead to species classification errors.

Acoustic approaches performed in the past decade measured the WBFs of male and female *Aedes aegypti* mosquitoes using pressure-gradient microphones. About 70 recordings were performed using a sampling rate of 24 kHz. The experiments were used to relate the implications of distance, phase and spherical spreading on the recording of audio signals. The results lead to the significant influence of phase discrepancy, amplitude variation, and the complexity of detecting harmonics in mosquito swarms signals. Specifically for the females of *Aedes aegypti*, the measured value was 511 Hz on average [34]. In another similar research, using an electric condenser microphone, the experiments performed with *Aedes aegypti* conferred a 480.6 Hz result for the female fundamental WBF [35].

Experiments performed using acoustic signal sources on the female *Aedes aegypti* mosquitoes WBF show that fundamental WBF is an essential method of communication among insects. Surprisingly, in addition to attracting male mosquitoes, the female *Aedes aegypti* mosquitoes' fundamental frequency was also effective in attracting pregnant female mosquitoes [36]. Based on this principle, many studies have explored behavioral interaction in the mating process among mosquitoes as a tool to identify the fundamental WBF of some species. Tests performed both between same-species and opposite-sex natural mosquito pairs, as well as individual mosquitoes stimulated by recordings containing sounds at the opposite-sex fundamental frequency, quantitatively indicate that the harmonics convergence phenomenon is part of the mating process of flying insects [37].

The study of mosquitoes mating process has generated relevant data that may imply the WBF. During controlled experiments of mosquitoes body mass variation through diet, it was observed that insect size influences the mating process successfulness. The relationship between different sizes mosquitoes samples registered consequences in the harmonics convergence process [38]. The behavior observed in swarming mosquitoes is a precedent sign of the mating process. Therefore, the prediction of these behaviors and the following prediction of the mosquitoes movement in a given environment is a factor to be considered in the development of more effective mosquito traps and sensors.

An investigation carried out with *Culex quinquefasciatus* mosquitoes presented several stimuli to male mosquitoes around the fundamental WBF of wing beat in an attempt to validate the harmonic convergence during the mating process, as described in previous studies. However, it was observed that male mosquitoes responded better at frequencies well below the female's fundamental frequency [39]. Male mosquitoes presented a phenomenon of rapid frequency modulation, which should represent a biological behavior different from previously reported harmonic convergence.

Recent studies address new ways for identifying mosquitoes in flight through the frequency of wing beating. The use of W-band and S-band entomological radars showed satisfactory results in the identification of flying insects. W-band radars, in particular, showed better performance and accuracy when compared to S-band radars. Besides, studies using radars could prove the possibility of identifying insects not only by modulating the signal in amplitude but also in phase [40]. Another unusual factor addressed in more recent research is the behavior of mosquitoes throughout the daytime, associated with visual stimuli that may influence the insects' prevalence in a given environment. *Aedes aegypti* mosquitoes have a typical diurnal behavior. The records show that for most of the daytime, insects search for dark-colored objects and places with lower luminous incidence [41].

The relation between the environmental temperature variation and the WBF measured value is a relevant criterion for the correct flying insects' identification in the environment. Experiments evidence that, while retaining body mass, controlled environment, and measurement methods, the variation of a species fundamental WBF tends to vary directly proportional to the temperature increase. In the case of female *Aedes aegypti* mosquitoes, the observed variation is from 8 Hz to 13 Hz per unit 1 celsius [42]. This conclusion provides us with essential data of electronic sensors implementation for mosquitoes detection and reinforces the necessity to climatic data contextualization. Technological advances in the monitoring and control of MBD, whether through monitoring of larvae foci, mosquitoes flight recordings, or even image processing have led to significant advances in modeling new public health measures [43]. It is necessary to move towards automated real-time monitoring, with low energy and processing requirements [44]. Thus, monitoring of disease vectors mosquitoes can become ubiquitous and reach remote regions where health teams often do not achieve.

Table 2.1: Main researches outcomes of flying insects classification by wing-beat frequency.

Author	**Country**	**Temperature**	***A. aegypti* ♀**
O. Sotavalta, 1952	Germany	-	480 Hz
A. Moore et al., 1986	USA	22 °C	508 Hz
B. J. Arthur et al., 2013	USA	23 °C	511 Hz
A. Aldersley et. al, 2014	UK	26 °C	480.6 Hz
L. J. Cator et al., 2011	Thailand	32.6 °C	664.3 Hz

The data presented in Table 2.1 shows that the literature itself and its respective database present disagreements regarding the WBF classification of flying insects. Further studies are essential to increase the accuracy and influence of these measures external factors. Among these factors, in addition to temperature, it is necessary to emphasize air humidity, atmospheric pressure, geographical and even socioeconomic conditions.

2.5 Electronic Approaches for Mosquito Detection

Most of the techniques employed in the MBD entomological surveillance come from larval counting methods. The most widely used strategy to predict the number of adult mosquitoes in a given environment is the BI. This index is the simple average between the number of positive foci for a total of 100 sites visited. Recent studies show that BI values above 4 are sufficient to recommend preventive actions against the progress of Dengue [23]. Although some research has shown this correlation between BI and Dengue incidence, especially in sites with low common mosquito infestation, other studies do not fully confirm this association [45]. Logistic regression methods have already been employed to predict receptors and sites more conducive to the proliferation of the *Aedes aegypti* mosquito in a given environment. However, the results show that the use of traditional larval and pupal counting methods, such as BI, would not have provided more significant conclusions about the geospatial mosquitoes prevalence [46].

Larval counting techniques are still the most employed today. However, there are alternative techniques for monitoring the diseases mosquito vectors prevalence such as the ovitraps and the sticky traps [47]. The ovitraps consist of attractive containers to the mosquito eggs disposal placed in the houses outer areas. These traps are monitored for eggs identification and counting in the laboratory. Similarly, the sticky traps are composed of dark containers attractive to the mosquitoes containing adhesive tapes for catching adult flying insects. Comparison between eggs and adult mosquitos monitoring techniques showed a low data correlation. At different stages of life, mosquitoes inhabit different places. This research result is an essential conclusion about the inefficiency of presuming the correlation between the *Aedes aegypti* larvae outbreaks and the Dengue incidence.

Traditional larval counting techniques for predicting MBD outbreaks should not be used as benchmarks for new techniques for adult mosquitoes sensing in the environment. As traditional techniques do not have sufficient accuracy and do not reflect the reality of the MBD geographical dispersion, they are not able to parameterize the accuracy of mosquito sensors. Acoustic tools and techniques for flying insects detection and classification been used for a long time. Therefore, it is more reasonable that the results obtained with the acoustical approaches are the adequate parameter to compare the performance of the new optoelectronic mosquito sensing techniques. The next subsections are devoted to the purpose of this comparison.

In order to address all the aspects of electronic approaches for disease vectors mosquitoes monitoring, this chapter suggests the structuring of solutions in a layered architecture. In this structure, the layer that interacts with the physical world can be split into three sublayers, one dedicated to the sensing system, another to the actuation system to mitigate flying insects, and the third to attractive mechanisms for the insects of interest. The next layer is dedicated to data processing. This layer is responsible for the sensors data collected treatment and peripheral mechanisms management, such as the performance and attraction of insects. Finally, at the architecture's top, the data transmission layer is positioned, addressing the most appropriate transmission technologies for these solutions to reach remote regions needy of MBD monitoring. This chapter focuses on Optical and Acoustical approaches at Physical Layer, as well as the main characteristics should enable these techniques to be used in an IoT scenario.

2.5.1 Physical Layer

The study of the WBF spectrum of flying insects has been arousing researchers' interest for a long time. Studies recorded in 1867 show the first techniques used to determine characteristic flying tone frequencies of each insect [27]. At that time, known frequencies instruments as tuning forks were used to tune a particular insect flight tone frequency in order to classify flying insects by species. This embryonic research was almost subjective, but it was the beginning of a research trajectory that currently offers an extensive database for flying insects classification. Some tools have been used over time to classify flying insects. In 1939, an article detailed the implementation of a simple stroboscope for insect classification based on cyclic movements [28]. However, this method efficiency was compromised in transitional movements, such as landings and takeoffs. Later publications, such as that presented in 1952, discuss the use of oscillographs, stroboscopes or even the combination of both methods for determining frequencies associated with the flight tone of several insect species [3].

The development of insect flight tones acoustic sensing techniques produced a large database containing typical frequencies for lack of mosquito species. Research published in 1988 offers, besides an extensive data table on diverse species WBFs, a relationship between wing loading, wingbeat and body mass of insect species variety [32]. In specific case of *Aedes aegypti*, the baseband frequency is determined at 480 Hz [31].

Mosquito flight tones were extensively studied mainly using microphones. However, the use of microphones to analyze wingbeat data is not a practical task, especially when there is interest in analyzing specific frequency spectrum produced by a several insects species in a single event [48]. Separating WBFs from an audio recording can be somewhat complicated, primarily when a collective insect detection event of different species is recorded. In light of this situation, optoelectronic solutions can easily detect these events and automatically classify species into different events.

2.5.2 Acoustical Sensors

The sounds produced by flying insects have aroused researchers' interest for more than a hundred years due to outbreaks of MBD. The first experiments to study the WBF of flying insects come from the biological sciences. The sounds produced by mosquitoes are even a communication mechanism between them. Mosquitoes have a structure called Johnston's sensory organ, capable of perceiving the frequency emitted by other flying insects [2]. Electronic-acoustic tools, such as microphones, associated with oscilloscopes provided the frequency analysis of the signals produced by these insects. Consequently, these researches generated the database for the classification of flying insects through their fundamental frequency of wing beat. The principle of this approach, used in the earliest electronic studies, can be verified in Figure 2.1.

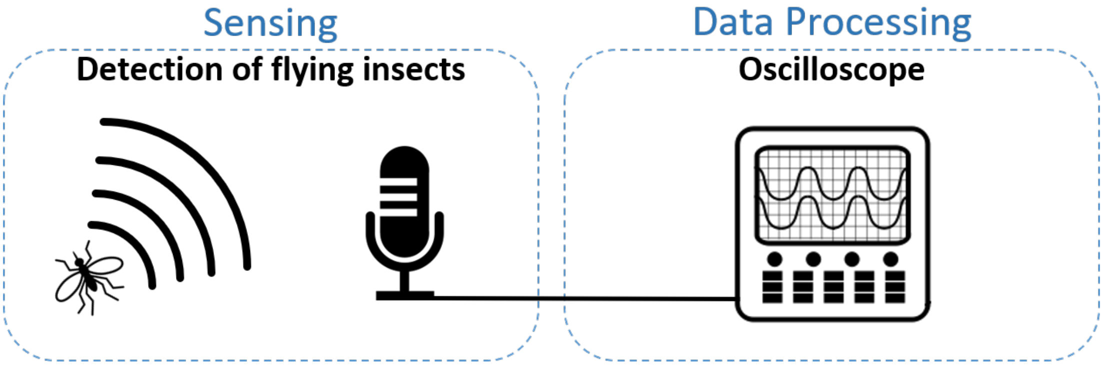


Figure 2.1: Fundamentals of acoustic sensing approach.

In 1949 there were already researches on flying insects classification that used microphones as the primary tool. At this point, the low amplitude sensitivity of the signals collected by the microphones available at the time and the need to implement filters capable of eliminating external noise was already a concern [49]. Considering that sounds produced by mosquitoes have a low energy level, their detection through microphones has always required a precision effort in devices construction.

The acoustic approach has been widely used in surveys to detect mosquito swarms in the 90s. In experiments performed at the Insect Attractants, Behavior, and Basic Biology Research Laboratory, from U.S. Department of Agriculture, a sequence of recordings was performed both in the open and in a hermetic cabinet in a laboratory controlled environment. The recordings were digitized, filtered and analyzed by a microcomputer. The results showed that for the technological conditions of the time, in a silent environment the swarms of mosquitoes could be detected at a distance of 10 to 50 meters [50].

The acoustic techniques used until the end of the 90s presented low accuracy in the identification of flying insect species. Research conducted in 2004 proposed the construction of an acoustic detector to overcome this difficulty [51]. Through a total of 250 h recordings, it was concluded that in isolation, both the fundamental frequency and the first two harmonics were not able to provide sufficient reliability. Therefore, through programming routines, the combination of the first four harmonics was able to offer a detection accuracy higher than 93%.

In 2011, a research conducted in Thailand adopted an array of microphones to measure the fundamental WBF and the respective harmonics of *Aedes aegypti* mosquitoes. The experiments were performed using a total of 8 equidistant arranged microphones, which recorded a total of 3.5 hours of acoustic signals from the mosquitoes. The value of the fundamental frequency found for the female *Aedes aegypti* mosquito in this study was 664.3 Hz, at an ambient temperature of 32.6 °C [52]. The high measured frequency value associated with high ambient temperature throughout the recordings is strong evidence of the relationship between the fundamental frequency and ambient temperature.

The response of mosquitoes to frequency signals tuned to the species fundamental WBF is a topic that still requires scientific deepening. Tests series performed with male *Aedes aegypti* mosquitoes responding to different frequency values showed an unexpected result. When submitted to signals at 440 Hz and 465 Hz, the male mosquitoes presented a different response when comparing laboratory tests with those performed in the field. At 465 Hz, laboratory results indicated a much higher accuracy in the attraction of male mosquitoes, but this result was not reflected in field trapping tests [53]. Therefore, it is necessary to advance in the studies on the flying insects WBFs, the main factors that influence these tones, as well as the impact of the insects' mating interaction on the fundamental frequency and its harmonics convergence.

Research developed in 2016 sought to create a new paradigm for the flying insects monitoring through the acoustic approach. This experiment carried out tests of several mosquitoes species using different mobile phone models. The study proved that even the simplest phones were able to record audio signals sensitive enough to identify mosquito species through WBF [54]. The result obtained turns personal phones into valuable instruments for monitoring MBD, since the collected audio signals are naturally contextualized by the date and geographic location where the sounds were measured [55] [56] [57] [58].

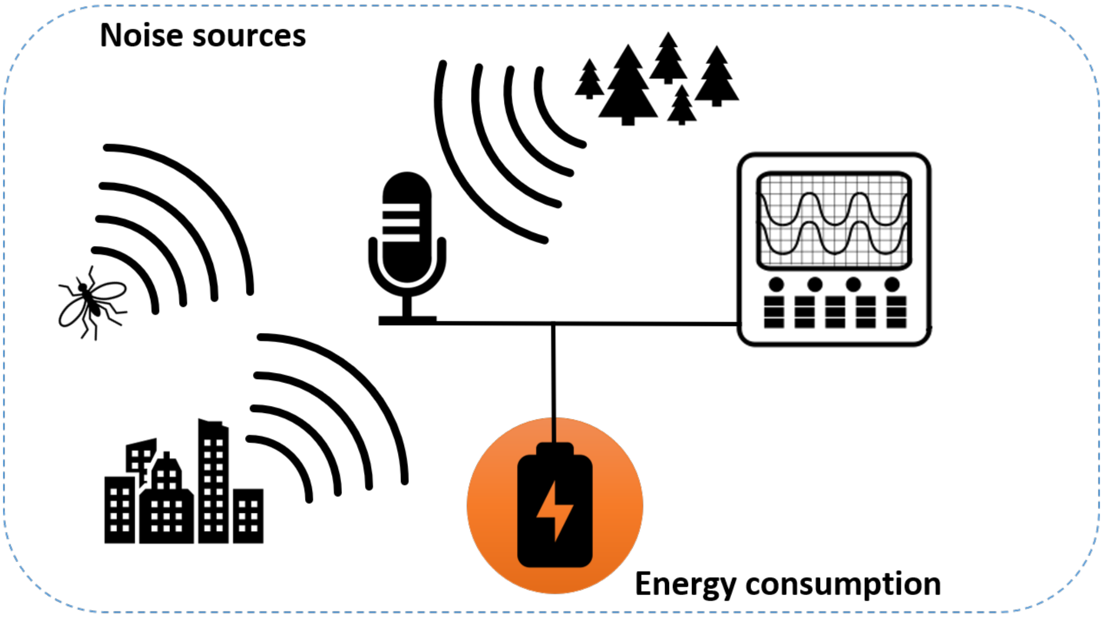


Figure 2.2: Main challenges for acoustic sensing approaches.

Foremost challenges for acoustic sensing approaches are energy consumption, processing power saving, and SNR (Signal-to-Noise Ratio) of recorded audio, as shown in Figure 2.2. Microphones deployed in mosquito traps in the field end up recording a diverse source of natural and artificial noises. Filtering insect detection events can then become a complex task, as well as requiring more system processing power. Besides, systems based on a set of microphone and recorder spend entire experiment running time making recordings. This condition is extremely challenging in a scenario where high battery efficiency is sought. Therefore, optical approaches presented in the next section offer significant performance advantages.

2.5.3 Optical Sensors

In 1955, it was realized that a photoelectric cell could perceive some sunlight modulation when a flying insect crosses its detection field [59]. This conclusion was the starting point for the development of studies based on an optical approach for sensing mosquitoes in the field.

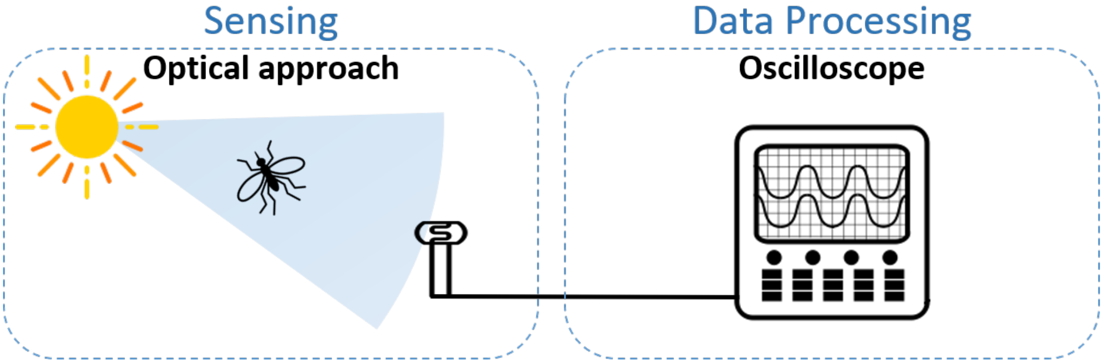


Figure 2.3: Fundamentals of optical sensing approach.

In 1986, there were already studies aimed at the construction of automated systems for flying insects detection based on optoelectronic sensing and its frequency spectrum signal analysis [30]. The sensor component of this individual insect flight monitor was based on an optical tachometer [60]. The system operation can be seen in Figure 2.4 [30]. The insect is placed in a transparent plastic cage with an acting light beam. The flying insect causes beam reflection on the sensor, a photodiode. The sensor output is directed to a microcomputer equipped with an ADC (Analog-to-Digital Converter) for an online system monitoring and an audio recorder inset of a frequency analyzer for offline monitoring. Changes in light intensity perceived by this sensor were used as a trigger for recording starts.

Considering these previous researches on acoustical and optical approaches, the state of the art in mosquito sensing is presented. The most recent studies consider that a pair of light emitter and receiver where a flying insect crosses creating light signal modulation is the basis of a fast, robust and noise-resistant sensor solution. The latest implementations of the emitter-receiver pair-based optical sensing model using LEDs/lasers and photodiodes are accurate enough to avoid false positives detection. The precision of optical sensors in WBF-based flying insects' detection and classification can exceed 90% [61].

In 2015, one of these studies proposes the use of two options of light sources for sensor construction, laser and LEDs (Light Emitting Diodes) [62]. Audio recordings using microphones were performed during all experiments for comparison purposes. As a result, it can be observed that both the laser and LEDs perform as well or even better than the acoustical sensing approach. Based on this previous study, in 2016, another article proposal takes advantage of optical sensors' large aperture to build a complete system that detects, processes, records, and time-stamps information about WBFs of various flying insects [63]. The system operates in

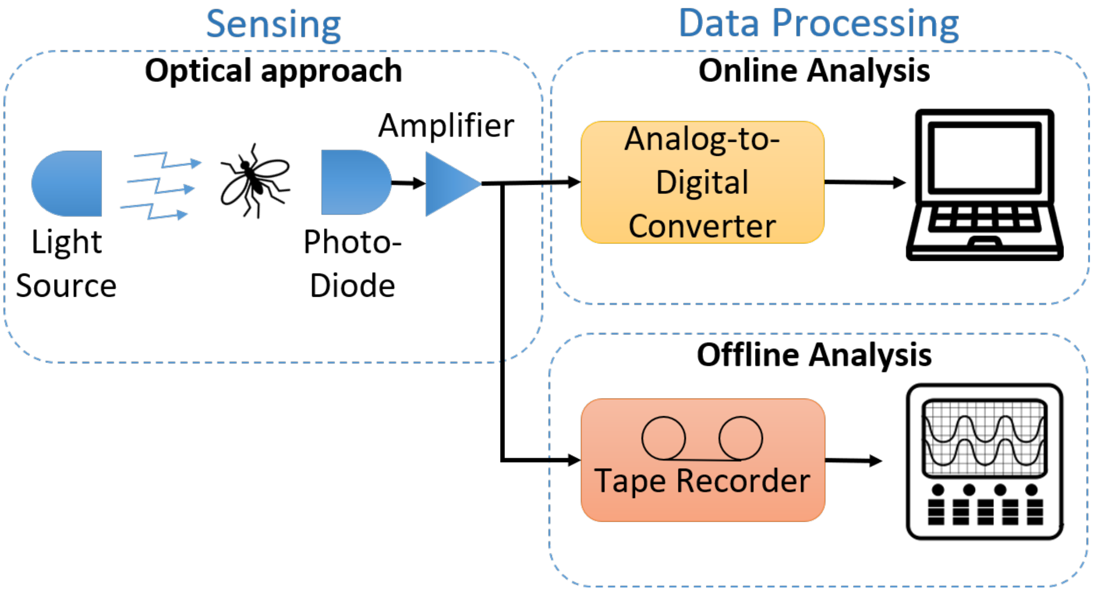


Figure 2.4: Automated identification of flying insects.

any ambient light condition and is robust enough to derive the WBFs in the order of hundreds or thousands of insects.

This sensor consists of an array of LEDs opposite to a waveguide (e.g., laptop computers liquid crystal displays) coupled to a photodiodes array, creating a FoV (Field of View) . When an insect crosses the FoV, fluctuations in light intensity are perceived by photodiodes. The signal containing information on the detected insect's WBF is then amplified, filtered and demodulated in an audio signal. The reason for treating an audio signal is the possibility of comparing results obtained with those present in literature for acoustic systems. The system has a microprocessor programmed in C/C++ capable of self-triggering the recording only when there are insect detection events in FoV. This operation mode is an important feature because it saves energy, considering a Li-Ion 3.7V battery powers the device. The diagram of system operation is presented in Figure 2.5 [63]. However, neither the noise-resistant optoacoustic sensor nor this new approach has been deployed in the field for performance evaluation considering a real pilot.

A recent study presents preliminary results using an optical device with a laser beam to detect three particular insect species based on WBFs, *Aedes aegypti*, *Culex quinquefasciatus* or *Anopheles stephensi* [64]. An interesting aspect of this study is that hardware deployment costs were taken into account, obtaining an inexpensive sensor. The research also focused on the use of a simple algorithm to increase accuracy in insect classification. Sufficient data were generated to study the spatial and temporal dynamics of mosquito behavior. Then, it was demonstrated that most challenges in insects' sensing have already been overcome using optical sensors [65]. Such sensors have enabled millions of recordings, providing enough data to accelerate researches and enable device deployment in a real-world setting. The process of developing this research culminates in the use of Machine Learning in order to provide an accurate classification system [66].

The concept of Machine Learning is also attached to infrared recording sensors to detect mosquito WBFs in free flight and automatically classify them regarding gender and species in real time [67]. This technique implementation was compared with previous results obtained from traditional algorithms. The results of this research show a significant advantage of using

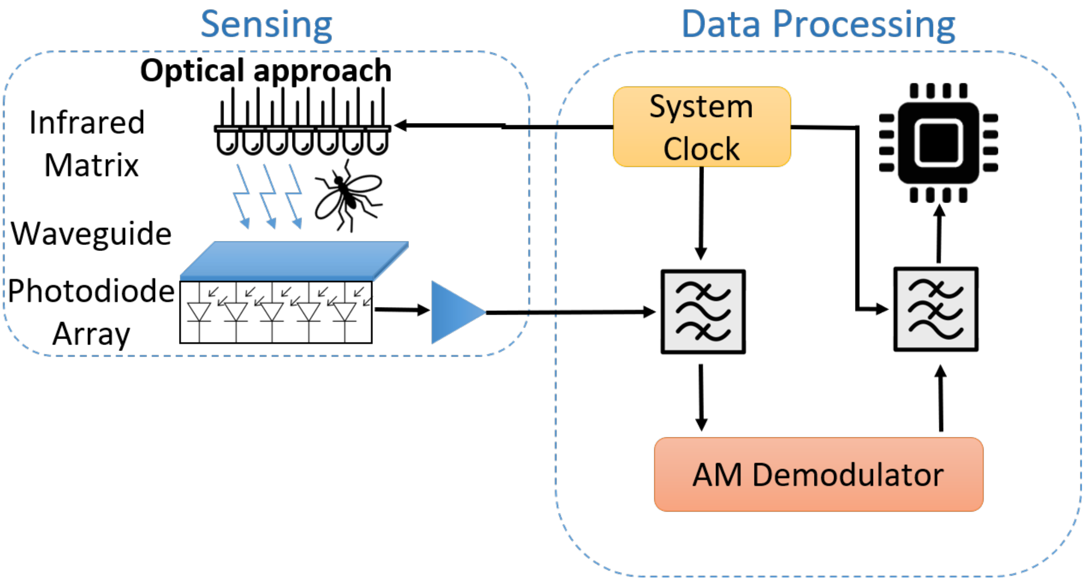


Figure 2.5: System diagram of optoacoustic device.

Machine Learning new algorithms concerning previous results, both in species and gender classification.

In another research, an improved system uses an optical system capable of highly specific vector control [68]. During experiments, two different species of insects were used to evaluate the classification capacity of the device. This system uses a sophisticated combination of optical sources, detectors, and software to detect and classify flying insects in real time. Besides, the system can eradicate insects using a lethal laser pulse. The device makes use of a PF (Photonic Fence) that performs advanced mid-range monitoring. Methods that use a laser to eradicate mosquitoes were also used in further studies [69].

Other solutions also address the concept of PF. One PF use proposal is to create a camera-trap using a low-power laser arranged in a fashion zigzag [70]. Another proposal can be the creation of a real fence using PF that can protect structures as big as a house or a farm [71].

An optical system can also be used for data processing and insect classification. A recent study presents and deploys an image treatment system for mosquito classification [5]. The prototype was designed using a digital microscope camera, an Arduino microcontroller and Support Vector Machine for mosquito species classification. However, the system still needs to be improved regarding camera focus automation, speed in image processing and, above all, the insertion of insect sensors into the system. The proposed solution works considering mosquito detection samples already provided by any given sensor.

2.6 Discussion

The correlation between the environmental temperature and the fundamental WBF should be investigated further. The frequency values available in the literature reveal evidence of this relationship. However, the diversity of additional factors that may influence the frequency measurements difficult this idea validation. However, there are a few studies directly connected to this data relationship [42]. A reasonable simple experiment of controlled temperature variation during fundamental frequency recordings of a given species may be useful to validate this correlation accuracy in different scenarios.

Relative air humidity is also a relevant factor to consider when classifying flying insects through the WBF. Similar to the ambient temperature, long-term studies with controlled variation of air humidity may confer meaningful data on the relationship between this magnitude and the frequency measured for a particular flying insect species. Increasing air humidity can increase the weight on the insect's wings by changing the frequency with which this insect flaps its wings. Especially for air humidity, studies available in the literature generally report that the experiments were performed under controlled air humidity, but there is a lack of data on the actual values measured during data recordings.

The state of the art on flying insect electronic sensing has reached a decisive stage: increasing precision, speed, energy efficiency, and processing capacity allows the integration of these devices and traps into new scenarios. This section presents open issues and upcoming opportunities in the development of automated mosquito sensors.

The first timely scenario is to make these devices smarter, considering new paradigms like the IoT. Thus, it will be possible to drive the technology advances to places where it would be most useful: remote regions where access is difficult, and MBD outbreaks are more worrisome. A second significant opportunity is a possibility of providing access to the database generated by these sensor networks. This information can be beneficial to the general public and health authorities.

Proper use of these data can generate new applications in public health, disease prevention and biological studies on mosquito behavior. Finally, it is necessary to make these technologies more affordable. Reducing the production costs of sensors and devices capable of mosquito swarm monitoring is a crucial step in making the benefits of these solutions ubiquitous. A broad device network can provide valuable data on mosquito swarm mapping over time and space, as well as moving towards the prediction and avoidance of future MBD epidemics.

Solutions have been studied in order to automate the transferring information which is until now manually collected by health agents using traditional mosquito traps. Considering that, a mobile application is deployed as a solution to speeds up information access by health authorities [72]. The use of mobile applications as a peripheral tool in an automated mosquito sensor implantation can have great value also in the general public access data for better MBD control.

New approaches to actuator devices in mosquito control show a trend to broaden the study scenario in electronic monitoring of insects [73]. A bug zapper implementation is proposed, using PWM (Pulse Width Modulated) LED Pulse Width Modulated Light Emitting Diode combined with a solar power module. The results demonstrate the built device can save 25.9% of total energy consumption and that the efficiency of mosquito capture using the PWM method is about 250% higher than that obtained with a conventional fluorescent lamp bug zapper.

A recent study established a commitment relationship between the efficiency of mosquito detection and battery life in sensor networks [74]. The project developed takes into account issues such as the temporal and spatial mosquito prevalence to determine the best-suited algorithm and network structure for an operative and energy efficient solution. Also, the research proposes the use of active sampling technique to reduce battery usage, based on mosquito detection event predictions. Such efforts are relevant when the use of these sensors is envisaged in an IoT solution with an extended lifespan in inaccessible regions [75].

The latest advances in flying insect control technologies offer new challenges. Many papers propose different techniques for mosquito detection and monitoring. However, these solutions have yet to be implemented in the field, verifying their real efficiency and relevant collection data for academic research development.

A relevant work proposal is the real field implementation of sensor pilots available in the literature for comparison with previous results obtained in the laboratory environment. Another possible approach is to use one of the sensing solutions for a real case study. It is also expected that new solutions for flying insect automated sensing will emerge in new approaches. Besides, it is essential to take the state of the art in mosquito monitoring to larger scenarios. These scenarios may include the use of emerging technologies in automated sensor networking, communication, actuation mechanisms, Big Data management, and even an IoT solution [76].

There are already proposals to include optoelectronic sensors using Embedded Machine Learning on Low Power IoT Platforms [77]. The solution combines algorithmic optimizations of sensor signal processing with hardware acceleration concerning energy efficiency and machine learning routines to provide a platform for classifying flying insects. This proposal highlights a broad scenario that can be explored by the automated mosquito sensing with the development of the IoT paradigm.

Chapter 3

Sensors Sensitivity and Noise Evaluation

3.1 Introduction

Mosquitoes play a biological role of significant impact on public health, being vectors of several diseases transmission. In particular, the *Aedes aegypti* mosquito is a vector of potentially fatal diseases such as Dengue, Zika, Chikungunya, and Yellow Fever. The studies progress on these insects biological properties is fundamental for the improvement of more accurate mosquitoes detection sensors. Therefore, the optoelectronic sensors for flying insects detection and classification taking into account the fundamental WBF of several insects species database available in the literature. Also, the optoelectronic approach is capable to perform insect sensing without needing uninterrupted data recording. This functionality is essential to reduce the sensor's power consumption and enable the construction of a low-power device ready for an IoT scenario. In this regard, this chapter aims to design and deploy an optoelectronic sensor module to validate the optoelectronic sensor operating principle and evaluate the main optical interference sources. Thus, it is possible to determine the best sensor's operating bandwidths for an optimal SNR and efficiency.

This chapter presents the practice validation of the most prominent technology in the literature for sensing mosquitoes in free flight, the optoelectronic sensing approach with HF (High Frequency) optical signal modulation. Also, alternative frequencies for optical signal modulation are presented according to the main optical interference sources found in the environment. For this, a reference model of an optoelectronic device for the mosquitoes detection through the WBF was used for the approach validation [62, 63]. The low-power optical sensing module was implemented, as well as the system clock aligned to the bandpass filter. The major laboratory and external environment interference sources were evaluated and, finally, the sensor selectivity through HF signal modulation was verified. All the results were verified through an oscilloscope and will be presented in the next sections.

3.2 Background

Over the years, mosquito species have been studied in the literature as disease vectors, while fundamental biological aspects of these insects were not addressed. An in-depth research of their biology and individual characteristics can provide relevant data on potential epidemics prevention and control. Studies show that mosquito swarms are predominantly male. The aspects related to these insects flight tones are so significant in their biology that are used by the male mosquitoes for females' localization. Besides, during the mating process, an event called "harmonic convergence" occurs where male and female mosquitoes adjust their WBFs to converge on their fundamental frequencies' harmonic components [52]. Therefore, it is essential to acknowledge fundamental biological aspects in the sensors' construction for the mosquitoes detection and classification. Moreover, the improvement of these devices is essential in generating new and updated consistent data on mosquito biology and in controlling epidemics. Acoustic and optical methods are the two main approaches for the flying insects' detection through the WBF.

3.2.1 Acoustic Approach

Several surveys are devoted to the insect species classification through the analysis of acoustic signals containing their flight tones. Recent studies address the mosquitoes biological properties through audio signals recordings using microphones. A laboratory-created *Aedes aegypti* mosquito population was used for a series of audio recordings containing their flight tones. After the recordings, the mosquitoes' biological parameters were measured, such as body mass and wing length. The study shows that the male mosquitoes fundamental WBFs are higher than those of female mosquitoes. However, for both sexes, the variation found for the fundamental frequency is large. Mean male mosquitoes fundamental frequencies ranged from 571 to 832Hz, while females fundamental frequencies ranged from 421 to 578Hz [34]. It indicates that measurements made using different mosquito samples in different places or environmental conditions are important to update the database on the species and their fundamental frequencies and harmonics.

Ambient temperature may cause changes in the insects' fundamental flight tones. In general, the WBF rises linearly as the temperature increases, and this also applies to mosquitoes. It is known that this increase can reach 13Hz/^{o}C in the *Aedes aegypti* case. However, for *Aedes aegypti* females, studies have verified that body size is not a factor capable of changing the fundamental WBF [42]. Therefore, it is important to contextualize climatic data in the region where a sensor for detecting *Aedes aegypti* mosquitoes is implanted to increase its accuracy. More than that, it is important to think on computational mechanisms able to adjust the sensor sensitivity according to the environment measured temperature. The acoustic approach was fundamental for the construction of a database on flying insects biological aspects. However, the major drawbacks of this technique are the high noise susceptibility and the need for continuous recordings to ensure the insects' detection, which requires more device's data processing and power consumption.

3.2.2 Optical Approach

The principle of optical signal analysis in the flying insects' detection has come with the perception that an insect in free flight can modulate the sunlight perceived by a photocell. However, the lack of instrumentation for the automated acquisition and measurement of biological data made it difficult to develop technologies capable for taking advantage of this principle until 1986 [30]. By this time, studies on the classification of flying insects by WBF had already developed enough to classify more than 200 insect species and to estimate considerable differences between WBFs among species of the same genus. It occurred when emerged the first studies for the development of flying insects classification automated sensors. These sensors operate through the analysis of WBF modulated optical signals to measure insects fundamental frequency and harmonics amplitudes and use these data toward mosquito species classification.

The optoelectronic approach is based on a pair of light emitter-and-receiver, creating a FoV. When an insect crosses the FoV, part of the emitted light beam is reflected in the receiver modulated by the insect's WBF. In addition to the light emitter-and-receiver pair, the sensor is based on a signal amplifier followed by an ADC and a computer for the signal frequency spectrum analysis. Whenever the system is triggered by a change in amplitude and frequency perceived by the light receiver, the computer samples the signal for counting and frequency spectrum analysis through the signal's FFT.

3.3 Related Work

Since 1986, the science behind optoelectronic sensors for detecting flying insects has evolved into cheaper devices with lower energy and processing requirements. Recent implementations used laser beams as a light source for real-time detection of three different flying insects species [64]. These devices accuracy has also evolved greatly over time, allowing sensors to be sensitive enough to distinguish different sexes from the same species mosquitoes. Besides, the data collected by these devices were contextualized about climatic, temporal, spatial, and biological factors, to contribute to the MBD prevalence prediction. The questions about the processing of the signals collected by these sensors have also been an important object of study [66]. This is a key factor linked to the sensors' limited processing capacity. It is already possible to obtain consistent results within a commitment relation regarding computational cost.

Recent researches are responsible for updating the database on flying insects, which had previously been collected using less efficient acoustic methods. In addition to the data quality improvement, the information accuracy is also superior, since optoelectronic sensors measurements can be performed with a higher samples number [65]. The research shows that the optoelectronic sensor is already capable of automatically detecting ten species of flying insects with accuracy always exceeding 79%. Increasing accuracy in these sensors is critical for real implementation reliability of mosquito detection devices in open environments.

Machine learning algorithms are already used in research for accuracy improvement for optoelectronic sensors development. Several compositions have been tested to neither compromise energy consumption nor data processing. Even so, an accuracy of more than 90% in detecting and identifying mosquitoes is already possible [66]. Other studies deal with the association of machine learning to optoelectronic sensors for gender and genus differentiation of three different mosquito species [67]. About traditional sensors, the use of machine learning presents significant gains in terms of accuracy. However, the concern with the impacts on data processing and energy consumption should be kept in mind. It does not consider these factors can jeopardize production costs and massive deployment of these devices.

Main references for the development of this study can be found in [62, 63]. This research involved the application of optoelectronic sensors in common McPhail traps. To do this, a pair of infrared LED and photodiode arrays were inserted into the trap entrance [78]. The collected data was then transmitted through a mobile communication network. Another implementation addresses the development of an optoelectronic sensor with optical signal modulation for immunization against optical interference. The frequency used for this modulation was 60kHz, and a laser beam was used as emitter [62]. The HF modulation has proved to be an essential tool for the development of sensors immune to optical interference. A newer implementation of the optoelectronic sensor uses a higher frequency, 455kHz. Besides, the emitting source has been replaced by an array of infrared LEDs. The results obtained with the array of LEDs and the laser beam were similarly efficient, and the choice of a higher frequency improved the SNR compared to the previous device [63].

All the advances obtained in the development of sensors for flying insects detection and identification are essential to prepare them for an IoT scenario. Optoelectronic sensors do not need to perform uninterrupted recordings to detect mosquitoes. It is already a breakthrough for reductions in devices' data processing and power consumption. Also, the proper choice of low-power LEDs and photodiodes should contribute to the sensors' power autonomy in the field. Recent studies already use platforms such as Raspberry Pi 3 for the development of sensors based on wing beating of flying insects [77]. Other research already uses a GPRS (General Packet Radio Services) modem coupled to the sensor to perform data collected connection to the Internet through HTTP (HyperText Transfer Protocol) requests [79].

3.4 Optoelectronic Sensor Module Construction

The optical model used to validate the optoelectronic sensor operating principle is based on the reference work [62, 63]. This model addresses optical signal modulation at HF. Such modulation is introduced to immunize the signal against the major interference sources found in both laboratory and external environments. The frequency chosen for modulation was 455kHz. This frequency was chosen because it is immune to the main interference sources and by the availability of a 455kHz bandpass ceramic filter during the construction of the reference sensor.

The system assembled to perform the experiments relies on the implementation of the two optical modules presented in the reference work, the optical emitter module, and the optical receiver module. For the general sensor operation principle validation at HF, an emitter circuit at 455kHz clock was inserted, and a 455kHz bandpass filter was also included at the receiver output. The obtained signal was analyzed with an oscilloscope. The complete system assembly scheme can be seen in Figure 3.1.

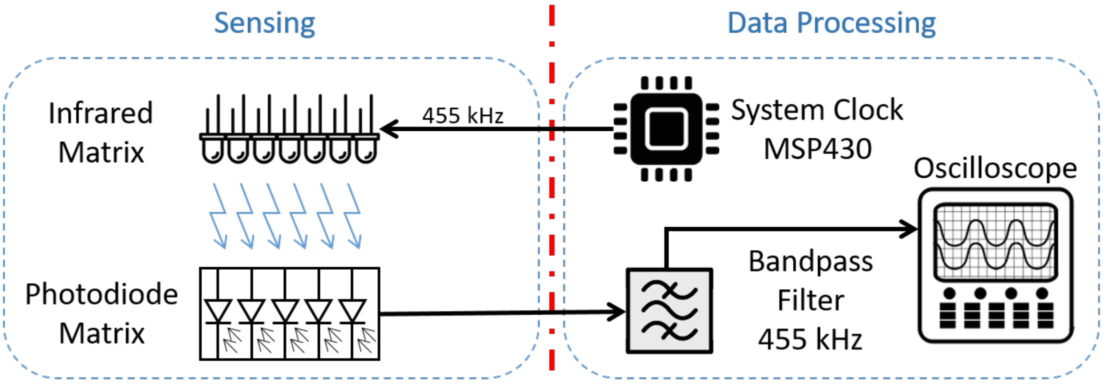


Figure 3.1: Diagram of the system designed to evaluate the optical approach.

The two optical modules were created as proposed by the authors, the 24 High-Speed Infrared TSHG5410 LEDs array module and the 22 TEMD5080X01 photodiodes array module with an OPA380 high-speed amplifier. The MSP430 16-bit microcontroller was used to generate the emitter module's 455kHz clock, and the receiver module output was connected to a 455kHz center frequency ceramic bandpass filter with 10kHz bandwidth. Figure 3.2 shows the image of this system assembly as well as the signal's FFT displayed on the oscilloscope. Highlights a) infrared matrix, b) photodiode matrix, c) MSP430 used for 455kHz clock, d) 455kHz ceramic bandpass filter, e) infrared LED matrix power supply, f) photodiode matrix power supply, g) 3.3V step-down regulator circuit, and h) oscilloscope.

The signal observed on the oscilloscope validates the sensor operation fundamental principle. All major interference sources have been filtered, and the 455kHz center spectral component stands out with a 26.25mV amplitude. The total bandwidth analyzed is 800kHz with

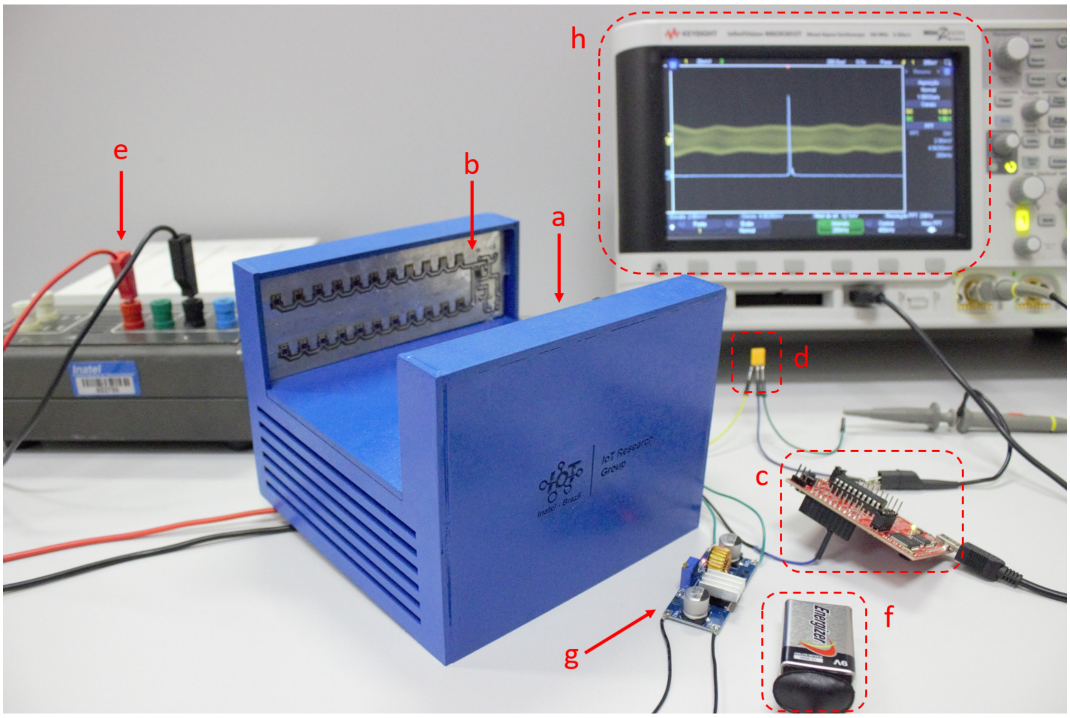


Figure 3.2: Structure assembled for the optical approach validation and analysis of main interference sources.

center at 455kHz. The Figure 3.3 shows the analyzed signal at the filter output as well as the signal's FFT.

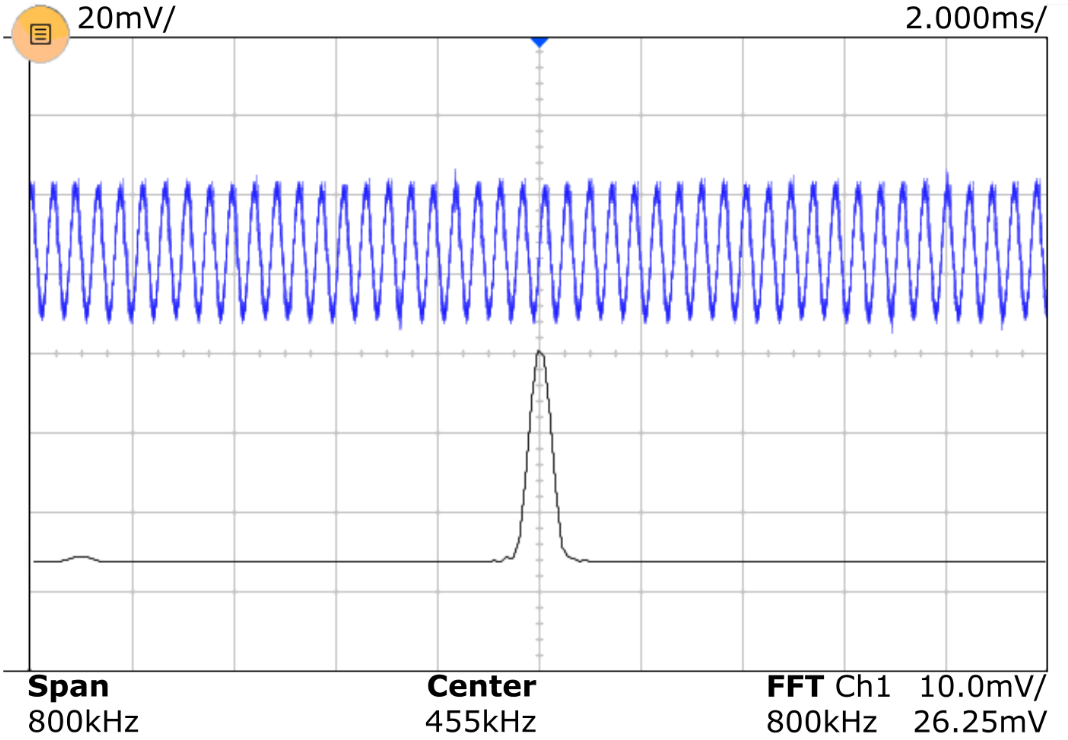


Figure 3.3: Demonstration of the optical signal modulation-demodulation process at 455 kHz.

3.5 Noise Evaluation and Results Analysis

The same model used for the sensor operating principle validation was later used for the main optical interference sources analysis. Differently, from the main related work's objective [62,63], this study focuses on the possibility to determine alternative frequencies for the optical signal modulation in the sensor. In this purpose, two major modifications were required in the system to verify the interference sources. The first change was the MSP430 as clock source at 455kHz removal. The LEDs were then fed directly by a 12V power supply. The second necessary adjustment was the bandpass filter removal so that it was feasible to analyze the environment optical sources influences across the spectrum.

Three scenarios and their main optical interference sources were evaluated. The first considered scenario was the laboratory environment with artificial light, the second scenario was the external environment during the day, and the third scenario was the external environment during the night. In this way, it was possible to cover the evaluation of all potential natural or artificial optical interference sources for the sensor, from residential fluorescent lamps to the lamp posts. In all the three scenarios, the frequency spectrum range analyzed on the oscilloscope is from 0 to 1MHz. The tests were performed for two days to ensure the reliability of the data presented. The results indicate that the optical interference sources produced spectral components at the same frequencies, regardless the ambient temperature or cloudiness. Figure 3.4 shows the vertically aligned obtained results for each one of the three scenarios for a broad overview of interference sources spectral components. These scenarios are: a) spectrum up to 1 Mhz in laboratory environment with artificial light, b) external environment during the day, c) and external environment at night with artificial light sources.

The main sources of interference have been verified, and most of them are common to all the three scenarios. Spectral components from optical interference sources were found at 185kHz, 370kHz, 560kHz, 745kHz, and 935kHz. Besides, two additional spectral components were observed only in the laboratory environment, at 580kHz and between 110-140kHz. As expected, the external nighttime scenario has lower amplitude interference components. The daytime outside scene is more affected by the interference due to the high external brightness. Also, it is verified that spectral components' amplitude decrease as the frequency increases. Once the main components generated by interference sources were confirmed, the interference-free bandwidths could be determined. The light yellow crossbars highlighted in

Figure 3.4 illustrate these bandwidths. The results are satisfactory and represent a wide range of scenarios and interference sources. Still, further studies can be conducted contemplating a greater temporal, spatial and noise diversity. The main interference-free zones found are between 200kHz and 355kHz, 395kHz and 540kHz, 600kHz and 725kHz, and 760kHz and 910kHz. The determination of these bandwidths is strategic for alternative frequencies choices for the optical signal modulation, as well as for capacitive bandpass filters design at these frequencies. The 455kHz ceramic filter used in the reference work was commonly used in older electronic devices development but is hardly ever found on the market today. Therefore, designing new filters through capacitive circuits may be a way to overcome this difficulty and broaden the modulation frequency choice possibilities. Thus, it becomes possible to choose a more generic filter as possible, that fits a wider range of scenarios.

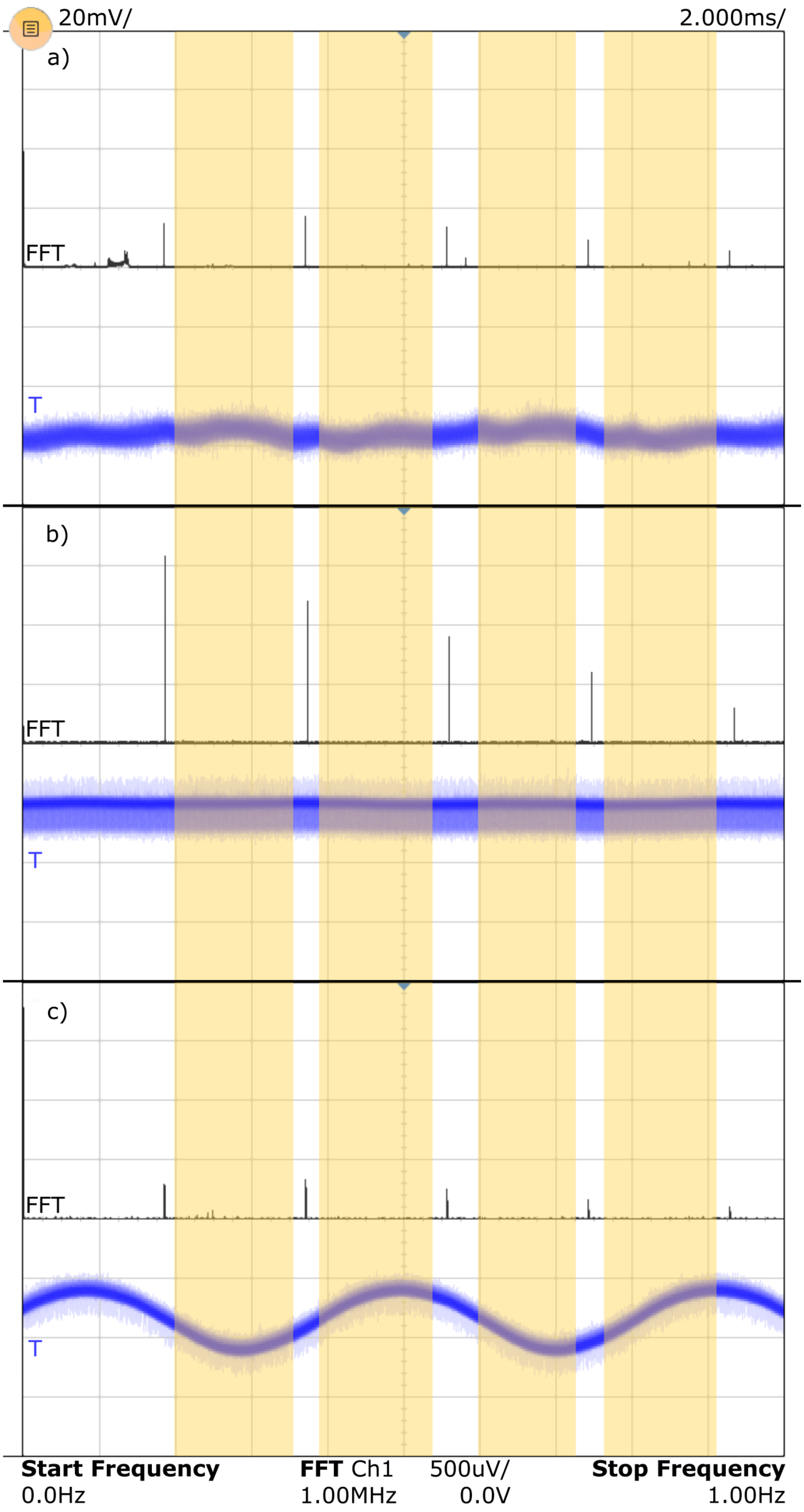


Figure 3.4: Main noise and interference optical sources in different light conditions evaluation.

Chapter 4

Proposal of an IoT-Based Solution for Mosquitoes Monitoring

4.1 Introduction

For several years, MBD have been a major global concern. Countries with warmer climates are these disease vectors primary victims. However, due to rising global temperatures, countries with no history of MBD have presented alarming statistics on the mosquitoes population lack control. Due to the importance of this subject, this chapter proposes a smart and selective IoT-based solution for monitoring the *Aedes aegypti* mosquito, main vector of diseases such as Yellow Fever, Dengue Fever, Zika, and Chikungunya. The central purpose of this study is the development of an optical sensor with electronic trap integrable to the internet through a communication module and a middleware solution. The trap is made up of a microcontroller that detects flying insects through an optical sensor and operates two DC (Direct Current) fans arranged at the ends of an aerodynamic structure. The construction of a prototype validates the project through results evaluation and discussion.

Based on the above-identified motivations for the *Aedes aegypti* identification and mitigation, this subsection aims to present an alternative to detect and mitigate the insect through a trap coupled to an optical flying insects sensor. For this, the trap validation experiments considered the output of the reference work optical sensor. After the sensor identifies a female *Aedes aegypti* mosquito, the microcontroller turns on a suction fan throwing the insect into a box they cannot escape. If the detected flying insect is not a possible Dengue vector, the device turns on an exhaust fan to expel the insect outside of the trap. The device has a Wi-Fi communication module that transfers the mosquito detection information to the In.IoT middleware. The proposed device presents low power consumption, and it is inexpensive. Applying this trap to a field testing scenario can take account of mosquito attractive mechanisms, such as a standing water container [80]. The device's implementation in a real setting can be a significant tool for the disease-vector mosquitoes possible infestations detection.

4.2 Optical Sensor

The optical flying insect detection system is designed based on the state of the art presented in Chapter 2 and validated in Chapter 3. Specifically, the development of the optical sensor is based on reference work implemented with LEDs and photodiodes. Therefore, the sensor design process began with the photodiodes specification of the optical signal receiver circuit. The reference photodiode chosen is TEMD5080X01. Figure 4.1 shows the typical photodiode output current curve. The photodiode current response ranges from 0.1µA to 90µA, depending on the illuminance applied.

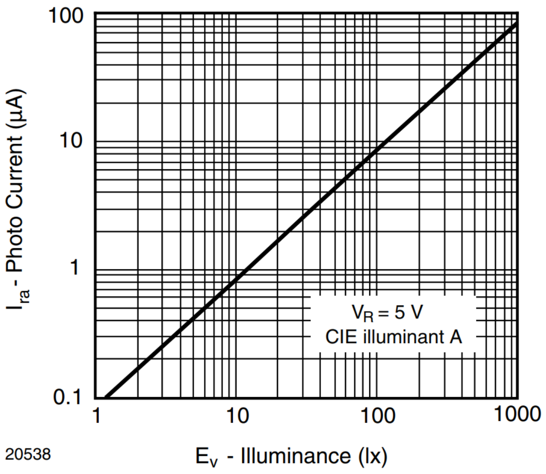


Figure 4.1: Photodiode output current curve.

The implemented receiving circuit has a configuration of 22 TEMD5080X01 parallel photodiodes. Thus, the minimum and maximum current values in the receiver circuit output must be multiplied by 22, obtaining a minimum current of 2.2µA and a maximum current of 1980µA. Once the receiver circuit output current values were set, it become possible to perform a simulation using Altium Designer (PSPICE Simulation) and evaluate the OPA380AID transimpedance amplifier response applied in the reference work. For simulation purposes, the optical signal receiver output has been replaced by a current source respecting the simulated current supply direction from cathode to anode. Figure 4.2 below represents the simulated current/voltage converter circuit.

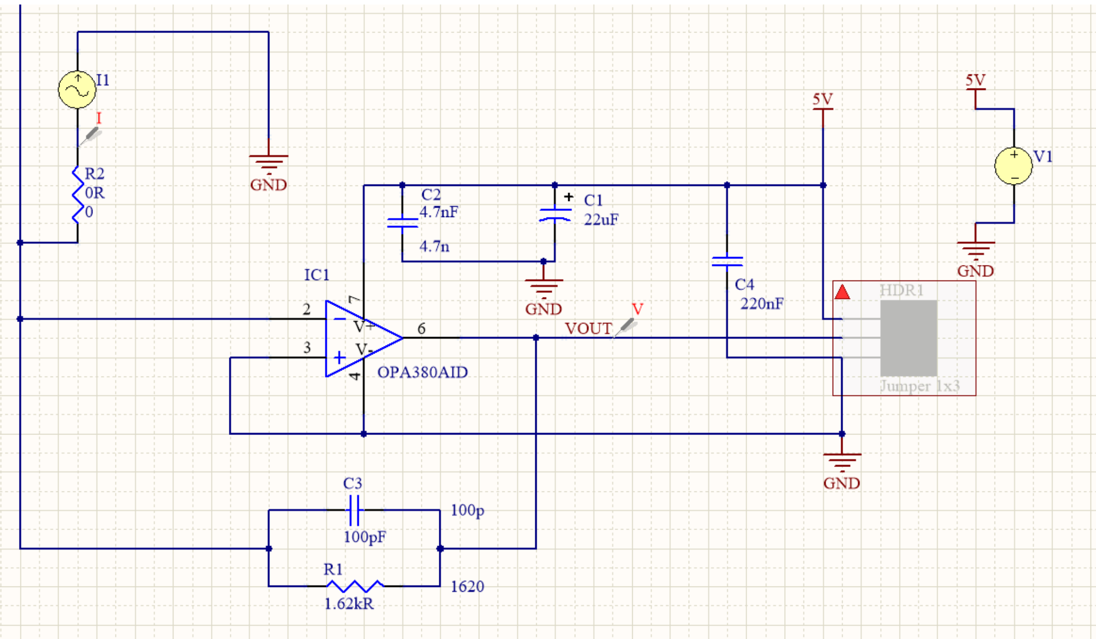


Figure 4.2: Simulated current/voltage converter circuit.

After simulating the circuit response, the transimpedance amplifier responses were evaluated. Initially, a signal is applied by the current sine generator I1. A new simulation was performed by changing the generator waveform from sinusoidal to linear. Thus, the signals at the input and output of the amplifier were again evaluated. Figure 4.3 shows all the signals obtained in transimpedance amplifier simulation: the amplifier input current using the sine generator, the voltage response obtained at the transimpedance amplifier output, the transimpedance amplifier input current using linear generator, and the voltage signal at the amplifier output. As a result of the simulation, it is observed that the output voltage ranges from 24.968mV to 3.1915V. These parameters will be used later in the signal filtering circuit design.

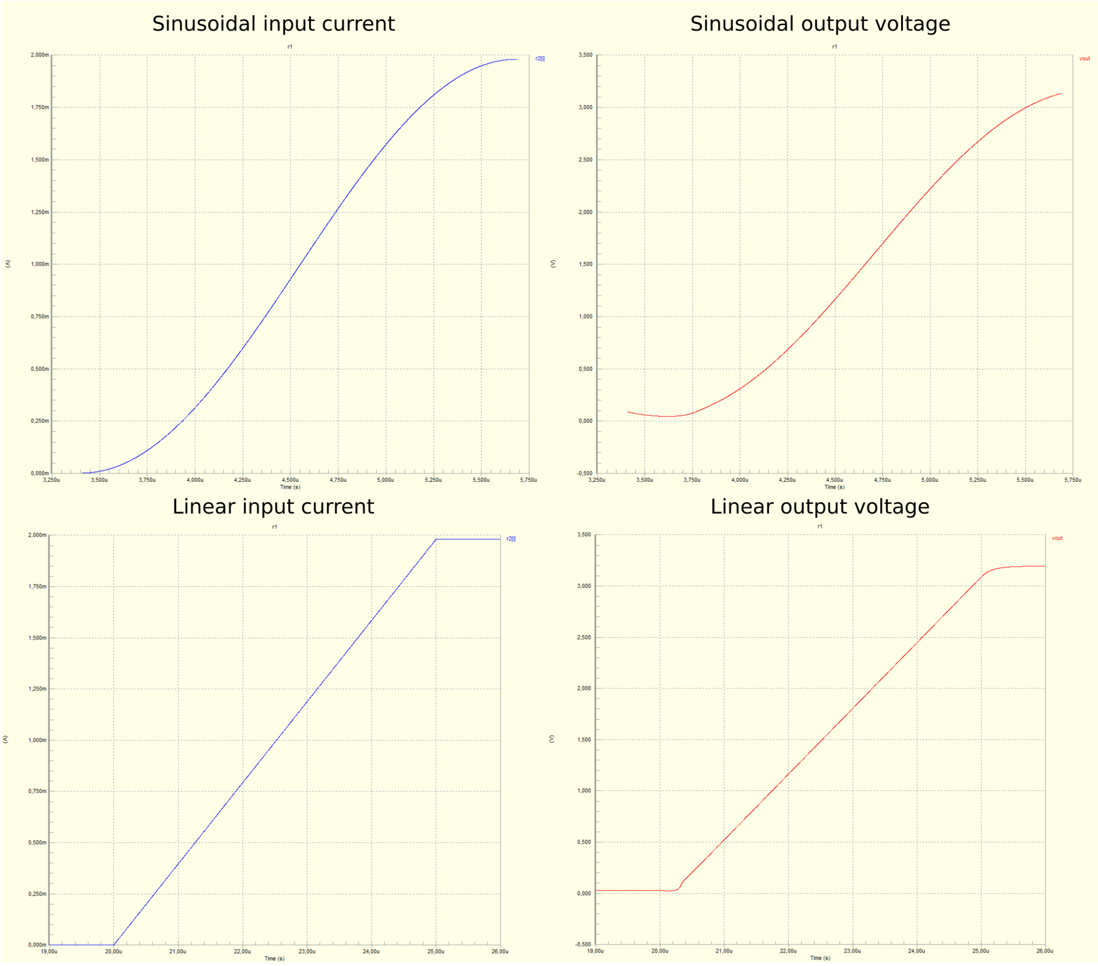
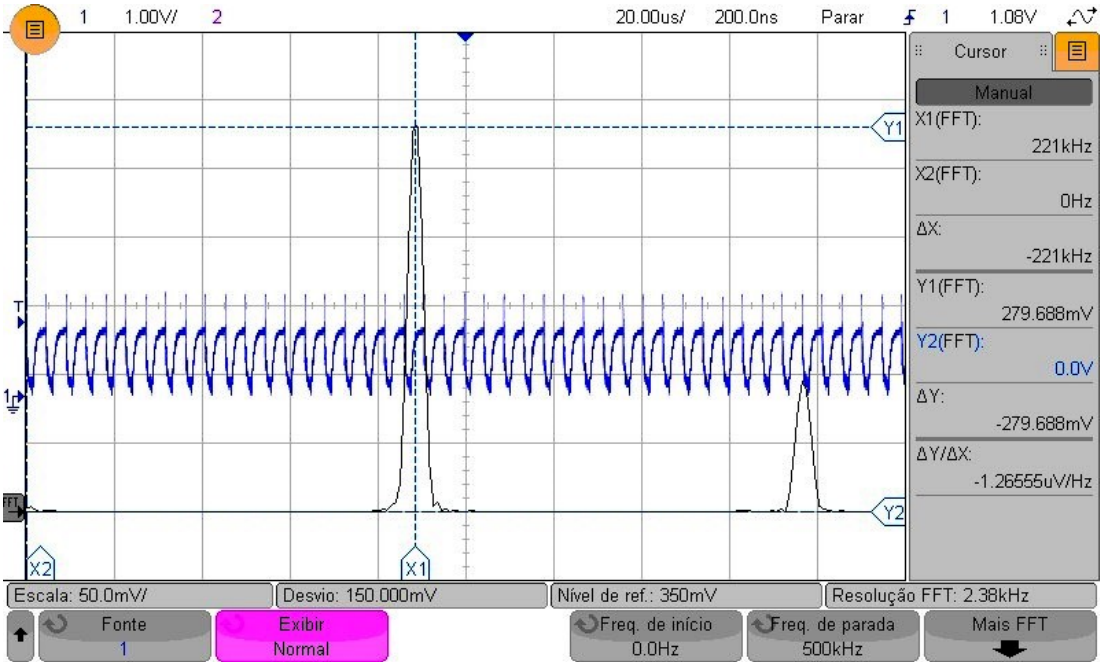


Figure 4.3: Signals observed in transimpedance amplifier simulation

4.3 Processing and Communication Module

Following the optical signal emitter and receiver circuits implementation, tests were performed with the receiver circuit through a modulated wave. These tests objective was to validate the *Aedes aegypti* mosquito detection built system functioning and processing. For this, the emitter and receiver modules were implemented as the reference work and positioned facing each other, creating a FoV. The receiver module was powered with a 3.3V voltage.

The first step of the tests was the validation of the receiver circuit operation. This incipient test will verify if the receiver module was able to detect in the receiver module a 220kHz frequency signal applied to the emitter module. Figure 4.4 shows the oscilloscope screenshot of the signal checked at the receiver module output. As shown in the picture, there is a 280mV amplitude 221kHz frequency component.



1 1.00V/ 2 20.00us/ 200.0ns Parar 1 1.08V

Cursor
Manual
X1(FFT): 221kHz
X2(FFT): 0Hz
ΔX: -221kHz
Y1(FFT): 279.688mV
Y2(FFT): 0.0V
ΔY: -279.688mV
ΔY/ΔX: -1.26555uV/Hz

Escala: 50.0mV/
Desvio: 150.000mV
Nível de ref.: 350mV
Resolução FFT: 2.38kHz
Fonte 1
Exibir Normal
Freq. de início 0.0Hz
Freq. de parada 500kHz

Figure 4.4: Detection of 220kHz frequency signal.

Next, the signal containing the *Aedes aegypti* mosquito WBF was simulatedly generated using a propeller attached to a motor, as shown in figure 4.5. When this engine is powered with 7V voltage, the propeller blades occlude the FoV at an approximately 420 Hz frequency. This frequency was chosen to simulate a real female *Aedes aegypti* mosquito.

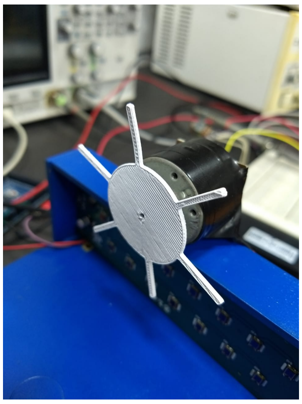
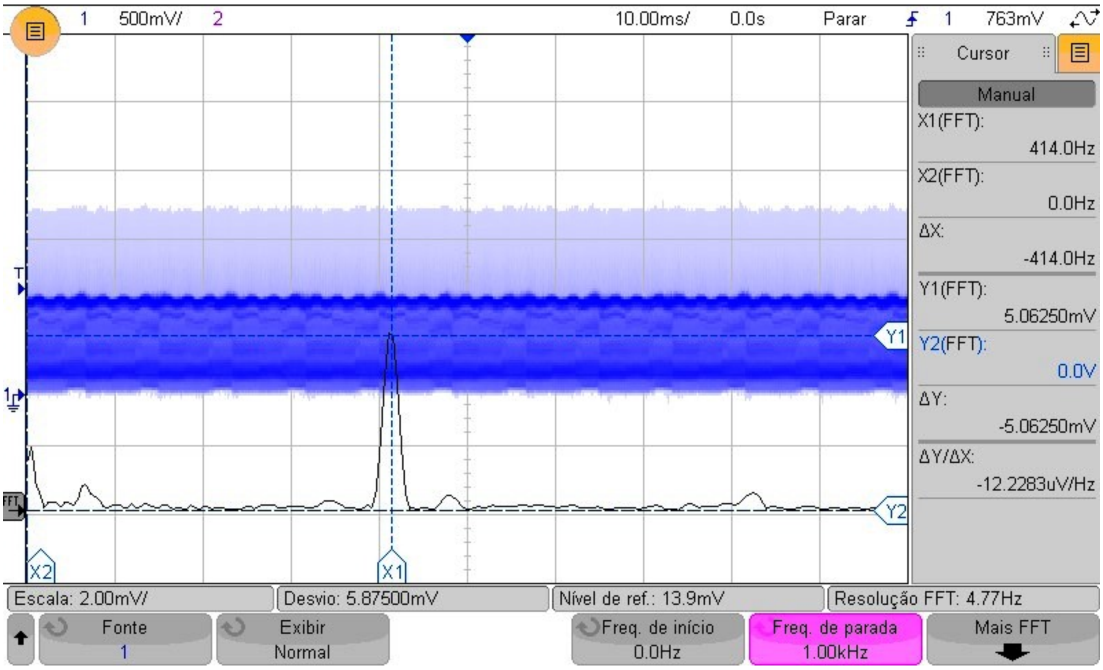


Figure 4.5: Mosquito WBF simulation engine.

After simulating the signal containing the mosquito WBF, the frequency components generated at the receiver module output were evaluated through an oscilloscope, as shown in Figure 4.6. This second test was also satisfactory, as the system recovered the WBF waveform generated by the simulated mosquito with a propeller and motor. The frequency component generated by the setup is centered at 414Hz and has 5mV amplitude. This voltage drop was already expected as the mosquito is a very small source of signal obstruction and modulation for the sensor.

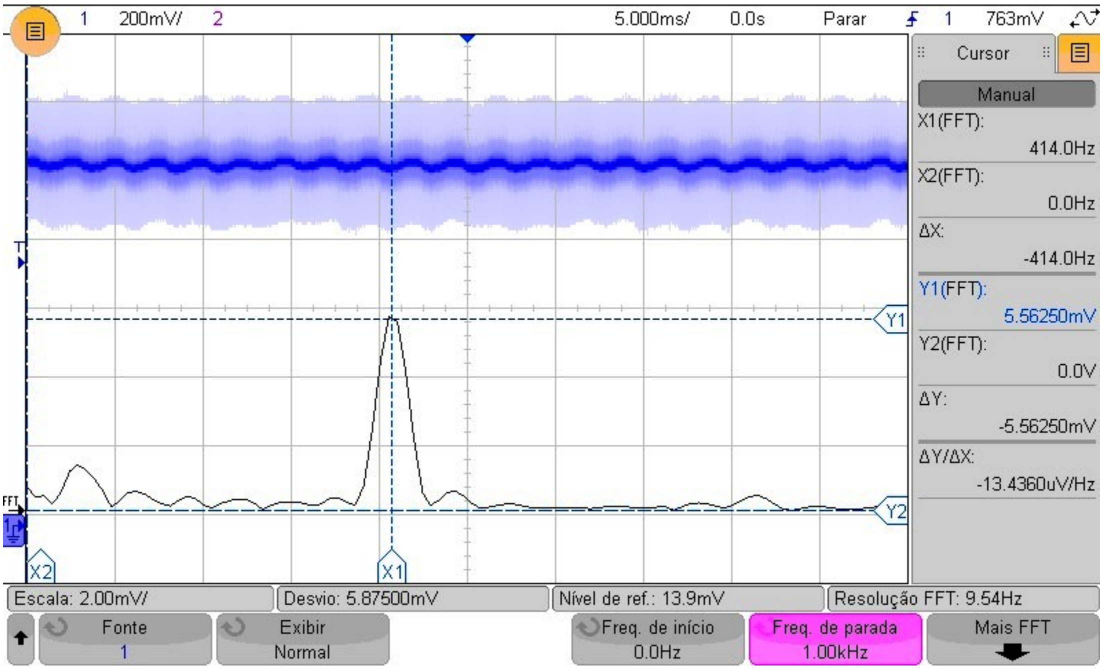


X1(FFT): 414.0Hz
X2(FFT): 0.0Hz
ΔX: -414.0Hz
Y1(FFT): 5.06250mV
Y2(FFT): 0.0V
ΔY: -5.06250mV
ΔY/ΔX: -12.2283uV/Hz

Escala: 2.00mV/
Desvio: 5.87500mV
Nível de ref.: 13.9mV
Resolução FFT: 4.77Hz

Figure 4.6: Detection of modulated WBF frequency signal.

The next objective was to demodulate this signal to obtain only the 414Hz waveform. The AD630 demodulator was used according to the reference work. After the AM signal demodulation process, the the signal of interest envelope must be recovered. The test result can be seen in the screenshot taken from the oscilloscope in the Figure 4.7.



X1(FFT): 414.0Hz
X2(FFT): 0.0Hz
ΔX: -414.0Hz
Y1(FFT): 5.56250mV
Y2(FFT): 0.0V
ΔY: -5.56250mV
ΔY/ΔX: -13.4360uV/Hz

Escala: 2.00mV/
Desvio: 5.87500mV
Nível de ref.: 13.9mV
Resolução FFT: 9.54Hz

Figure 4.7: Demodulated WBF frequency signal.

The last test was also successfully completed and it was possible to obtain the simulated mosquito (propeller + motor) WBF waveform envelope. The next steps were to filter this signal using a three-stage low-pass filter and then amplify using an ADC to facilitate signal handling through a microcontrolled circuit. This prototype was implemented using Arduino Uno board.

Publications are performed using the MQTT (Message Queuing Telemetry Transport) protocol and JSON (JavaScript Object Notation) format. MQTT is a public-to-sign protocol used in IoT applications for small, low-power devices. JSON is a compact, open-standalone, simple, fast data exchange format between systems. Flying insect detection logs are then sent to the In.IoT middleware. Middleware enables communication and data management for distributed applications. A dashboard was created on the platform to present the data collected through a time chart, as shown in Figure 4.8.

Figure 4.8: Middleware dashboard

4.4 Fan-Based Actuator

The low power consumption actuator system proposed in this subsection must be integrable to the optical sensor described in subsection above. The electronic circuit was composed by a microcontroller, a display, and two DC fans. The structure was built in MDF (Medium-Density Fiberboard) and the walls are aerodynamically designed so that they can direct the airflow out of the trap or into the cage. In this way, the trap can capture female *Aedes aegypti* mosquitoes and eject other flying insects species.

When the device is turned on, the microcontroller starts reading the sensor's output signal at the input pin. The microcontroller processes each of these values and relates them to a frequency content through a quantized level that identifies what flying insect species and genus crossed the sensor's FoV. The trap prototype uses the Arduino Uno. This device has microcontroller, memory and input/output peripherals. In this project development, two digital output are responsible for triggering exhaust and suction DC fans.

Reading the frequency signal can lead to three different responses from the actuator, which are shown on display and may or may not turn on one of the DC fans. If the microcontroller does not indicate any frequency, the trap reports that no flying insect has come into the trap. If the detected insect is not a female *Aedes aegypti*, the exhaust DC fan expels it from the trap while the display indicates that the insect is not the Dengue vector. Otherwise, the screen warns the user about the mosquito appearing and the suction DC fan launches it into the cage. In order to validate the proposal, the propeller engine simulates the insects WBF to the optical sensor.

This device construction used two DC fans with dimensions of 80 x 80 millimeters. One of them is at the trap's top. That fan is responsible for throwing the *Aedes aegypti* into the trap's cage. Another DC fan is located on the horizontal trap's end. Its function is to expel non-*Aedes aegypti* insects outside of the trap. A transistor switching system was used to turn between the two DC fans. This straightforward circuit helps in better communication between the Arduino Uno and the DC fans. When logic requests the suction DC fan drive, for example, the microcontroller digital output feeds the transistor's base, which in turn drives the DC fan. The supplies used in this actuator construction are represented in Figure 4.9

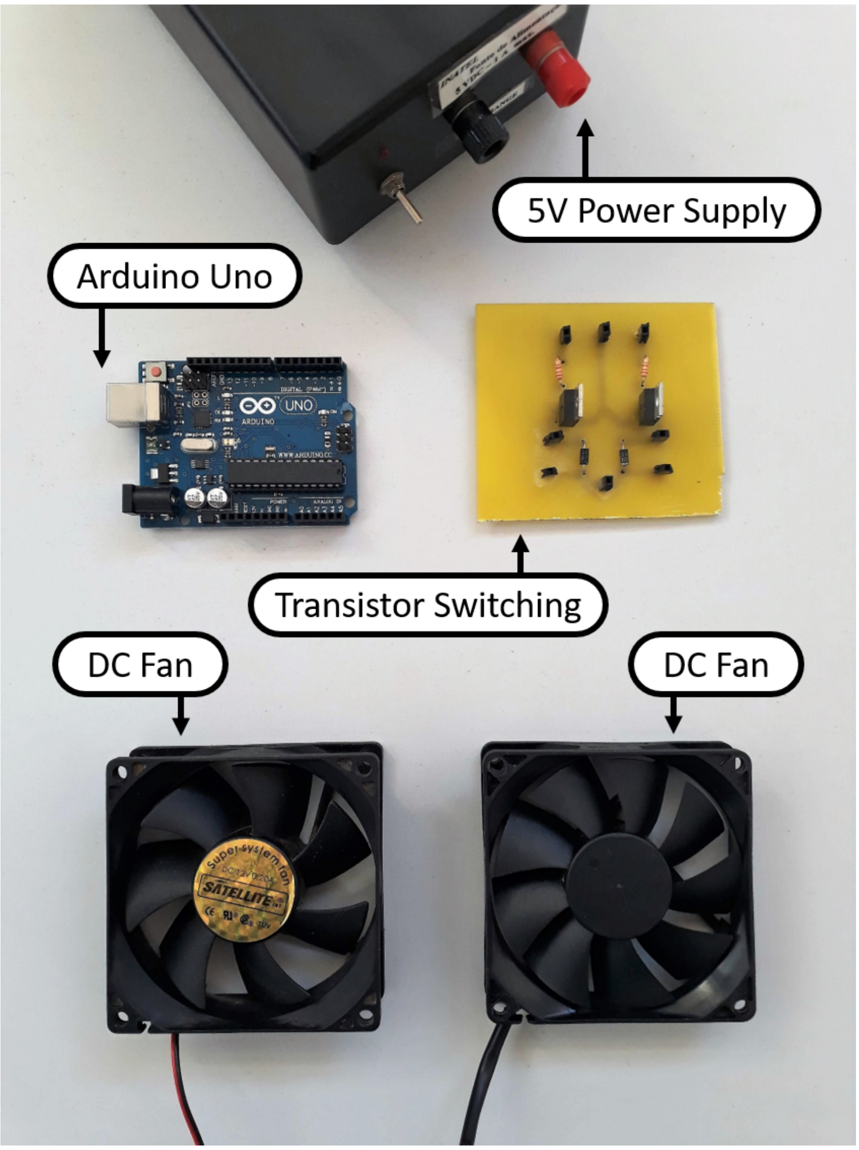


Figure 4.9: Supplies and devices used in the prototype construction.

The trap structure is an essential point in this project. Some aerodynamic adaptations have been designed for the best functioning of the structure. The trap's ends were designed in a pyramidal format to provide the best airflow and prevent the insects from getting trapped on the trap's edges. The dimensions of the prototype are as follows: 45 centimeters in length, 25.50 centimeters in width and 23.50 centimeters in height. The bottom of the trap contains a cage where the mosquitoes are trapped. The cage is coated with an adhesive tape that is responsible for preventing mosquitoes from leaving the trap after the suction DC fan stops working. The structure also has a top door that allows access to the trap's interior and system's maintenance. The Figure 4.10 shows the trap MDF structure.

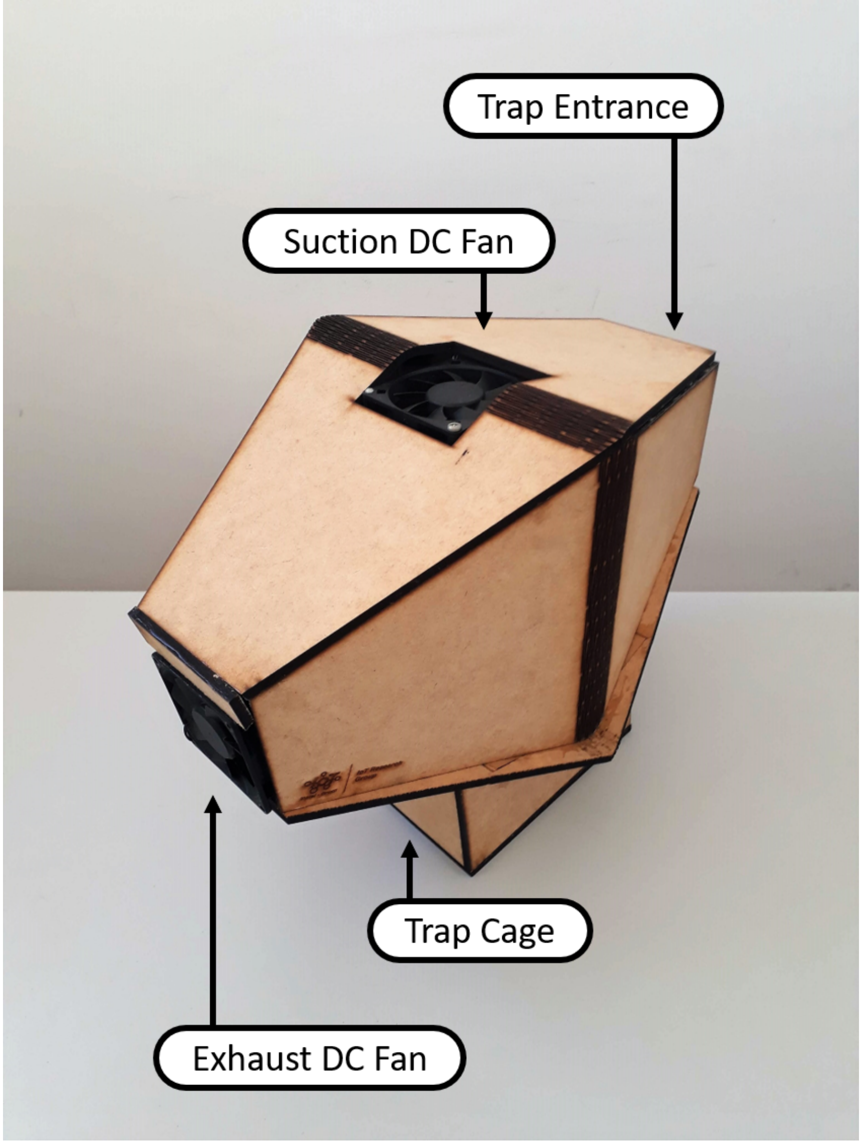


Figure 4.10: Trap structure in MDF.

The actuator prototype validation experiments were performed using the Proteus Design Suite, specific simulation software for PCB (Printed Circuit Board) layout design development. Figure 4.11 presents the prototype connections. Since the project uses an Arduino Uno board, The high-level language utilized for programming the prototype was C++. The trap features a 16 x 4 LM016L LCD (Liquid Crystal Display) for facilitating the user interface. It alerts the user how the fans are working and if the insect inside the trap is a female *Aedes aegypti* mosquito.

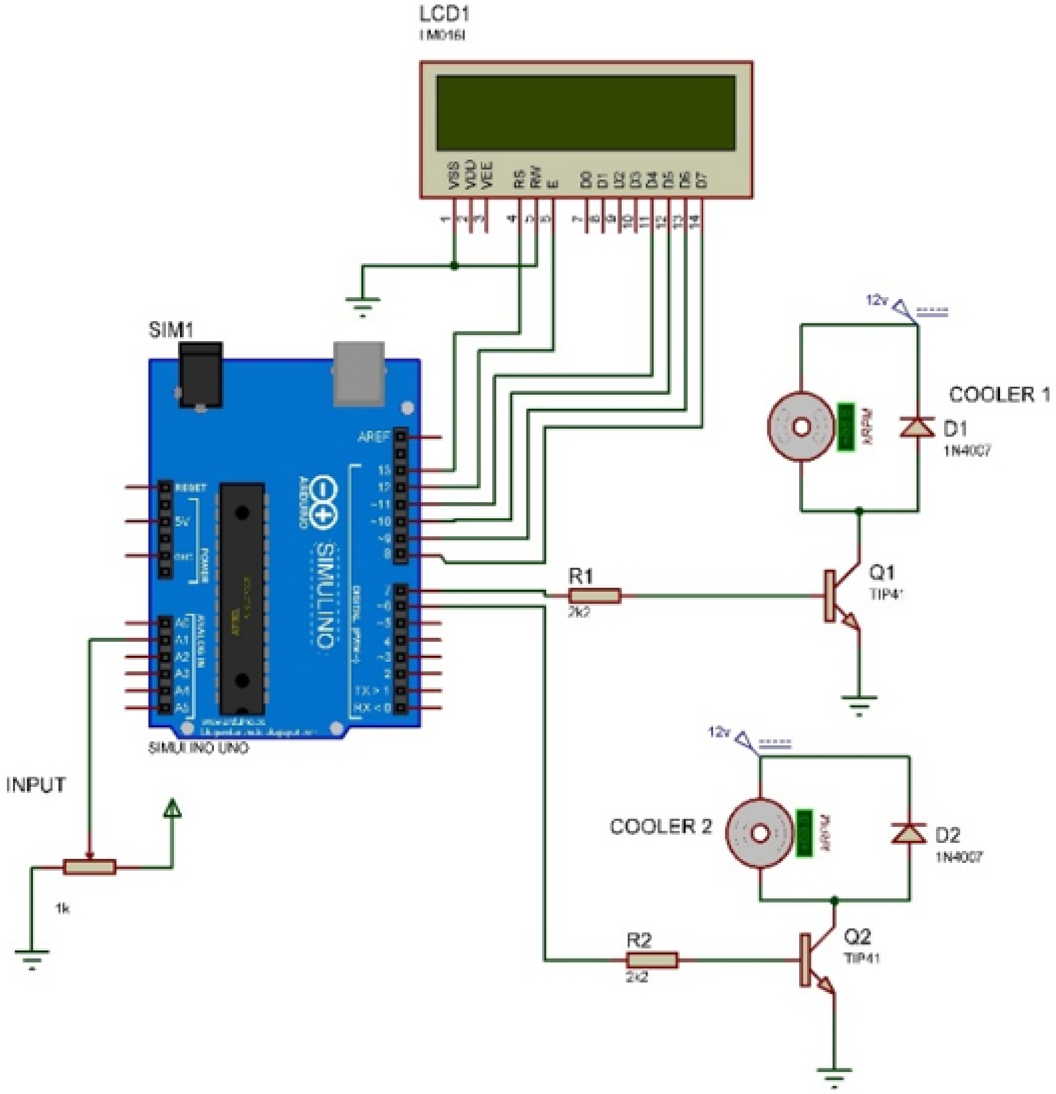


Figure 4.11: System simulation in software.

4.5 System Validation and Evaluation

During the experiments, the prototyping platform chosen in the project was the Arduino Uno. This component has an Atmel AVR microcontroller with six analog inputs and 14 digital outputs. The detection system delivers a square wave signal with voltage values of -12V and 12V. Arduino Uno is capable of reading voltage values up to 5V. Therefore, the use of this microcontroller required the implementation of a voltage lowering circuit, shown in Figure 4.12. The system was then assembled using the optical sensor, fan-based actuator, Arduino Uno microcontroller and ESP8266 to transmit the data collected using Wi-Fi to In.IoT middleware.

The WBF flying insect simulation system, consisted of propeller and motor, was used to generate different frequency values detectable by the optical sensor. To validate all sensing possibilities, different voltage values were applied to the motor and the results were read in two stages: at the receiver circuit output and also after the demodulation, filtering and amplification stage. The values found can be seen in Figure 4.13 and validate the detection of a female *Aedes*

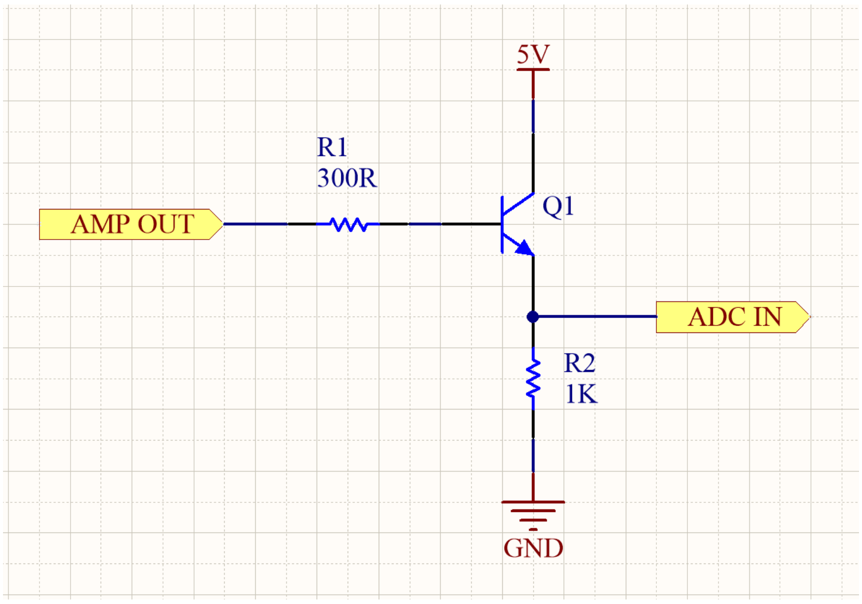


Figure 4.12: Voltage lowering circuit.

aegypti mosquito, a male *Aedes aegypti* mosquito, and any other flying insect case.

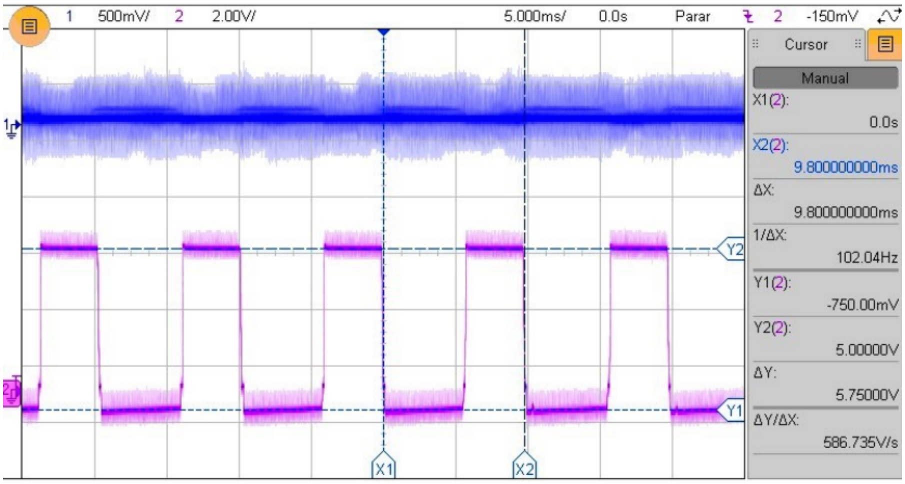
Observing the oscilloscope screenshots, the signals highlighted in blue on Channel 1 represent the output from the receiver circuit and the signals highlighted in magenta on Channel 2 represent the signal after the demodulation, filtering, and amplification stages. So, the signal observed on Channel 2 represents the WBF recovered by the system. The signals recovered with frequencies of 102Hz, 505Hz and 684Hz represent, respectively, the detection of any insect, *Aedes aegypti* female mosquito, and a male *Aedes aegypti* mosquito.

The recovered signals are applied to the Arduino Uno input. The microcontroller has been programmed to detect and classify these signals according to frequency. If values between 421Hz and 575Hz are detected, the system records the detection of an Aedes aegypti femea mosquito. If the detected values vary between 576Hz and 832Hz they are recorded as detection of a male Aedes aegypti mosquito. Any other frequency values between 10Hz and 1000Hz are recorded as another detected flying insect.

From the records made during periods of 10s, the microcontroller performs some actions. If Aedes aegypti femea mosquitoes are detected, the actuation system is activated to turn on the DC insect capture fan. If the registry identifies the detection of any other insect, the actuation system is triggered to expel the insect from the trap. In addition, the system generates publications to be sent to the middlewere through the ESP8266 using Wi-Fi.

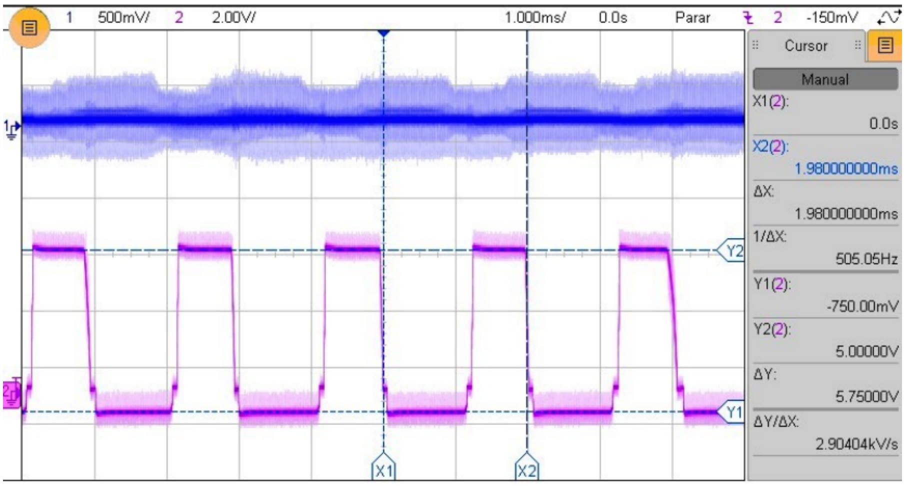
The results observed through the experiments performed were satisfactory. Implementation using real mosquitoes is critical, but testing with the propeller-based frequency simulator has proven very efficient. The system was able to perform frequency detection, retrieve the signal, record data and successfully transmit information to the platform. The detection system showed great noise immunity facilitating data processing using simple microcontrollers.

non-*Aedes aegypti* detection



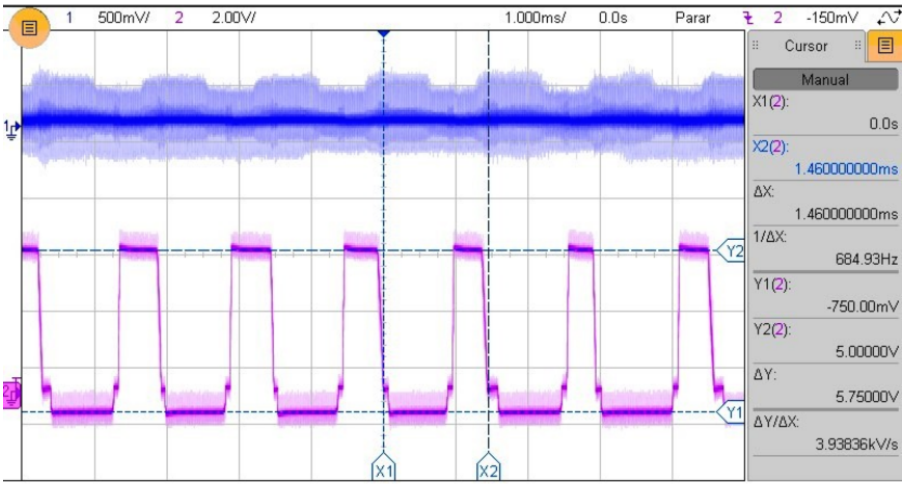
X1(2): 0.0s
X2(2): 9.800000000ms
ΔX: 9.800000000ms
1/ΔX: 102.04Hz
Y1(2): -750.00mV
Y2(2): 5.00000V
ΔY: 5.75000V
ΔY/ΔX: 586.735V/s

Female *Aedes aegypti* detection



X1(2): 0.0s
X2(2): 1.980000000ms
ΔX: 1.980000000ms
1/ΔX: 505.05Hz
Y1(2): -750.00mV
Y2(2): 5.00000V
ΔY: 5.75000V
ΔY/ΔX: 2.90404kV/s

Male *Aedes aegypti* detection



X1(2): 0.0s
X2(2): 1.460000000ms
ΔX: 1.460000000ms
1/ΔX: 684.93Hz
Y1(2): -750.00mV
Y2(2): 5.00000V
ΔY: 5.75000V
ΔY/ΔX: 3.93836kV/s

Figure 4.13: Signals observed during the final simulation

Chapter 5

Conclusion and Future Works

The development of acoustic sensors for flying insects detection was fundamental for the establishment of mosquito monitoring metrics. These studies allowed the determination of specific WBFs for each species and gender classification. The literature is abundant in acoustic, electronic and biological studies that support sensor implantation for diseases monitoring transmitted by specific mosquitoes.

The enhancement of flying insect detection techniques through WBF is notorious under energy efficiency and computational processing aspects. The optical sensing approach advancement was the basis for the development of sensors that can operate in standby mode until a flying insect detection event occurs. Thus, it is possible for these devices to operate in extremely remote locations with satisfactory battery life.

Optical sensors for detecting flying insects should play a key role in MBD surveillance advances. These devices, placed throughout a geographic region, can remotely provide valuable information about the prevalence of disease-transmitting insects. This paradigm shift on MBD surveillance can mean, in the long run, consistent energy savings for maintenance of low-energy sensors as well as a reduction in the use of combustible natural resources for locomotion of health teams.

Besides, the use of insect detection sensors can play an essential role in the agricultural cleaner production process as these sensors are adjustable for the WBF of interest. Thus, it is possible a remote and low-consumption monitoring of agricultural pests. The use of chemical agents for pest control can be reduced and directed appropriately, reducing production costs, electric energy for the fields monitoring, and the impacts of agribusiness on the environment.

The development of optical sensors for the flying insects' detection can play a key role in serious diseases surveillance of global significance by controlling the population of diseases vectors mosquitoes. Optoelectronic sensors have significant advantages over acoustic sensors, such as speed, reliability, and reduced energy consumption. Unlike acoustic sensors, optoelectronic sensors only record when triggered by flying insects, allowing large savings in power consumption and data traffic. Also, optoelectronic sensors capable for modulating the optical signal at HF can eliminate major optical interference sources, increasing the sensor's efficiency without further requirements in data processing. All these requirements are fundamental to prepare these devices for an IoT application.

The cases numbers of Dengue Fever, Yellow Fever, Zika Virus, and Chikungunya are growing over the years not only in tropical and subtropical countries. These numbers tend to grow even more because of rising temperatures on the globe. It is expected that even temperate weather countries with lower *Aedes aegypti* prevalence rates will be more affected by MBD shortly. These alarming data, coupled with the lack of adequate methods or tools to control the mosquito population and their diseases, point to the need for urgent research in this subject.

5.1 Lessons Learned

During the research, some lessons were learned that may help the development of new studies. The first point to be made is that the literature contains some disagreements about the WBF recorded for each species. In some circumstances, the *Aedes aegypti* WBF can range from 550 Hz to 750 Hz while the *Culex quinquefasciatus* has a range from 310 Hz to 650 Hz. Therefore, the band from 550 Hz to 600 Hz is common to both species. This situation can cause misunderstandings in the insect identification by the device [81]. This scenario highlights the need for experiments in real environment to better validate the WBF of each species and also to study possible influences of air temperature and humidity on these values. The literature is not yet unanimous about the influence of these factors.

The experiments performed with the prototype proved to have a fast and highly efficient response in catching *Aedes aegypti* mosquitoes. However, more studies are needed to determine the WBF of the Dengue mosquito contextualized by the climatic conditions in which the study is performed. An alternative is to couple a weather station to the system for long-term data analysis. Besides, it becomes possible to study other characteristics of mosquito behavior in addition to the WBF, such as it prevalence throughout the day or the seasons.

5.2 Concluding Remarks

There are several reasons for mosquito sensors had switched from an acoustic to an optoelectronic approach. Unlike microphones, which need to record the whole experiment period to then extract the mosquito detection events, optoelectronic sensors only generate sensing data when an actual detection event occurs. This advantage is necessary to save data regarding processing, storage, and transmission. Besides, optoelectronic sensors provide higher SNR than microphones, that record all surrounding noise sources.

This research work presented the validation of the optoelectronic sensors' operation principle. Besides, the main optical interference sources and the alternative frequency bandwidths for signal modulation were presented. Thus, it will be possible to overcome the technical difficulty of finding specific frequency ceramic filters on the market. As future work, it is expected to design capacitive circuits capable of replacing the ceramic filter with the same efficiency in alternative higher frequencies, without compromising the whole system energy consumption. Moreover, mosquito's experimenting is required to obtain sufficient samples to validate the sensor accuracy and update the database on mosquitoes fundamental and harmonic frequencies.

Despite advances in optical sensors development, most of the studied optical approaches were implemented only as laboratory prototypes. Deploying them in the field will cause new challenges in calibration, performance evaluation, and new metrics establishment. However, this new step followed by the introduction of new technologies such as Machine Learning, Big Data, and the Internet of Things, can mean a revolution in current methods for mosquitoes detection and their diseases control.

This research work proposed the creation of a low energy consumption selective trap to capture the female *A*edes aegypti automatically through an exhaustion and suction system. In the first experiments, the prototype proved to be very efficient, adopting a selectivity range between 421Hz and 575Hz. This range is a programmable parameter. Consequently, the trap can be scaled to capture different flying insects' species and genus by adjusting the interest frequency. This actuation system is integrated with a low-power optical sensor, as well as other data sources for contextualization, as a weather station. Thus, a long-term study can be performed that will feed back the decision logic to a more effective system project.

5.3 Future Work

The conclusion of this study proposes some future work. In principle, the next step in advancing research is the final implementation of the entire processing and transmission module beyond the laboratory prototype. Some mechanical adjustments will be required so that the entire detection, processing, actuation and transmission solution can be wrapped in the same enclosure.

Also, there are some improvements that can be made in device development. Since these devices may be installed in remote environments, it is necessary to check the power supply via batteries and solar panels. This will require further study of the best protocols to reduce consumption and processing requirements.

Another point to note is a deeper study on WBF overlap of Aedes aegypti females and males, as well as mosquitoes of other species. Defining frequency boundaries more assertively can prevent false positives in field mosquito detection. Finally, it would be very useful to detect the amount of insects and not just their presence. This information can be very useful in studies of territorial and temporal prevalence of mosquitoes in a given territory.

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