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# Bracelet for early detection of epileptic seizures

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## Dedication (Etud1)

*Praise be to Allah with love, gratitude, and appreciation for both the beginning and the end. And the last of our supplications is that all praise is due to Allah, the Lord of the worlds.*
*This journey was neither short nor easy, but I made it through. All praise is due to Allah who facilitated the beginnings and led us to the end through His grace and generosity.*
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*To the one who taught me morals before letters, my angel in life, the source of love, tenderness, and sincerity, the smile of my life, and whose prayers were the secret of my success, my beloved mother.*
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# Dedication (Etud2)

**بسم الله الرحمن الرحيم**

{ يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ } صدق الله العظيم

الحمدلله حبا وشكرا وامتنانا على البدء والختام الحمد لله الذي وفقني لاتمام هذا العمل وبلغني هذه اللحظة

إلى روح جدي الطاهرة، رحمه الله وأسكنه فسيح جناته، الذي غاب عن ناظري ولم يغب عن قلبي، أهدي ثمرة جهدي وتخرجي وفاءً لذكراه العطرة.

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إلى اخوتي واصدقائي وكل من ساندني وشجعني ورافقني في رحلة السعي نحو هذا الانجار

.أهديكم ثمرة جهدي المتواضع، راجيةً من الله أن يجعل هذا النجاح بدايةً لمستقبلٍ مشرق

# Abstract

The graduation project aims to design and develop a low-cost smart bracelet dedicated to monitoring epilepsy patients and enabling real-time early detection of seizures. The system relies on Internet of Things (IoT) technologies and biomedical sensors to collect the patient's physiological data, such as heart rate and movement, which are then processed using artificial intelligence algorithms to detect early signs of an epileptic seizure. The bracelet also provides instant notifications to family members or medical staff when an abnormal condition is detected, enabling rapid intervention and reducing risks. This project combines both technical and practical aspects with the goal of improving patients' quality of life and offering a smart and effective solution for modern healthcare.

**Keywords:**

Epilepsy, Seizure Monitoring, Smart Bracelet, Internet of Things (IoT), Vital Signs Monitoring, Biosensors, Early Detection, Real-time Alert System, Smart Healthcare, Artificial Intelligence.

# Résumé

Le projet de fin d’études vise à concevoir et développer un bracelet intelligent à faible coût destiné à surveiller les patients épileptiques et à détecter précocement les crises en temps réel. Le système repose sur les technologies de l’Internet des objets (IoT) et des capteurs biomédicaux afin de collecter les données physiologiques du patient, telles que le rythme cardiaque et les mouvements, puis de les traiter à l’aide d’algorithmes d’intelligence artificielle pour détecter tout signe précoce d’une crise d’épilepsie. Le bracelet permet également d’envoyer des alertes instantanées aux proches ou au personnel médical en cas d’anomalie, facilitant ainsi une intervention rapide et réduisant les risques. Ce projet combine les aspects techniques et pratiques dans le but d’améliorer la qualité de vie des patients et de proposer une solution intelligente et efficace pour les soins de santé modernes.

**Mots-clés :**

Épilepsie, Surveillance des crises, Bracelet intelligent, Internet des objets (IoT), Surveillance des signes vitaux, Biocapteurs, Détection précoce, Système d’alerte en temps réel, Santé intelligente, Intelligence artificielle.

# ملخص

يهدف المشروع الى تصميم وتطوير سوار ذكي منخفض التكلفة مخصص لمراقبة مرضى الصرع والكشف المبكر عن النوبات في الوقت الحقيقي.يعتمد النظام على تقنيات انترنت الأشياء .والحساسات الحيوية لجمع البيانات الفزيولوجية للمريض ،مثل معدل ضربات القلب والحركة ،ثم معالجتها باستخدام خوارزميات الذكاء الاصطناعي لاكتشاف أي علامات مبكرة تدل على حدوث نوبة صرع.كما يتيح السوار ارسال تنبيهات فورية الى الاهل او الطاقم الطبي عند رصد أي حالة غير طبيعية،مما يسهل التدخل السريع ويقلل من المخاطر.ويجمع هذا المشروع بين الجانبين التقني والتطبيقي بهدف تحسين جودة حياة المرضى وتقديم حل ذكي وفعال للرعاية الصحية الحديثة.

**الكلمات المفتاحية:**

الصرع، مراقبة النوبات، السوار الذكي، إنترنت الأشياء، مراقبة العلامات الحيوية، المستشعرات الحيوية، الكشف المبكر، نظام التنبيه في الوقت الحقيقي، الرعاية الصحية الذكية، الذكاء الاصطناعي.

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# General Introduction

The contemporary world is witnessing a profound technological transformation that has fundamentally reshaped modern systems, most notably the healthcare sector. This sector is increasingly relying on smart technologies rather than traditional models. The digital revolution, propelled by the Internet of Things (IoT), embedded systems, and artificial intelligence (AI), has enabled a paradigm shift in healthcare delivery: from a reactive model to a proactive one grounded in continuous monitoring, real-time data analysis, and the early detection of critical conditions before they deteriorate into life-threatening situations.

In this context, wearable medical devices have emerged as innovative solutions that have brought about a major breakthrough in patient health monitoring. Healthcare is no longer limited to clinical or hospital settings; instead, it has evolved into a continuous process seamlessly integrated into the patient’s daily life. The significance of these devices lies in their ability to transform raw physiological data into meaningful and accurate indicators that support swift, informed, and effective medical decision-making.

Epilepsy stands as one of the most prevalent and clinically significant chronic neurological disorders, demanding continuous and precise monitoring owing to its sudden onset and unpredictable nature, as well as the serious physical and psychological risks it poses. Despite notable medical advancements in this field, traditional monitoring approaches remain inadequate in providing real-time, effective, and reliable surveillance, underscoring the pressing need for intelligent systems capable of continuous monitoring and early seizure detection.

In response to this challenge, this work aims to design and develop a smart wearable bracelet dedicated to the continuous monitoring of epilepsy patients. The proposed system integrates a set of physiological and motion sensors, including a heart rate sensor, an accelerometer, and a galvanic skin response (GSR) sensor, alongside an ESP8266 microcontroller and a GSM communication module to ensure real-time alert transmission, enabling rapid intervention and reducing health associated risks.

The significance of this work lies in its convergence of biomedical engineering, embedded systems, and IoT technologies, striving to achieve an optimal balance between accuracy, low cost, and ease of implementation, thereby rendering it suitable for deployment across diverse healthcare environments.

Furthermore, this work opens promising future perspectives for continued development toward more advanced smart solutions, with the potential to evolve into a fully marketable and clinically validated medical product.

This work is structured into six main chapters, structured as follows:

**Chapter One** presents a comprehensive theoretical framework on epilepsy, including its definition, types, causes, symptoms, and medical and social impacts, with the aim of establishing a solid scientific foundation for understanding the studied problem.

**Chapter Two** reviews existing epilepsy monitoring solutions such as medical bracelets and wearables, highlighting their role in tracking vital signs and remote healthcare, while analyzing their limitations to identify gaps the project addresses.

**Chapter Three** focuses on the hardware design of the proposed system, providing a detailed description of the sensors, processing unit, communication modules, overall system architecture, signal flow, and the rationale behind component selection.

**Chapter Four** addresses the software aspect of the system, including physiological signal processing, filtering techniques, and seizure detection algorithms, all aimed at enhancing the system's accuracy, robustness, and reliability.

**Chapter Five** presents the practical implementation stage, from prototype development to experimental testing, and includes a thorough performance analysis along with a discussion of the technical challenges encountered and the potential improvements identified.

**Chapter Six** explores the economic feasibility and commercialization potential of the proposed solution, with particular emphasis on its transition into a marketable smart healthcare product, including the prospective integration of artificial intelligence technologies to further enhance its capabilities.

Accordingly, this study proposes a comprehensive technical approach that bridges medical analysis, engineering design, and practical implementation, with the overarching goal of developing an intelligent system capable of enhancing the continuous monitoring of epilepsy patients and improving the efficiency of emergency response mechanisms.

Ultimately, this work aspires to contribute to the transition toward a smarter and more efficient healthcare system based on prevention and prediction rather than relying solely on post-event treatment.

# Chapter I. General Concepts of Epilepsy and Detection Systems

## I.1 Introduction

Epilepsy is recognized as one of the most prevalent chronic neurological disorders, resulting from disturbances in the electrical signals within the brain. These disturbances manifest as sudden and recurrent seizures that vary in nature, severity, and duration. Such seizures may appear in the form of muscle convulsions, transient loss of consciousness, or alterations in behavior, perception, and movement. Due to their unpredictable nature, these episodes pose substantial risks to patients, potentially leading to physical injury and adversely impacting their quality of life, as well as their and psychological social well-being.

Driven by recent technological advancements in medicine, modern solutions using smart devices and embedded electronic systems have emerged to continuously monitor epilepsy patients. These systems rely on various sensors that measure vital physiological parameters such as heart rate, blood oxygen saturation, body movement, and skin conductivity reflecting the patient's physiological state.Furthermore, the integration of Internet of Things (IoT) technologies and artificial intelligence has contributed to the development of more efficient systems capable of collecting and analyzing data in real time to detect abnormal patterns associated with seizures. These systems send instant alerts to caregivers or medical staff, thereby improving healthcare quality and reducing potential risks.

Accordingly, this chapter aims to provide a comprehensive overview of epilepsy including its definition and main types. It also presents key smart technologies and wearable systems currently used for early seizure detection and patient monitoring.

## I.2 Definition of Epilepsy

An epileptic seizure is defined as a transient occurrence of signs or symptoms resulting from abnormal, excessive, or synchronous neuronal activity in the brain. This definition was established and updated by the International League Against Epilepsy (ILAE) in 2005 and remained unchanged during the revision of the epilepsy definition in 2014. Epilepsy is described as a chronic neurological disorder characterized by a persistent predisposition of the brain to generate recurrent seizures. Epilepsy is diagnosed when one of the following conditions is met: (1) the occurrence of at least two unprovoked seizures separated by more than 24 hours, (2) a single unprovoked seizure with a high probability of further seizures, comparable to the recurrence risk after two unprovoked seizures (i.e., a risk of 60% or higher over the next 10 years), or (3) the identification of a well-defined epilepsy syndrome. The 60% threshold was adopted as the minimum statistical estimate reflecting the likelihood of seizure recurrence, based on findings from previous clinical studies.

In addition, certain medical indicators such as epileptiform activity on electroencephalography (EEG) or structural abnormalities detected through brain imaging increase the probability of future seizures. Recent research, including the PRO-LONG study, has shown that patients diagnosed according to these updated criteria exhibited a high long-term seizure recurrence rate exceeding 80% over ten years, supporting the possibility of diagnosing epilepsy even after a single seizure in specific cases. Accordingly, a person is classified as having epilepsy when the probability of a second seizure reaches or exceeds 60%, making their risk comparable to individuals with a history of two or more unprovoked seizures.

In some cases, epilepsy may be considered in remission or functionally resolved, particularly when age-dependent syndromes are surpassed or when a long seizure-free period occurs after discontinuation of treatment. The International League Against Epilepsy redefined epilepsy as a “disease” rather than a “disorder” to emphasize its seriousness and clinical impact, despite ongoing debate regarding the terminology. However, an epilepsy diagnosis does not necessarily imply immediate treatment, as therapeutic decisions are made individually based on clinical evaluation and the patient's condition [1].

Additionally, epilepsy is a chronic neurological condition of the brain that occurs when groups of nerve cells (neurons) repeatedly send abnormal or incorrect signals , leading to epileptic seizures. Under normal conditions, neurons produce electrical and chemical signals that are transmitted to other neurons, as well as to muscles and organs, helping to regulate human thoughts, emotions, and behaviors. During a seizure, a large number of neurons fire simultaneously and much faster than normal, resulting in a sudden increase in electrical activity in the brain. This abnormal activity may cause involuntary movements, sensory changes, unusual emotions or behaviors, and can sometimes lead to loss of consciousness due to disruption of normal brain function.

After the seizure ends, some individuals recover consciousness quickly, while others may require a longer recovery period ranging from minutes to hours. During this time, they may experience fatigue, drowsiness, weakness, or mental confusion. Epilepsy can present in different forms and have various causes, and its severity and impact vary from one person to another. It may also be associated with other medical conditions. For this reason, it is sometimes referred to as a “seizure disorder” due to the diversity of its types. Some patients may experience muscle convulsions and loss of consciousness, while others may have brief seizures involving a temporary pause in activity with staring spells and momentary loss of awareness. The frequency of seizures also varies widely among patients; some may experience them very rarely, while others may have them daily. Although any seizure is a condition that requires attention, experiencing a seizure does not necessarily mean that a person has epilepsy. Other conditions can also cause similar seizure-like events, such as first-time seizures, febrile seizures, non-epileptic events, or eclampsia during pregnancy. Therefore, it is essential to consult a physician after any seizure to determine the exact cause [2].

## I.3 Epileptic Seizures classifications

The modern framework for classifying epileptic seizures includes two levels of detail: a basic (simplified) classification and an extended (detailed) classification. The choice depends on the user's expertise and purpose . The basic version, derived from the extended one, suits daily clinical practice for general practitioners, pediatricians, non-neurology healthcare professionals, nurses, and other healthcare workers. The extended classification is intended for epilepsy specialists, clinical neurophysiologists, and researchers, though some researchers may use only the basic version, while others outside specialty groups prefer the detailed format. Before classification, it is essential to confirm with reasonable certainty that the event is an epileptic seizure. This system applies to all ages except neonates (who have a separate classification) and excludes subclinical electrical seizures without observable clinical manifestations.

### I.3.1 Basic classification

The classification of a seizure is based on its onset pattern, which can be categorized as focal, generalized, of unknown onset, or unclassifiable.

- The term "focal" has replaced the older term "partial."
- The term "generalized" remains in use. A generalized seizure involves both cerebral hemispheres from the onset. Its manifestations may appear symmetrical or asymmetrical, depending on clinical and electroencephalographic (EEG) findings.
- Unknown onset is used when the initial phase of the seizure cannot be clearly identified, despite other observable features.
- The unclassifiable category is reserved for rare cases that do not fit clearly into any of the other groups.

Additionally, focal seizures are further described by the level of awareness during the event:

- Focal aware seizure (awareness is preserved), corresponding to the former *simple partial seizure*.
- Focal impaired awareness seizure (awareness is impaired), corresponding to the former *complex partial seizure*.

However, awareness in this context does not simply refer to complete loss or preservation of consciousness. It specifically describes the patient's ability to perceive their surroundings and interact purposefully during the seizure. If awareness is impaired at any point during the event, the seizure is classified as a focal impaired-awareness seizure،This descriptor may be omitted if sufficient clinical information is not available.Following this determination, focal seizures in the basic classification are further categorized into motor and non-motor types.

Furthermore, seizures previously described as "secondarily generalized" have been renamed focal to bilateral tonic-clonic seizures. This updated terminology more accurately emphasizes that the seizure activity begins in a focal region before spreading to involve both cerebral hemispheres.

Generalized seizures are also categorized based on the level of awareness (aware or impaired awareness) and their motor or non-motor characteristics. Generalized motor seizures may include tonic-clonic patterns or other motor manifestations. The same principles can also be applied to seizures of unknown onset.

In some cases, terminology may be simplified by omitting redundant words when the meaning remains clear, such as using “focal tonic” may be used instead of “focal motor tonic.” However, the term “tonic-clonic” must be used precisely, as it has a strict definition and should not be applied broadly to all motor activity. The term “onset” may also be omitted when it is implied by context. Seizure onset remains a critical factor in classification. A seizure whose onset is not witnessed and is later followed by tonic-clonic activity should be classified as an “unknown onset bilateral tonic-clonic seizure.” . In clinical practice, The level of confidence in determining focal or generalized onset is estimated at approximately 80% .

### I.3.2 Extended classification

The extended classification system builds upon the basic system by further subdividing the motor and non-motor categories across all onset types, including focal, generalized, and unknown onset seizures.

For focal motor seizures, the level on awareness is assessed at any stage of the event; if awareness is impaired, the seizure is classified as a focal impaired-awareness seizure. If awareness cannot be reliably assessed or sufficient information is not available, as may occur in brief seizures, This Descriptor may be omitted.

The next level of classification is based on the first observable sign or symptom at seizure onset, even if it is not the most prominent feature later. This initial manifestation is prioritized because it most closely reflects the origin of the epileptic activity.

An exception to this rule is made for focal behavioral arrest seizures, where behavioral arrest must be the dominant feature throughout the entire event. Other common subtypes at this level include seizures with automatisms or emotional manifestations.

After classification, further clinical descriptors may be added from standardized seizure description systems, published classification lists, or free-text clinical observations. For example, a seizure may be described as a focal impaired-awareness seizure accompanied by left facial numbness and anxiety. In this description, only the emphasized terms represent the core seizure type, while the additional details provide a more complete clinical picture [1].

#### I.3.2.1 Focal Seizures

Focal seizures originate in a specific area of one hemisphere of the brain. Their symptoms depend on the location where the abnormal electrical activity begins. These seizures are divided into two main categories:

- **Focal aware seizures:** During these seizures, the patient remains conscious and aware of their surroundings. Symptoms may include unusual sensations, involuntary movements, visual disturbances, or emotional changes.
- **Focal impaired awareness seizures:** In this type, the patient's awareness is partially or completely impaired. The individual may appear confused, stare blankly, or perform repetitive automatic movements such as lip-smacking, chewing, or hand rubbing. Focal seizures may involve motor symptoms, sensory disturbances, autonomic changes, or cognitive and emotional manifestations. In some cases, the seizure may spread to both hemispheres and evolve into a focal-to-bilateral tonic-clonic seizure.

#### I.3.2.2 Generalized Seizures

Generalized seizures involve both cerebral hemispheres from the onset and are usually associated with impaired consciousness. The main types include:

- **Absence seizures:** Brief episodes of staring and loss of awareness, usually lasting only a few seconds.
- **Tonic seizures:** Sudden muscle stiffening affecting part or all of the body.
- **Clonic seizures:** Repetitive rhythmic jerking movements caused by alternating muscle contraction and relaxation.
- **Tonic-clonic seizures:** Characterized by an initial phase of muscle stiffening followed by rhythmic jerking movements.
- **Myoclonic seizures:** Sudden, brief muscle jerks affecting one or several muscle groups.
- **Atonic seizures:** Sudden loss of muscle tone, often resulting in falls and possible injuries.

#### I.3.2.3 Unknown-Onset Seizures

Unknown-onset seizures are diagnosed when the beginning of the seizure is not observed or when there is insufficient information to determine whether the seizure started as focal or generalized. As more clinical or electroencephalographic information becomes available, these seizures may later be reclassifies.

## I.4 Physiological Signals Associated with Epileptic Seizures

Physiological signals are essential biological markers that describe the functional condition of the human body. In epilepsy studies, these signals are extensively utilized for the detection, monitoring, and forecasting of epileptic seizures. During seizure events, patients experience involuntary alterations in brain activity, cardiovascular function, muscular activity, respiration, and autonomic regulation. Such physiological changes can be captured using clinical equipment or wearable sensing technologies. The integration of multiple physiological modalities has greatly enhanced the performance of seizure detection systems, as each signal contributes complementary information regarding different physiological systems involved in epileptic episodes.

### I.4.1 Electroencephalography (EEG)

EEG is the most fundamental and reliable modality for identifying epileptic seizures. It measures the brain's electrical activity using electrodes placed on the scalp. Seizure occurrences are commonly associated with abnormal EEG patterns such as spikes, sharp waves, and rhythmic discharges.

### I.4.2 Electrocardiography (ECG)

ECG records the electrical activity of the heart. During seizures, dysfunction of the autonomic nervous system may result in variations in heart rate, including tachycardia, bradycardia, or changes in heart rate variability.

### I.4.3 Electromyography (EMG)

EMG captures the electrical signals generated by skeletal muscles. It is particularly effective in detecting motor seizure manifestations by recording involuntary muscle contractions and abnormal muscular activity.

### I.4.4 Respiratory Signals

Seizures may influence breathing patterns, leading to irregular respiration, apnea, or hyperventilation. Monitoring respiratory activity helps in identifying autonomic disturbances associated with epileptic events.

### I.4.5 Photoplethysmography (PPG)

PPG is an optical sensing technique used to detect variations in blood volume within the microvascular tissue bed. It is commonly integrated into wearable devices to measure heart rate and oxygen saturation, both of which may be affected during seizures.

### I.4.6 Motion and Accelerometry

Accelerometers and motion sensors detect abnormal physical movements such as convulsions, tremors, or sudden falls. These signals are widely employed in wearable seizure detection systems, particularly for generalized motor seizures.

### I.4.7 Electrodermal Activity (EDA) / Skin Conductance

EDA measures changes in skin electrical conductance associated with sweat gland activity. During seizures, increased activation of the sympathetic nervous system can elevate skin conductance levels.

### I.4.8 Audio and Video Signals

Audio and video recordings provide supplementary information about seizure events, including vocalizations, abnormal motor behavior, and changes in patient activity. These modalities are commonly used in clinical monitoring systems and AI-based seizure detection approaches.

Physiological signals are among the most important biological indicators for early detection of epileptic seizures, as involuntary bodily changes can be monitored using wearable sensors. Physiological signals are essential biological indicators that researchers and clinicians rely on for the early detection of epileptic seizures and for continuous patient monitoring. When a seizure is about to occur or during its onset, the patient’s body exhibits a series of involuntary changes resulting from disturbances in the autonomic nervous system. The most common of these changes include an increase in skin temperature or skin flushing, excessive sweating, and noticeable variations in heart rate. These indicators can be continuously monitored using modern sensing technologies integrated into wearable devices, such as temperature sensors, electrodermal activity (EDA) sensors, photoplethysmography (PPG) sensors, and accelerometers used for motion tracking. Advances in sensing technologies and intelligent systems have significantly improved the ability of these devices to collect and analyze physiological data with high accuracy, making them effective tools in epilepsy monitoring systems.

Epileptic seizures vary from one patient to another depending on their motor and physiological manifestations. They are generally divided into two main categories: convulsive and non-convulsive seizures.

- ***Convulsive seizures*** are characterized by repeated, involuntary muscle contractions followed by alternating periods of relaxation, resulting in rhythmic and clearly observable shaking movements that can be easily detected using motion sensors and accelerometers.
- In contrast, ***non-convulsive*** seizures are more complex to detect because they are not always accompanied by obvious physical movements. They may appear as temporary loss of attention brief absence of consciousness, or sudden muscle weakness. For this reason, their

detection requires the use of precise physiological indicators and continuous analysis of the patient's biological data.

## I.5 Systems and Devices Used for Epileptic Seizure Detection

A wide range of systems and technologies are employed for the detection and monitoring of epileptic seizures. These approaches vary in terms of methodology, performance accuracy, and application context, extending from clinical environments to wearable and home-based healthcare solutions.

### I.5.1 Electroencephalography (EEG)-Based Systems

EEG-based systems are regarded as the gold standard for epilepsy diagnosis and monitoring. They measure the brain's electrical activity through electrodes placed on the scalp. These systems are highly effective in identifying abnormal neural patterns associated with seizures, such as spikes and rhythmic discharges. However, their use is generally restricted to clinical settings due to the requirement for specialized equipment and electrode application.

### I.5.2 Wearable Devices

Wearable devices enable continuous and real-time monitoring of physiological signals in everyday life. They may incorporate sensors for heart rate, motion, skin conductance, and respiration. These systems are valuable for early seizure detection and enhancing patient safety outside clinical environments. Their main advantage lies in portability and user comfort, although their performance may depend on sensor quality and system design.

### I.5.3 Video-Based Monitoring Systems

Video monitoring systems are widely used in hospitals and epilepsy monitoring units to record patient behavior and movements during seizure events. They assist clinicians in visually verifying seizures and correlating physical activity with physiological data. Nevertheless, they may raise privacy issues and often require continuous observation or automated video analysis techniques.

### I.5.4 Multimodal Detection Systems

Multimodal systems integrate multiple physiological signals such as EEG, ECG, EMG, and motion data to enhance detection accuracy. By combining different sources of information, they provide a more complete understanding of seizure activity and help reduce false alarms. These systems are generally more reliable than those based on a single signal.

### I.5.5 Implantable Devices

Implantable devices are surgically placed under the skin or within the body to continuously monitor neural activity. They offer long-term, highly accurate monitoring, particularly for patients with severe epilepsy. However, they are invasive in nature and require surgical intervention.

### I.5.6 Smartphone and IoT-Based Systems

These systems rely on mobile applications and interconnected sensors to enable remote patient monitoring. Data collected from wearable devices can be transmitted to smartphones and cloud-based platforms for analysis. This allows real-time alerts and remote supervision by caregivers, improving response time and patient safety.

### I.5.7 Artificial Intelligence-Based Detection Systems

Artificial intelligence-based systems utilize machine learning and deep learning techniques to automatically analyze physiological signals and identify seizure patterns. They enhance detection performance by learning from large datasets and can be integrated with wearable and IoT technologies to enable real-time seizure prediction and classification. With the rapid development of the Internet of Things (IoT) and the widespread use of wearable devices, a range of smart solutions has been developed to accurately monitor epilepsy patients and detect seizures at an early stage.

## I.6 Developmen of Epilepsy Monitoring and IoT-Based Seizure Detection System

### I.6.1 Evolution of Epilepsy Monitoring

Over the past decades, the medical field has witnessed remarkable development in the use of computer-based systems for monitoring patients’ health conditions, as continuous electronic monitoring applications began to emerge in the 1950s , alongside the early idea of providing clinical care and health monitoring within home environments .

Regarding epilepsy, the adoption of computational technologies began after the development of computed tomography (CT) in 1972 by the British engineer Godfrey Hounsfield , although specialized systems for monitoring epilepsy patients did not become widely used until recent years.

With the rapid advancement of Internet of Things (IoT) technologies, smart healthcare has emerged through the development of connected devices equipped with sensors capable of collecting patients’ health data, often integrated into smart clothing or mobile devices, with the aim of detecting, predicting, and monitoring seizures. This shift reflects a growing trend toward personalized healthcare based on continuous monitoring and remote sensing technologies. In parallel, there is increasing interest in designing more efficient intelligent systems for managing various medical conditions, where wearable devices such as smartwatches, electronic wristbands, and sensor-embedded clothing are considered promising solutions for epilepsy monitoring, although there is still a need for more integrated and comprehensive systems. Studies have also shown that intelligent monitoring techniques can effectively detect early signs of physical and psychological health issues , and that observing individuals during their normal daily activities provides more accurate and realistic health data .

### I.6.2 IoT-Based Seizure Detection Systems:

In recent years, several IoT-based healthcare systems have been developed to enable continuous remote monitoring of patients, such as the Wireless Health Sensors (WHS) system, which tracks vital signs including heart rate, lung function, blood pressure, and body temperature . This system relies on predictive analytics in smart healthcare environments and uses sensors connected to Arduino boards to collect patient data, which is transmitted via Wi-Fi for storage and analysis, allowing healthcare professionals to access the information through dedicated online platforms and receive early alerts in case of abnormal or dangerous health changes [3]. In this context, the development of intelligent technologies for managing epileptic seizures began in the 1970s, when researchers and clinicians worked on designing implantable devices capable of predicting seizures and triggering direct therapeutic interventions for patients with drug-resistant epilepsy.

Thus, it becomes clear that the rapid development of the Internet of Things (IoT) and smart technologies has significantly contributed to the enhancement of modern healthcare monitoring systems, particularly in the field of epilepsy patient monitoring. Wearable devices and smart sensors now play an important role in continuously collecting and analyzing physiological data, enabling the early detection of seizures and improving the speed of medical intervention. Despite the notable progress in this field, several challenges still remain, such as the need to improve system accuracy, reduce false alarms, and develop more comfortable and user-friendly solutions for daily use. Therefore, the development of integrated and intelligent systems represents a necessary step toward improving the quality of healthcare provided to epilepsy patients.

### I.6.3 Physiological Sensors Used in Seizure Detection

Wearable devices designed for the detection of epileptic seizures contribute to improving patient monitoring and enabling faster intervention during seizure events, which helps reduce potential risks and complications.

The selection of an appropriate detection device mainly depends on the nature of the seizure and the physiological changes associated with it during its occurrence. Seizures can be identified through a range of sensors that monitor different physiological signals, in addition to tracking abnormal movements and sudden falls.

These systems rely on multiple sensing technologies, including electroencephalography (EEG), electrocardiography (ECG), heart rate monitors, electromyography (EMG), blood oxygen saturation (SpO2) sensors, visual monitoring systems, accelerometers, electrodermal activity (EDA) sensors, as well as bed sensors and eye-tracking technologies. In addition, many commercial seizure detection devices have been developed, each relying on the monitoring of one or multiple physiological indicators associated with seizures, such as muscle convulsions, sudden violent movements, and increased heart rate, among other vital signs [4].

In the context of practical developments in this field, Mackenzie and colleagues conducted a study using a wearable technology for detecting both generalized and focal epileptic seizures. They employed the EPOC+ neuroheadset from Emotiv Systems in Sydney, Australia, which is equipped with 14 electroencephalography (EEG) channels and wirelessly connected to a tablet device for seizure monitoring and detection. This system demonstrated a good level of safety, with no reported safety issues; however, its effectiveness was limited in correlating the recorded physiological signals with actual seizure events, despite its relatively high accuracy in capturing biometric activity.

In another study conducted by Beniczky and colleagues, a wearable device based on surface electromyography (sEMG) was evaluated for the detection of generalized tonic-clonic seizures using the IctalCare detector, which is placed on the biceps muscle; this device was characterized by its small size, fast response time, and efficient detection performance. Additionally, a study by Jeppesen and colleagues investigated a wearable electrocardiography (ECG) device known as the ePatch, which showed relatively good performance in seizure detection, with an average false alarm rate of approximately one alarm per day [4].

## I.7 Conclusion

This chapter provided a comprehensive overview of epilepsy as a chronic neurological condition characterized by recurrent seizures resulting from abnormal electrical activity in the brain. It reviewed the fundamental concepts of epilepsy and presented the main classifications of epileptic seizures, including focal, generalized, and unknown-onset seizures, emphasizing the importance of accurate classification for effective diagnosis and treatment. The chapter also examined the principal physiological signals associated with epileptic seizures, such as electroencephalography (EEG), electrocardiography (ECG), electromyography (EMG), respiratory signals, photoplethysmography (PPG), motion signals, and electrodermal activity (EDA). These physiological indicators provide valuable information about the body's response to seizure activity and serve as essential components of modern monitoring and detection systems. Furthermore, various technologies and systems used for seizure detection and patient monitoring were discussed, including EEG-based systems, wearable devices, video monitoring systems, multimodal detection approaches, implantable devices, Internet of Things (IoT)-based healthcare solutions, and artificial intelligence techniques. The integration of these technologies has significantly enhanced continuous patient monitoring, real-time seizure detection, and rapid alert generation, thereby improving patient safety and healthcare quality. Despite the considerable progress achieved in this field, challenges related to detection accuracy, false alarm reduction, user comfort, and long-term system reliability still remain. Therefore, ongoing research and technological advancements continue to focus on developing more efficient, accurate, and user-friendly solutions. The concepts, physiological signals, and detection technologies presented in this chapter provide the theoretical and technological foundation for the proposed smart bracelet system for epileptic seizure detection and continuous patient monitoring, which will be developed and discussed in the following chapters.

# Chapter II. Study of Existing Solutions

## II.1 Introduction

In today's digital era, healthcare has shifted from traditional hospital settings to continuous remote monitoring, where medical bracelets and smart wearable devices have become indispensable tools for managing chronic conditions, particularly epilepsy. These technologies play a crucial role in providing real-time physiological data that enable medical teams and families to monitor patients outside clinical environments, thereby enhancing patient autonomy and ensuring rapid intervention in emergencies. Nevertheless, despite notable technological progress, such systems still face major challenges that hinder their full effectiveness. One of the most significant obstacles is the lack of detection accuracy, as certain sensors fail to capture subtle physiological signals during the early stages of a seizure. Even more concerning is the issue of false alarms, often triggered by routine daily activities such as walking or eating, which resemble seizure-like motion patterns. These recurrent false alerts not only drain device power but also contribute to a state of "alarm fatigue" among caregivers, increasing the risk of overlooking a genuine emergency at a critical moment. This chapter focuses on analyzing existing devices and identifying the technical gaps that our project aims to address.

## II.2 Medical bracelets

Continuous and real-time monitoring is a fundamental element in improving the management of patients suffering from chronic diseases, such as cardiovascular disorders, diabetes, and neurological conditions. According to estimates by the World Health Organization (WHO), these diseases are responsible for nearly 75% of global deaths, in addition to imposing significant economic burdens. Consequently, there is a pressing need to adopt effective strategies for monitoring and diagnosing such conditions, among which wearable devices (HWDs) stand out [5], especially medical bracelets, which are considered one of the most prominent and widely used technologies for continuous daily monitoring.

Since 1956, people suffering from medical disorders have worn medical bracelets to help identify their conditions and enable emergency healthcare providers to respond quickly. Several medical studies have shown that the use of medical bracelets provides important medical alerts for patients with conditions such as diabetes, epilepsy, and allergies, thereby reducing the risk of complications and relapses.

The first medical alert bracelet was invented by Dr. Marion Collins and his daughter Linda in 1953. Linda suffered a severe injury and was taken to the hospital, but the medical staff were unaware of her allergy to tetanus antitoxin. According to the hospital protocol, the medical team performed a skin test before administering the injection, and even this small amount caused an allergic reaction. At that moment, Dr. Collins realized the need for a method to inform healthcare professionals about a patient's medical condition and allergies. This led to the design of the first medical alert bracelet in 1966 [6].

Medical bracelets are considered among the most important modern innovations in the field of health monitoring, as they provide a convenient and effective way to continuously track vital signs throughout the day. With the rapid advancement of wearable technologies, it has become possible to measure physical activity, heart rate, sleep quality, and other health indicators with high accuracy, contributing to improving lifestyle and reducing the risk of diseases. These devices are not limited to activity tracking only; some offer advanced features that make them similar to a personal health assistant, providing alerts and information that help support and monitor overall health more effectively [7]. Medical bracelets is a small electronic device worn on the wrist, equipped with advanced sensors that collect various health-related data such as heart rate, blood oxygen saturation, blood pressure, and sleep quality analysis. This data allows the user to continuously monitor their health status and receive real-time alerts in case of abnormal readings or sudden changes in vital signs. With technological advancements, this device can also be used to set personal health goals and track progress, such as counting daily steps or estimating calories burned during physical activities, while also providing a detailed analysis of sleep patterns that helps users better understand their sleep behavior and improve their overall lifestyle [7]. In addition, a study conducted by the American College of Cardiology (ACC) found that medical bracelets have a high ability to detect atrial fibrillation with great accuracy and sensitivity. This finding is particularly important for patients suffering from this cardiac disorder, as these devices enable continuous and regular monitoring of heart rate. The study also indicated that medical bracelets may help in the early detection of atrial fibrillation even in individuals who do not show any visible symptoms [8]. Wearable devices primarily function as wrist-worn bands, typically worn on the wrist, to monitor chronic diseases. These devices collect data on acceleration, heart rate, body temperature, blood pressure, and peripheral oxygen saturation, with a particular focus on neurological and cardiovascular diseases. To translate this into practical application, we recommend that future research prioritize real-world clinical trials using medically certified devices. This means that these devices are not only used to display simple health information, but also play a crucial role in continuous and accurate health monitoring. They help physicians make faster and more precise decisions, reduce the need for frequent hospital visits, and enable patients to track their own health at any time, thereby enhancing the efficiency, flexibility, and overall quality of healthcare [9]. Thus, Medical bracelets represent a pivotal step toward the future of digital healthcare, as they combine accuracy, convenience, and continuous monitoring of human health.

## II.3 Wearable devices

Since the beginning of human civilization and the gradual progress toward urban development, the world has experienced continuous technological transformations. However, the most recent period has been marked by an unprecedented technological leap. A number of modern innovations have significantly changed daily life, such as the spread of the Internet, the development of wireless communication systems like Wi-Fi, the emergence of GPS navigation systems, computers and electronic chips, as well as sensors and sensing devices, in addition to major advances in nanotechnology. All these developments have made the world more interconnected and have accelerated change at an extraordinary pace. Among the most important outcomes of these advancements is the rise of wearable technologies, which have become a prominent field in the modern era . It should be noted that there is no single precise definition for wearable technologies; however, the scientific literature uses several closely related terms such as wearable devices, wearable computers, and wearable electronics. Although these terms differ in wording, they largely refer to the same concept and are often used interchangeably. They describe electronic devices or computing systems that are integrated into clothing or accessories, allowing them to be worn comfortably on the human body while providing smart functionalities at the same time.

The main idea behind wearable technologies is that they combine a physical component that can be worn on the body, such as watches, bracelets, glasses, and similar items, with a functional electronic component such as sensors or motion measurement units like accelerometers. These devices collect data from the user and then use it for different purposes, such as improving physical performance in fitness tracking devices or monitoring vital health indicators in medical wearable devices.

Wearable devices generally refer to technologies that are worn on or around the human body. This concept is not limited to clothing only, but also includes shoes, jewelry, and accessories that contain electronic components capable of input, output, or both. However, this category excludes implanted medical devices, prosthetics, and handheld portable devices.

From another perspective, a smart wearable device can be defined as a garment or accessory worn by a user that is equipped with integrated electronic and computing systems capable of collecting or displaying data. This data includes a wide range of information such as physical activity levels, movement, heart rate, ultraviolet exposure, and temperature, as well as audio and visual data that can later be analyzed or used for reference purposes. Despite the variety in their forms, these devices often share similar core functions .

Wearable devices can also be described as electronic or mechanical systems integrated into clothing or attached to the body using straps or clips, making them easy to wear. These systems perform various functions such as sensing, communication, navigation, and sometimes decision-making. A more advanced category has also emerged that focuses on environmental interaction, such as augmented reality technologies. In general, these systems are characterized by simple designs, which make them convenient to use with everyday clothing .

***Figure II- 1: Use of the Smart Patch in the medical field.***

The most comprehensive definition of wearable technologies describes them as applications based on computing devices capable of receiving and processing data. These devices are usually embedded in clothing or used as body-worn accessories and may operate independently or through connection with a smartphone to enable more effective user interaction. They can be located on the body, such as smart patches, around the body, such as watches, bracelets, and headbands, or even inside the body in the form of implanted sensors that monitor vital functions such as heart activity and detect cardiac irregularities ,See Figure (II.1).

The origins of wearable technology can be traced back to early centuries. The English friar Roger Bacon is credited with the invention of spectacles and the use of corrective lenses, as described in his book Opus Majus in 1266. Several centuries later, in the 17th century, the French mathematician Jean Leurechon documented the first hearing assistance devices, known as ear trumpets, in 1624.

In 1887, the first full-eye glass contact lens was introduced. By the mid-20th century, significant advancements had been made in this field. In 1960, the first successful long-term implantation of a cardiac pacemaker was achieved. This was followed by the introduction of soft contact lenses in 1971 and digital hearing aids in 1987. Around the same period, insulin pumps (Figure (II.2) were also developed, marking an important milestone in healthcare technology.

With rapid technological progress, Google Glass was launched in 2012, leading to a surge in wearable device applications across various fields. Since then, wearable technologies have diversified significantly, including devices such as the Apple Watch, Xiaomi Mi Band, and Fitbit, which are widely used in fitness, healthcare, and many other domains.

***Figure II- 2 : The first device for injecting insulin into the body and the modern form of the insulin pump, which is now equipped with a digital display.***

A study conducted by the independent research company Ipsos indicated that about one in five adults in the United States planned to purchase a wearable device in 2014, alongside the expansion of major technology companies into this field. Globally, the wearable technology market is expected to experience significant growth, reaching more than 150 billion dollars by 2026, compared to about 30 billion dollars in 2016, reflecting rapid development and a notable transformation in this sector ,See Figuret(II.3).

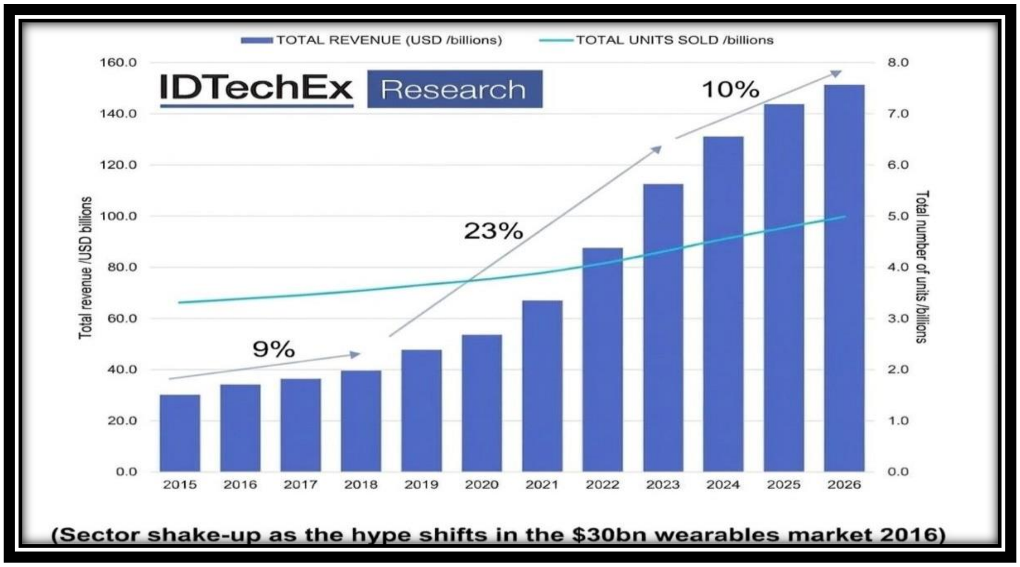


***Figure II- 3 : A chart showing the rising growth in sales of wearable technology.***

Wearable technology applications can help individuals meet the demands of daily life and workplace environments by providing support and tools that assist them in performing a variety of tasks more efficiently. Their uses have a broad impact on healthcare, fitness, and aging, where the main goal of this technology is to seamlessly and effectively integrate the functions of portable electronics and computers into everyday life.

Currently, with the rapid development of information technology and the growing interest in healthcare, wearable technology in the medical field has gained increasing attention over the past decade. This is due to several factors, including population growth and the rising prevalence of lifestyle-related diseases. Modern physiological measurement systems rely on wearable devices that are typically worn on the wrist or integrated into smart clothing. These solutions include shirts, vests, and accessories capable of measuring various vital signs. In addition to data collection, wearable systems enable continuous real-time monitoring in daily life, thereby improving healthcare delivery outside traditional medical institutions.

Moreover, applications of wearable healthcare technology include rehabilitation systems designed to automatically collect data and transmit it to supervising physicians during the rehabilitation process, as well as provide feedback to patients to help them monitor and improve their health conditions continuously.

According to a report published by P&S Market Research, the global wearable healthcare devices market is expected to reach approximately 1,630.3 million USD by 2020, with a strong compound annual growth rate (CAGR) of 46.6% during the period from 2015 to 2020. These devices are characterized by combining health-related functions with modern technological features, as well as enabling the continuous monitoring and real-time transmission of users' health data .

For example, by wearing devices such as smart bracelets or necklaces throughout the day, users can continuously monitor various vital indicators, including sleep quality, calories burned, heart rate, and even the distance traveled during daily activities, all in real time. Analyzing this data helps individuals better understand their health status, make appropriate decisions, and improve their lifestyle and overall fitness level.

Furthermore, studying the role of wearable technology in elderly care requires first understanding the characteristics and daily needs of this group, as well as their ability to interact with and benefit from modern technologies in order to enhance their quality of life [10].

### II.3.1 Smartwatches

A smartwatch is a small wearable digital device worn on the wrist that serves as an extension of smartphones, allowing users to perform a wide range of tasks without directly using their phone. It is not limited to displaying the time, but also enables running various applications, performing calculations, translating text, playing audio and video, as well as receiving and answering phone calls. It operates through wireless connectivity with a smartphone using technologies such as Bluetooth and Wi-Fi. Some models are also equipped with advanced features such as built-in sensors, GPS (Global Positioning System), cameras, and intelligent digital assistants [11]. (See Figure II.4)

Wearable devices, especially smartwatches, have become important modern tools in the healthcare sector, as they are used to continuously monitor individuals' health status and contribute to improving diagnosis and treatment methods. These devices rely on advanced sensing technologies that enable them to measure various vital signs, such as blood pressure, blood oxygen saturation, heart rate, as well as monitoring sleep patterns and daily physical activity levels. They can also be used to encourage healthy behavior by sending reminders for exercising or taking medication on time, in addition to tracking movement and geographic location.

With the significant development in sensing and digital communication technologies, these devices are now capable of transmitting health data in real time and with high accuracy without direct intervention. This has helped enhance remote healthcare services and improve the speed of medical response. Smartwatches are also characterized by their ease of use and wear compared to traditional monitoring tools, which has made them an integrated part of users' daily lives and an important source of health information relied upon by both patients and healthcare professionals in making appropriate decisions [12].

Smartwatches have become one of the most prominent modern technological innovations, combining multiple functions in a single compact device. However, this development is not without drawbacks that may affect the user experience and limit their wider adoption. Unlike traditional watches, which can operate for years without the need for frequent charging, most smartwatches rely on batteries that require regular recharging on a daily or every few days basis. This can become an additional burden alongside the many electronic devices used daily, such as smartphones, laptops, and wireless earbuds, requiring constant monitoring of battery levels. Moreover, battery depletion leads to the loss of essential functions, particularly continuous health tracking features. Privacy is also a major concern associated with these devices, as smartwatches collect highly sensitive personal data such as geographic location, physical activity, sleep patterns, and various health indicators. Although manufacturers claim to implement strong data protection measures, the risk of hacking and data leaks remains a significant issue for many users, especially those who prefer to limit the amount of personal information shared with technology companies [13].

Hence, smartwatches are considered an important step in the development of wearable technology, as they offer a wide range of functions that combine communication, health monitoring, and the facilitation of daily life. However, their effectiveness remains dependent on users' acceptance of certain challenges, particularly those related to battery life and privacy issues.

Therefore, their use requires a balance between benefiting from their advanced features and maintaining awareness of their technical and security limitations.


***Figure II- 4 : Illustration of a smartwatch and its health monitoring features***

## II.4 Limitations of Wearable Technologies for Epileptic Seizure Detection

Despite the increasing adoption of wearable technologies in healthcare, such as smartwatches, wristbands, and biosensors, their use in epileptic seizure monitoring still faces several challenges that affect their reliability and limit their widespread implementation. These technologies are designed to provide real-time alerts and continuous monitoring of patients outside clinical settings, with the aim of enhancing safety and enabling rapid response during seizures. However, despite these important advantages, they remain promising but still incomplete solutions for continuous seizure detection [14].

### II.4.1 Functional Limitations

One of the primary drawbacks of wearable seizure detection technology lies in its limited capacity to recognize the full spectrum of seizure types. While most commercially available devices perform well in detecting generalized tonic-clonic seizures — which are characterized by pronounced motor activity and distinct physiological shifts — they tend to struggle with focal and absence seizures. These seizure types typically manifest with little to no visible physical signs, making them particularly challenging to identify through wrist-based sensors [14]. False alarms represent another significant concern. Routine physical activities like walking, running, or abrupt arm movements can produce signals that closely resemble those generated during a seizure, resulting in false positives. At the same time, seizures that occur without notable movement or physiological changes risk being missed entirely. Additional factors such as inconsistent sensor placement, poor skin contact, and motion-related interference can further compromise the reliability of these systems [15].

Beyond these issues, the majority of wearable devices are restricted to monitoring a narrow set of physiological indicators, including motion, heart rate, and electrodermal activity. This reliance on indirect measures — rather than direct neural monitoring — means that wearable systems inherently fall short of the diagnostic accuracy offered by clinical EEG-based approaches.

### II.4.2 Economic Limitations

While wearable devices are generally considered more cost-effective than hospital-based monitoring systems, their price point continues to pose a significant obstacle for many patients. Medical-grade smartwatches and specialized wristbands, for instance, require an upfront financial commitment that may place them out of reach for a considerable portion of users. Beyond the initial purchase, ongoing expenses further add to the financial strain. These include the costs associated with device maintenance, accessory replacement, compatible mobile applications, and potential subscription-based services. Compounding this issue, many healthcare systems do not provide full insurance reimbursement for such devices, leaving patients and their families to shoulder a disproportionate share of the financial burden.

Economic disparities further widen the accessibility gap, particularly in low- and middle-income countries where the availability of advanced medical technologies remains constrained. As a result, the populations that may stand to benefit most from these innovations are often the least equipped to access them [16].

### II.4.3 User Experience Limitations

The long-term viability of wearable seizure detection technologies is critically dependent on user acceptance. Physical discomfort, skin irritation, or general inconvenience resulting from prolonged use of wristbands or smartwatches can pose real challenges — particularly during sleep or physical activity [15].

Frequent recharging requirements stand out as another notable drawback, as interruptions to continuous monitoring can directly compromise the reliability of these devices. Setting up the device, pairing it with a smartphone, or correctly interpreting incoming alerts may also prove difficult for certain user groups, most notably older adults and those with limited familiarity with digital technology.

Social and psychological dynamics further complicate the picture. The visibility of medical wearables in public settings can trigger feelings of stigma among some patients, and this discomfort may gradually undermine their commitment to consistent, long-term use.

### II.4.4 Security and Privacy Limitations

The continuous collection of sensitive health data including movement patterns, heart rate, and various physiological signals is a fundamental feature of wearable seizure detection devices. However, the transmission of this data to mobile applications or cloud-based platforms for storage and remote monitoring has given rise to legitimate concerns surrounding privacy and data security [17].

Cybersecurity vulnerabilities represent a particularly pressing issue. Wireless communication protocols such as Bluetooth and Wi-Fi can serve as potential entry points for unauthorized access or data interception, and without robust security measures in place, confidential medical information may be exposed to serious risk of breach.

Adherence to established data protection frameworks most notably the General Data Protection Regulation (GDPR) is therefore not merely a legal obligation but a cornerstone of responsible patient data management. When adequate safeguards are lacking, the consequences extend beyond regulatory non-compliance; patient trust is eroded, and the broader adoption of wearable health technologies within clinical settings is ultimately hindered.

## II.5 Conclusion

Wearable technologies such as smartwatches, wristbands, and physiological sensors represent an important advancement in epilepsy monitoring. However, limitations related to detection accuracy, financial accessibility, user comfort, and data security continue to restrict their effectiveness. Improving sensor reliability, reducing costs, enhancing usability, and strengthening cybersecurity are essential steps for future development.

# Chapter III. System Design

## III.1 Introduction

This chapter presents a comprehensive design of a smart bracelet for monitoring epilepsy patients. The system is based on integrating Internet of Things technologies with GSM cellular communication networks to ensure continuous and effective real-time health monitoring. This design relies on a set of integrated electronic units working in synergy to collect the patient's physiological and motion data, process it locally via a microcontroller, and then make the appropriate decision upon detecting any abnormality that may indicate an epileptic seizure or a imminent health risk.

The chapter begins with a presentation of the overall system architecture, which clarifies the device's operating principle and its independence from the traditional internet network. It then details the hardware architecture, including  the sensors, processing units, and communication modules, followed by the software architecture that illustrates the data processing mechanism and decision-making within the microcontroller. The IoT architecture that explains is also discussed, explaining the system layers and their integration.

The chapter also reviews the methodology for selecting the key electronic components such as the ESP8266, motion and pulse sensors, and the GSM SIM900 module, highlighting the rationale for each choice in terms of performance, power consumption, and suitability for wearable medical applications. It complements this by describing the electronic design of the system, including the block diagram, electronic schematic, and module interconnection mechanism, thereby illustrating the data flow path from the sensing stage to the transmission stage.

The chapter furthermore dedicates

devotes special attention to power management, through an in-depth analysis of power consumption and optimization strategies such as sleep modes and sensor power reduction techniques, aimed at extending battery life and ensuring the continuous operation of the smart bracelet under various conditions.

## III.2 Global System Architecture

The proposed system is designed as a smart monitoring device that integrates Internet of Things (IoT) technologies with cellular (GSM) networks, enabling it to operate entirely independently of traditional internet infrastructure. The device continuously and accurately tracks the patient's physiological and motion indicators using a set of sensors embedded in the wristband.

The collected data is processed locally by the ESP8266 microcontroller, which analyzes the incoming signals and detects any deviation from normal ranges that may indicate an epileptic seizure or a medical emergency. Upon identifying an abnormal reading, the GSM SIM900 communication module automatically activates to issue immediate alerts in the form of short text messages (SMS) or automated phone calls, directed to the caregiver's phone or pre-programmed emergency numbers.

This design gives the device a key advantage: complete independence from Wi-Fi networks, enhancing its reliability and expanding its usability across diverse real-world environments, including remote areas with limited or no internet coverage.

### III.2.1 Hardware Architecture

The system hardware architecture represents one of the most important stages in designing the smart bracelet intended for monitoring epilepsy patients. It forms the electronic structure that enables the system to operate in an integrated and organized manner. This system relies on a group of sensors and electronic modules working together to monitor the patient’s vital signs and detect abnormal changes that may indicate an epileptic seizure, then send alerts quickly to the user or family members.

The system was designed to be compact, lightweight, and suitable for daily use as a wearable smart bracelet. During the design process, low power consumption was also considered to ensure long operating time without frequent recharging. The general architecture of the system is based on several main units, including the processing unit, sensing units, communication modules, and power supply unit.

#### III.2.1.1 The ESP8266 module

The ESP8266 board equipped with a display screen is considered the main control and processing unit of the system. This board receives the data coming from different sensors and processes it using the embedded software.

The ESP8266 was selected because of its small size, low power consumption, wireless communication capability, and ease of programming using the Arduino IDE environment. In addition, the integrated display screen is used to show important information such as heart rate values or the operating status of the system.

#### III.2.1.2 The MPU9250 sensor

To monitor the patient’s body movement and detect seizure-related convulsions, the MPU9250 sensor was used. This sensor contains a three-axis accelerometer and a three-axis gyroscope, allowing accurate measurement of movement, vibration, and rotation. When abnormal motion or sudden convulsions occur, the sensor sends the measured values to the ESP8266 unit for processing and comparison with the normal stored values. The importance of this sensor lies in its ability to detect rapid and repetitive movements commonly associated with epileptic seizures.
The Motion Sensor MPU9250 was also used as an important sensing component in the system. This sensor integrates a three-axis accelerometer and a three-axis gyroscope, enabling accurate

monitoring of body movement and orientation. It helps detect sudden vibrations and convulsions that may accompany epileptic seizures. In addition, the MPU9250 is characterized by low power consumption and easy integration with Arduino-based systems, making it suitable for wearable medical devices.

#### III.2.1.3 The CJMCU-6701 sensor

In addition, the CJMCU-6701 sensor was integrated into the system to improve motion sensing accuracy and monitor body orientation and vibration. This sensor contributes to detecting abnormal body movements that may occur during epileptic seizures and enhances the reliability of the monitoring system due to its high sensitivity and low power consumption, making it suitable for wearable medical devices.

#### III.2.1.4 The MAX30102 sensor

The MAX30102 sensor was also integrated into the system to measure heart rate and blood oxygen saturation levels. This sensor operates using optical sensing technology with LEDs and highly sensitive photodetectors. When the sensor touches the skin, it emits light through body tissues and analyzes the reflected light to calculate heart rate and oxygen saturation. These measurements help identify physiological changes that may occur during epileptic seizures, such as increased heart rate or reduced oxygen levels.

#### III.2.1.5 The SIM900 module

For emergency situations, the SIM900 module equipped with an external antenna was used to provide GSM network communication. This module enables the system to send SMS alerts or make automatic phone calls when a severe epileptic seizure is detected. This feature is very important, especially when the patient is away from family members, as it guarantees rapid emergency assistance.

During the initial development and testing phase, a Breadboard MB102 and jumper wires were used to assemble the electronic components temporarily and verify the correctness of the electrical connections.

The breadboard simplified the testing and modification process without the need for direct soldering, making system development more flexible and convenient.

After successfully testing all components and ensuring the proper operation of the system, the electronic parts can be mounted onto a 7×9 cm PCB board. This board helps organize the components, reduce the overall circuit size, improve connection stability, and increase system reliability during practical use.

The system operates by continuously collecting physiological data through the sensors and transmitting them to the ESP8266 board using suitable communication protocols such as I2C. The processing unit then analyzes the received data and compares them with predefined normal values.

Whenever abnormal conditions such as severe convulsions or irregular heart rate are detected, the system immediately activates an alert and sends notifications through the GSM network to family members, allowing quick intervention and timely assistance to the patient. This architecture provides several important advantages, including compact size, portability, low power consumption, fast response time, and the possibility of future improvements such as integrating artificial intelligence techniques or connecting the system to Internet of Things platforms to enhance seizure detection accuracy and overall system performance.

### III.2.2 Software Architecture

The software architecture of the system is built upon a set of functions embedded within the ESP8266 microcontroller, operating in a precise logical sequence that ensures data collection, processing, and real-time decision-making. Upon system startup, the setup() function executes only once, during which it initializes the core components such as configuring the digital ports (GPIO) and activating the Serial Communication, thereby preparing the microcontroller for proper operation and readying all modules for launch.

Subsequently, the loop() function runs in a continuous, uninterrupted cycle as the system's main loop, periodically reading data from the sensors and passing it through the processing and decision-making stages, thus maintaining constant real-time monitoring of the patient's condition. To fulfill sensing requirements, the readSensor() function retrieves raw values from the sensors connected to the microcontroller and returns them to feed the subsequent processing stages. These values are then analyzed by the detectSeizure() function, which compares them against a pre-defined threshold to determine whether they fall within normal limits or indicate an abnormal condition that may signal an impending epileptic seizure.

Should any anomaly be detected, the alert() function intervenes to trigger an immediate local alarm, such as activating an LED indicator or an audible buzzer, accompanied by a notification sent to the user. Complementing this is the sendData() function, responsible for displaying or transmitting data via the serial port or forwarding it to the communication module, enabling moment-to-moment tracking of the patient's health status.

On a broader level, this software architecture ensures a smooth and rapid data processing sequence, with all functions operating in close coordination within the ESP8266 microcontroller to achieve immediate and accurate responses, while keeping power consumption at its lowest possible levels.

### III.2.3 IoT Architecture

The system is built upon an Internet of Things architecture that relies on cellular communication networks as an alternative to conventional wireless internet connectivity. This architecture is composed of multiple integrated layers that work in concert to carry out the system's functions in the most effective manner.

The data collection layer forms the foundational pillar of this architecture, encompassing the array of sensors tasked with continuously and uninterruptedly measuring the patient's vital and motion-related signals. Above it sits the processing layer, driven by the ESP8266 microcontroller, which is responsible for receiving the incoming data, analyzing it, and deriving the appropriate decision in real time. Following this is the communication layer, underpinned by the GSM SIM900 module, which handles the transmission of alerts and data from the device to the outside world via the cellular network.

As for the application layer, while it has yet to be realized in the current prototype, it represents the future horizon of the system. Subsequent development could give rise to a dedicated mobile application or an integrated monitoring platform, offering organized display of alerts and professional reception of notifications — elevating the quality of service delivered to both the patient and the caregiver alike.

## III.3 Component Selection

This section presents the main electronic components on which the proposed system is based. Each component was carefully selected according to precise criteria, including performance efficiency, low power consumption, and suitability for wearable medical applications. This well-considered selection ensures reliable data acquisition, efficient processing, and stable communication between the different parts of the system.

### III.3.1 ESP8266 Microcontroller:

The ESP8266 serves as the central processing unit in the system, combining low power consumption with efficient performance, which makes it an ideal choice for embedded applications. Within the scope of this project, this microcontroller is responsible for processing data received from the sensors and making appropriate decisions based on real-time analysis of physiological signals. Although it includes a built-in Wi-Fi module, it is not utilized in this system, as it is replaced by the GSM SIM900 module for communication, thereby dedicating the microcontroller primarily to processing and control tasks within the smart bracelet. The ESP8266 operates within a supply voltage range of 3.0 to 3.6 volts, making it well-suited for battery-powered systems. It has an average current consumption of approximately 80 mA during normal operation, while it supports advanced power-saving modes; the consumption drops to about 1mW in standby mode and decreases further to around 1 µA in deep sleep mode. These characteristics significantly contribute to extending battery life and improving overall system efficiency in wearable device applications [18].

### III.3.2 Motion Sensor MPU9250

The MPU-9250 sensor is classified as a high-performance nine-axis motion sensing unit, integrating a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer within a single compact chip. This integration enables accurate measurement of motion and orientation, making it suitable for a wide range of modern smart electronic systems and applications. The sensor supports both I2C and SPI communication interfaces, facilitating easy connection with microcontrollers, and it also includes a Digital Motion Processor (DMP) that processes and fuses sensor data to reduce the load on the main processor and improve overall system performance. The MPU-9250 is based on MEMS (Micro-Electro-Mechanical Systems) technology, where the gyroscope measures angular velocity in programmable ranges up to ±2000°/s, while the accelerometer measures linear acceleration up to ±16g. The AK8963 magnetometer is used to determine orientation by sensing the Earth's magnetic field with good accuracy. One of the main advantages of this sensor is its low power consumption, as it offers multiple power-saving modes, making it ideal for battery-powered portable and wearable devices.

The MPU-9250 is widely used in various technological applications such as drones, smart robotics, virtual reality (VR), augmented reality (AR) systems, IoT devices, and wearable health monitoring systems. In the smart bracelet project designed for epilepsy seizure detection, the sensor is used to continuously monitor the patient's body movements and detect abnormal patterns such as violent shaking or sudden falls. The collected data is then sent to the microcontroller for processing in order to take appropriate actions, such as sending alerts or emergency notifications when necessary. Its small size, high accuracy, and shock resistance contribute to improving the reliability and efficiency of smart health monitoring systems [19].

The MPU-9250 sensor is an important component in an epilepsy monitoring bracelet, as it continuously tracks body movements by measuring acceleration, angular velocity, and motion direction. It helps detect abnormal movements such as seizures or falls, then sends the data to the microcontroller to take appropriate actions, such as triggering an alert or sending an emergency notification. It is characterized by its small size and low power consumption, making it suitable for wearable devices and improving the accuracy and reliability of the monitoring system.

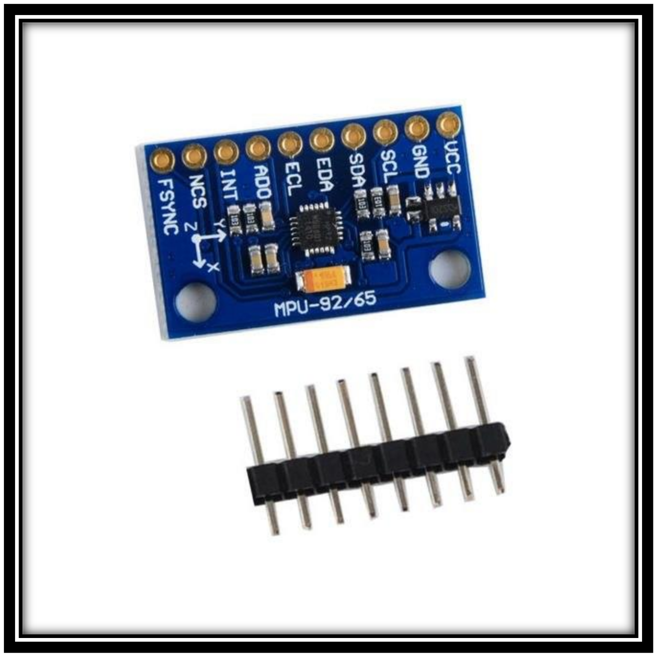


*Figure III. 1: Sensor MPU9250*

### III.3.3 MAX30102 Heart Rate Sensor

The MAX30102 is an integrated sensor that measures heart rate and blood oxygen saturation ($SpO_2$). It includes internal LEDs, photodetectors, optical components, and low-noise electroniccircuits with ambient light rejection, forming a ready-to-use system easily integrated into wearable and portable device.

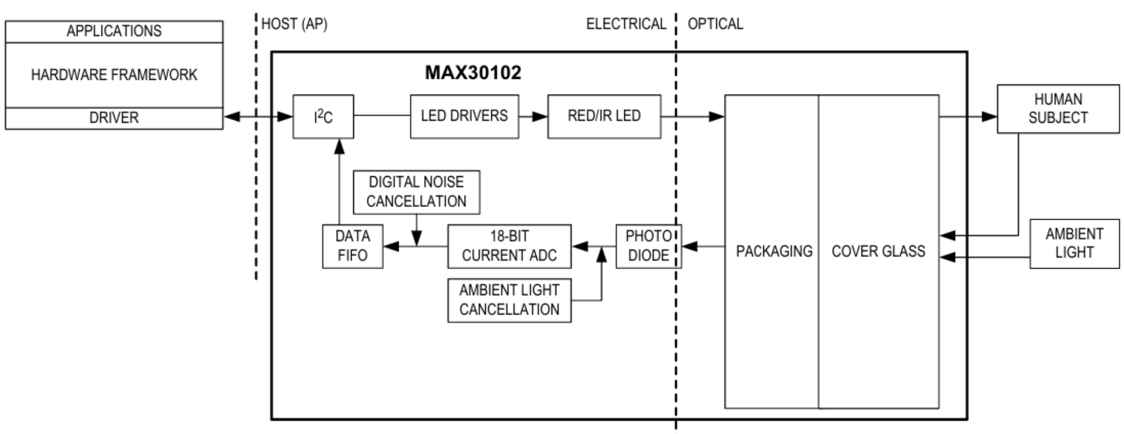


*Figure III. 2: System Diagram of MAX30102 module*

The sensor operates using a 1.8V power supply for its main circuitry, along with an additional 3.3V supply dedicated to the LEDs, and it communicates via a standard I2C interface. It also supports software shutdown with zero standby current consumption while keeping the power rails active at all times. This sensor is housed in a compact 5.6 × 3.3 × 1.55 mm, 14-pin package and includes an integrated protective glass cover to improve durability and measurement accuracy.

It is characterized by extremely low power consumption, making it ideal for portable devices, and it allows adjustable sampling rates and LED current levels to optimize energy usage. The device consumes less than 1 mW in heart-rate monitoring mode, with an ultra-low shutdown current of approximately 0.7 µA. In addition, it offers fast data output, high sampling rates, strong resistance to motion artifacts, a high signal-to-noise ratio (SNR), and it operates reliably across a wide temperature range from -40°C to +85°C [20].

The MAX30102 sensor is used in the device as a key component for monitoring the user's vital signs, as it accurately and continuously measures heart rate and blood oxygen saturation ($SpO_2$ ). In the smart bracelet for epilepsy patient monitoring, this sensor collects important physiological data, such as sudden heart rate changes or oxygen desaturation, which may indicate the onset of an abnormal situation. These measurements are sent to the processing unit for analysis and appropriate action, such as triggering an immediate alert or an alarm system.. This enhances health monitoring and speeds up emergency response.

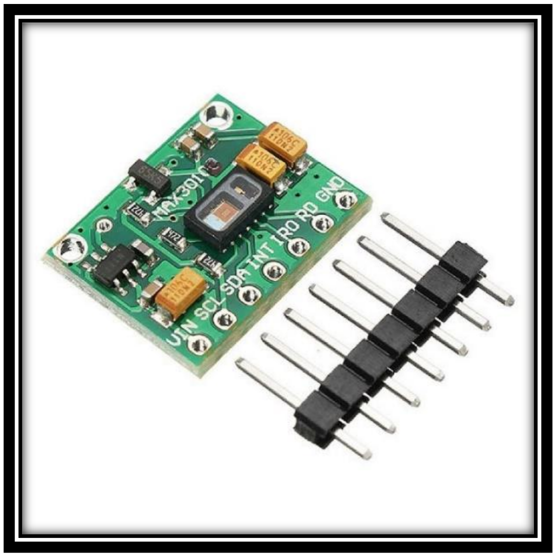


***Figure III. 3 : MAX30102 Heart Rate Sensor***

### III.3.4 CJMCU-6701 Sensor

The CJMCU-6701 is a compact, highly efficient accelerometer module used for motion detection, orientation sensing, and vibration monitoring across diverse applications. Its flexibility and high accuracy make it suitable for smartphones, gaming systems, robotics, wearable devices for activity tracking, and embedded systems requiring precise real-time motion and orientation control [21].

In the medical field, this sensor is crucial for intelligent monitoring , particularly in fall detection for elderly individuals and patients. It is also used in advanced healthcare projects such as smart epilepsy monitoring bracelets, where it detects abnormal movements, seizure-related vibration patterns, and sudden falls. This enhances early warning systems and improves patient safety.

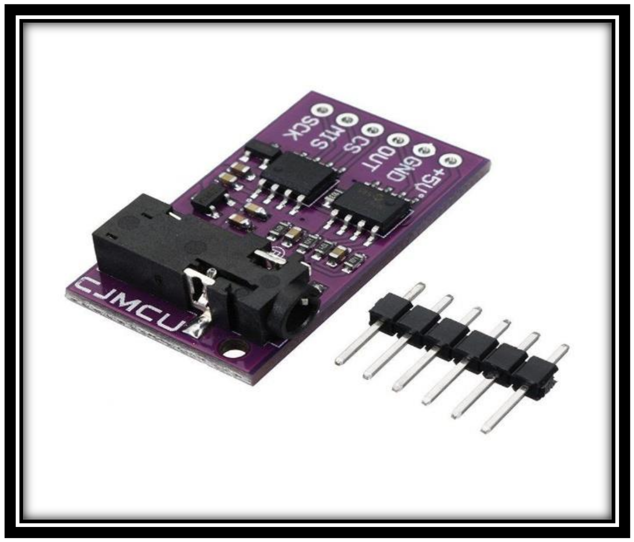


***Figure III. 4 : CJMCU-6701 Sensor***

### III.3.5 GSM SIM900 Communication Module

The SIM900 module is a compact, highly reliable wireless communication unit based on GSM/GPRS technology. Its support for four frequency bands 850, 900, 1800, and 1900 MHz enables its deployment across a wide range of mobile networks worldwide. The module is controlled via standard AT commands through the UART serial communication interface, which facilitates seamless integration with microcontrollers and straightforward management of its various functions. Its capabilities include sending and receiving SMS messages, making and receiving phone calls, as well as supporting software-based power-on and reset operations. The module operates within a voltage range of 3.1 to 4.2V and features a compact footprint of 60 × 53 mm, making it well-suited for embedded systems and wearable medical applications [22]. It was selected for this project due to its ability to operate independently of Wi-Fi networks, ensuring continuous alert transmission even in areas with no internet coverage. Additionally, its ease of integration with the ESP8266 microcontroller and its low operational requirements further justified its inclusion in the system.

### III.3.6 Battery and Power Supply

Lithium Polymer (Li-Po) batteries hold a prominent position among the battery types used in modern electronics, particularly in portable and wearable applications, owing to their ability to deliver high energy density at a low weight and compact size. Their manufacturing flexibility, which allows them to be produced in a wide variety of shapes and dimensions, makes them especially well-suited for space-constrained devices such as smartwatches and smart bracelets. Among their most notable characteristics is a low self-discharge rate of approximately 5% per month, enabling them to retain their charge for extended periods even when not in use. They are also distinguished by their ability to supply continuous and stable power to devices, making them an ideal choice for applications that demand uninterrupted operation, such as medical monitoring systems. These batteries are widely employed in mobile devices, power banks, slim-profile gadgets, and various other applications requiring reliable energy in a compact form. Nevertheless, they require careful handling during charging and operation to avoid potential risks such as overheating or damage resulting from improper use [23].

By virtue of their well-balanced combination of light weight, high energy density, and operational efficiency, Li-Po batteries represent the most suitable power source for wearable systems such as the smart bracelet proposed in this project. They support appropriate discharge rates that ensure smooth and stable operation of various electronic components, including microcontrollers, communication modules, and sensors, without experiencing sudden voltage drops during operation. Their rechargeability over numerous cycles further enhances their suitability for long-term applications, particularly in medical wearable devices that demand continuous and dependable performance. The rapid advancement of battery management technologies has also contributed to improving their safety and reducing overheating risks, thereby consolidating their role as a fundamental pillar in the ecosystem of modern smart systems.

## III.4 Electronic Design

This section covers the electronic design of the proposed system, explaining how the physical components are interconnected within the smart bracelet. It traces the data flow path starting from the sensors, passing through the processing unit, and ending at the communication unit. Additionally, the section elaborates on the block diagram, the electronic schematic, and the integration mechanism of the various modules, ensuring seamless coordination and efficient system performance.

### III.4.1 Block Diagram

This block diagram illustrates the complete architecture of the smart bracelet designed for early detection of epileptic seizures. The system integrates multiple sensors, including MPU9250 and MPU9250 units to monitor vibrations, rotations, and body orientation, the high-precision CJMCU-6701 sensor to capture subtle motion changes, and the MAX30102 sensor to track vital signs such as heart rate and oxygen saturation using optical PPG technology. All collected data is processed by the ESP8266 microcontroller, which performs acquisition, analysis, anomaly detection, and alert management. The results are then transmitted through the GSM communication module (SIM900), enabling the sending of SMS messages or emergency calls when necessary. An OLED display provides real-time visualization of vital information, while a lithium-polymer battery ensures continuous power supply for the entire system. The diagram also highlights the general workflow of the device, starting from data collection, through processing and analysis, to the generation of alerts, reflecting a functional integration aimed at enhancing patient safety through continuous monitoring and immediate response.

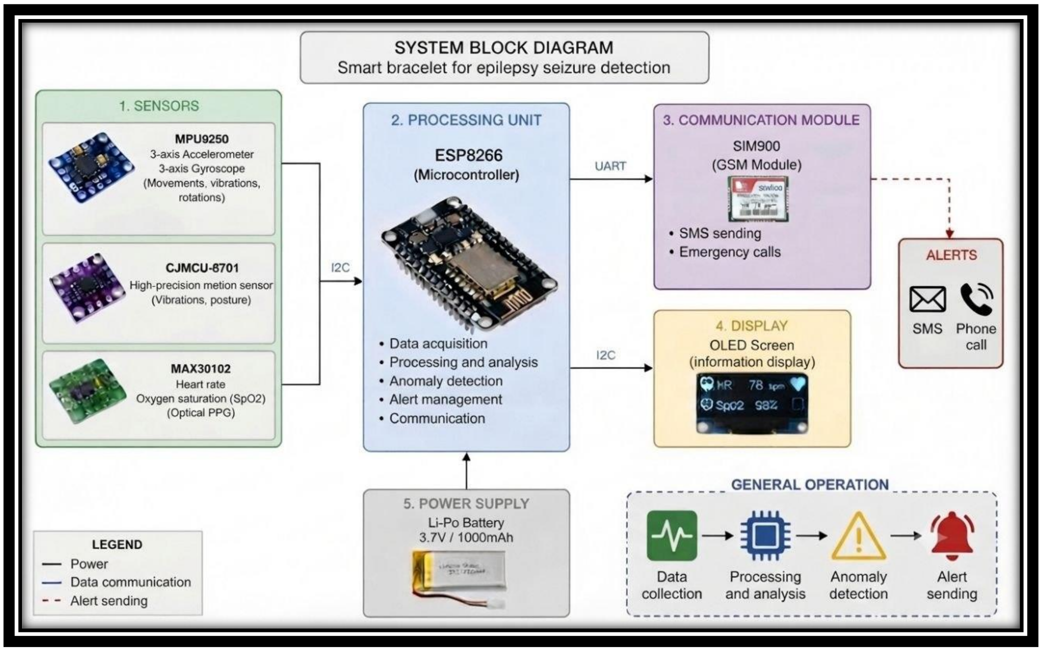


***Figure III. 5 :System block diagram***

### III.4.2 Electronic Schematic

The electronic schematic reflects the actual configuration of how the system components are interconnected, illustrating the wiring of the sensors, the ESP8266 processing unit, and the GSM SIM900 communication module within the electronic circuit. The purpose of this schematic is to translate the theoretical design into a practical and executable implementation, while ensuring that all components operate in full harmony. The development process begins by assembling the circuit on a Breadboard, with the aim of verifying the integrity of all electrical connections, confirming that the sensors respond correctly with the ESP8266 unit, and ensuring that the GSM SIM900 module can receive and execute commands accurately. This stage is of great importance as it allows for the detection of technical issues such as wiring faults and signal conflicts, enabling them to be resolved before progressing to the final design.

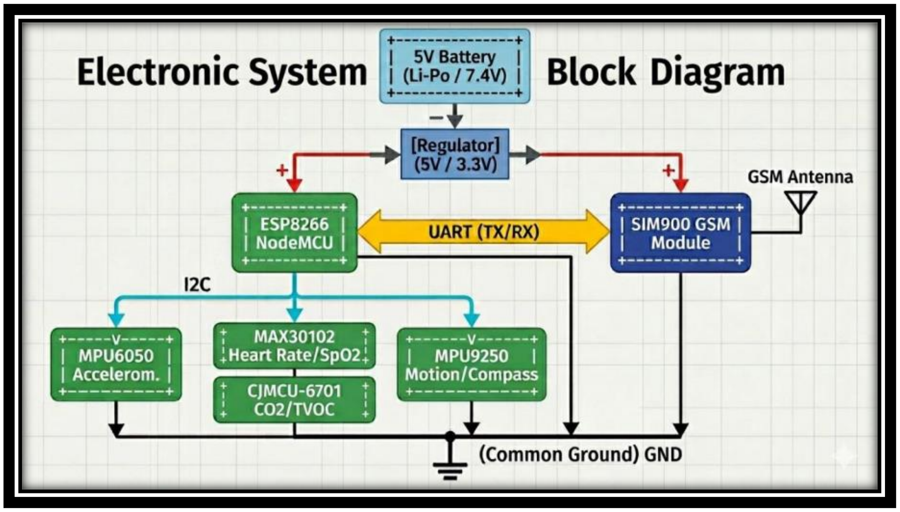


***Figure III. 5 : Electrical diagram***

Once the testing phase is complete and system stability is confirmed, the circuit is transferred to a dedicated PCB, with the goal of enhancing design quality by reducing size, organizing components more professionally, and minimizing tangled wiring that could generate electrical interference. The adoption of a PCB also contributes to improved system stability and reliability, particularly in wearable devices that require continuous operation over extended periods. The schematic diagram below illustrates the detailed electronic circuitry and wiring of the system:

### III.4.3 Module Interconnection

The interconnection of system components follows a precise methodology that ensures fast and efficient data exchange between all units. The ESP8266 serves as the central controller responsible for receiving data from the sensors, processing it, and making appropriate decisions in real time. The sensors are connected to the ESP8266 via the I2C protocol, a serial communication protocol that combines simplicity with effectiveness, allowing multiple devices to be linked using only two data lines: SDA and SCL. This protocol provides adequate data transfer speed while significantly reducing the number of wires required, making it a suitable choice for embedded systems such as the smart bracelet.

The GSM SIM900 module is linked to the ESP8266 via the UART serial communication protocol, where data exchange takes place through TX and RX signals. The module is controlled using AT commands, which enable automatic transmission of SMS messages or phone calls as soon as an abnormal condition is detected, ensuring prompt alerting without the need for user intervention.

On another front, the power distribution system is carefully designed to ensure that all components are supplied from a single source, namely a Li-Po battery, with strict attention to voltage stability and the prevention of any sudden drops that could lead to system restarts or shutdowns. This guarantees continuous and reliable operation of the bracelet in real-world usage environments.

## III.5 Power Management

Power management represents one of the fundamental pillars in the design of wearable systems, as these systems rely on limited-capacity batteries, making energy consumption efficiency a pivotal factor in ensuring operational continuity. Based on this, embedded systems are built according to a methodology that achieves a precise balance between functional performance and power requirements, through intelligent management of the activation of sensing, processing, and wireless communication units. In this context, recent studies in the field of Internet of Things consistently indicate that improving power management is one of the most prominent determinants that extend the lifespan of smart devices and enhance their overall reliability [24].

### III.5.1 Sensor Power Consumption

Sensors occupy a prominent position among the components that most significantly impact power consumption in embedded systems, as this consumption varies from one sensor to another depending on its type and operating method. In the context of wearable devices, low-power sensors are employed that operate according to the Duty Cycling pattern, which is based on activating the sensor for brief time periods in order to collect data, then switching it to idle mode or shutting it down entirely, so as to limit the overall power consumption. Research specialized in wireless sensor networks has revealed that this approach achieves a substantial reduction in power consumption compared to continuous operation, thereby contributing to a noticeable extension of battery life [25].

### III.5.2 Low Power Modes

The ESP32 microcontroller is distinguished by its support for a diverse range of power management modes, enabling the consumption level to be adapted in accordance with the system's requirements at each stage. These modes are distributed across three progressive levels: Active Mode constitutes the highest consumption stage, in which the processor operates at maximum capacity to simultaneously perform computational operations, process data, and manage communications.

In Light Sleep Mode, non-critical peripheral units are disabled with the aim of reducing consumption, while the system retains its ability to wake up instantly and return to activity rapidly upon receiving any trigger signal.

As for Deep Sleep Mode, it represents the optimal choice for power saving, as it shuts down the majority of system components and retains only the memory contents. This reduces the current consumption to extremely precise levels measured in microamperes, making it the most suitable solution during extended idle periods [26].

### III.5.3 Battery Life Estimation

Battery life estimation in embedded systems is based on the relationship between the average electrical current consumption of the system and the capacity of the battery used. Since actual power consumption is variable and not constant depending on the current operating mode, whether Active Mode, Light Sleep Mode, or Deep Sleep Mode, the calculation of average current consumption is carried out in a weighted manner based on the proportional time the system spends in each of these modes. Studies specialized in low-power system design confirm that the optimal utilization of sleep modes contributes fundamentally to multiplying battery life, which in turn positively impacts the continuity of device operation and reduces the need for frequent recharging [27].

## III.6 Conclusion

The proposed design of the smart bracelet constitutes an integrated and effective system for monitoring epilepsy patients in real time, built upon a precise integration of hardware, software, and Internet of Things technologies, ensuring reliable and accurate performance. The analysis revealed that employing the ESP8266 microcontroller alongside the vital sensors MPU9250, CJMCU-6701, and MAX30102, together with the GSM SIM900 communication module, produces a mature technical solution capable of detecting physiological and motion changes with high accuracy and triggering immediate alerts upon the detection of any abnormal condition. On the software front, the architecture based on core functions within the microcontroller ensures rapid data processing and real-time decision-making, which enhances the system's efficiency in handling emergency situations and responding to them with the required speed. This is further reinforced by the adoption of a multi-layer IoT architecture that organizes data flow and tightens the integration between sensing, processing, and communication units within a consistent and interconnected system.

On the hardware design front, the study of components and electronic design demonstrated that the system is distinguished by its compact size, low power consumption, and ease of integration, qualities that make it an ideal candidate for wearable medical applications. This is further supported by the adoption of advanced power management strategies that contribute to extending battery life and ensuring uninterrupted device operation over extended periods.

Based on the foregoing, this design can be regarded as a pioneering qualitative step toward developing next-generation smart health monitoring systems, with promising prospects for future development including the integration of artificial intelligence technologies and linking the system with smartphone applications, thereby raising the ceiling of accuracy and effectiveness in patient care and enhancing their quality of life.

# Chapter IV. Development and system implementation

## IV.1 Introduction

This chapter focuses on the practical aspects of designing and implementing the proposed epilepsy monitoring system by presenting the different development stages used to build the project. The ESP8266 module is employed as the main core responsible for control and data processing, due to its good performance, compact size, and low cost, which make it highly suitable for embedded systems and Internet of Things applications.

The chapter describes also the software structure of the system through a set of dedicated functions used for reading sensor data, analyzing it, generating alerts, and transmitting information when necessary. It also explains the communication mechanism using AT commands and the integration of the SIM900 GSM module to improve system efficiency and ensure reliable notifications during emergency situations. Finally, the seizure detection algorithm adopted in the system is presented, along with the possibility of future enhancement using Artificial Intelligence techniques to improve monitoring accuracy and increase patient safety.

## IV.2 The ESP8266 Module

The ESP8266 is a low-cost, high-performance integrated electronic module designed to enable Wi-Fi communication and convert it into a serial communication interface. It belongs to the “Smart Connectivity” platform developed by Espressif Systems, which aims to provide embedded solutions supporting wireless Wi-Fi connectivity for developers of embedded systems while maintaining low cost and high performance. This module is available in several versions ranging from ESP8266-01 to ESP8266-13, where each version introduces gradual improvements in hardware and capabilities. The ESP8266-01 is considered the basic and simplest version in terms of features, while higher versions such as ESP8266-13 offer enhanced capabilities, including a greater number of GPIO pins, improved support for communication protocols, and upgrades in memory, antenna type, and packaging method (either through-hole or surface-mount).

### IV.2.1 Hardware Characteristics and Performance of the ESP8266 Module

The ESP8266-01 mainly consists of :

- a low-power 32-bit microcontroller;
- two GPIO pins, a UART interface;
- an integrated PCB antenna.

Whereas other versions include additional features such as:

- an analog-to-digital converter (ADC);

- support for protocols like SPI and I2C;
- more input/output pins.

Despite its important technical advantages, information about this module was initially limited due to its relatively recent introduction, but it gained widespread popularity since the end of 2014 thanks to its extensive use in Internet of Things (IoT) applications.[1]

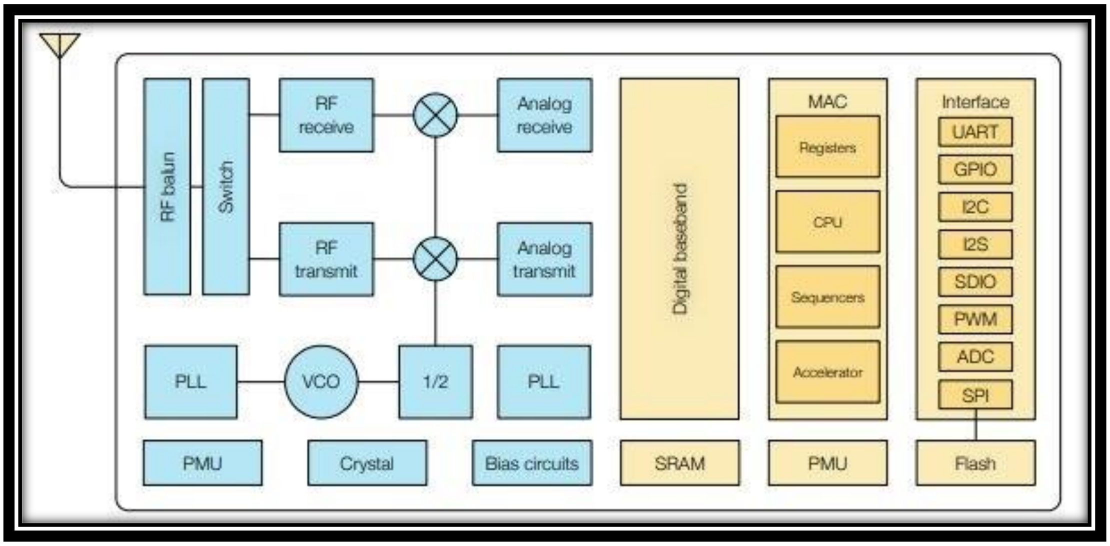


***Figure IV. 1: LESP8266 Module Block Diagram***

The ESP8266 module is characterized by strong performance despite its small size, as illustrated by its functional block diagram in Figure 1. It supports several built-in sleep modes, which help reduce power consumption and improve efficiency in embedded systems. The module also features a compact size (24 × 16 mm), making it easy to integrate into various electronic applications, in addition to its low cost compared to other wireless communication modules. It is based on a 32-bit processor that provides sufficient computational power to support a range of essential functions that facilitate the development of Internet of Things (IoT) applications, such as support for a Real-Time Operating System (RTOS), operation in Station mode or Soft Access Point mode, or both simultaneously, as well as an integrated TCP/IP protocol stack.

Previous studies have shown that these features, along with the processing capability of the module, allow it to be directly integrated into middleware systems based on the Publisher–Subscriber model widely used in IoT applications, making the ESP8266 a suitable choice for

[1] Mehta, M. (2015). ESP 8266: A breakthrough in wireless sensor networks and Internet of Things. International Journal of Electronics and Communication Engineering & Technology (IJECET), 6(8), 7–11. ISSN: 0976-6464 (Print), 0976-6472 (Online).

developing WiFi-connected devices that are easy to program and integrate with the internet[2]. Figure 2 illustrates the NodeMCU ESP8266 development board used in the implementation of the proposed system.

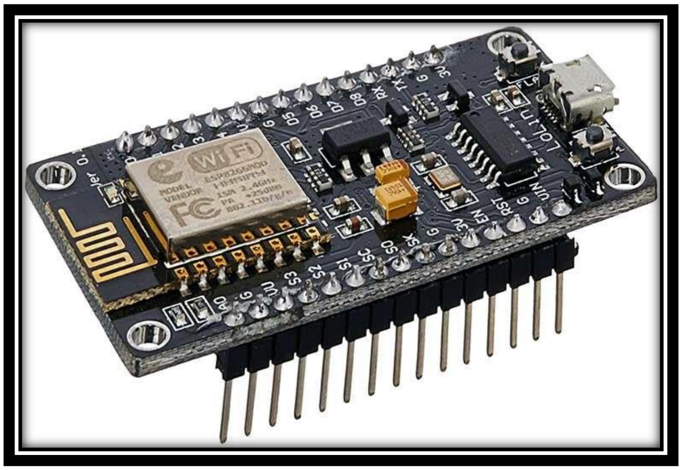

***Figure IV. 2: NodeMCU ESP8266 Development Board for IoT Projects***

### IV.2.2 Software ESP8266 Module

After programming the ESP8266 module and setting up the development environment, the system software was designed using a set of functions. This modular approach helps organize the code into clearly defined tasks, making it easier to understand, maintain, and extend. Each function is responsible for a specific operation, such as system initialization, sensor data acquisition, data processing, and decision-making (e.g., triggering alerts or transmitting data). The following section presents the main functions used in the system along with their respective roles.

- **Functions Description:**
  - ➢ **Function setup():**

The setup() function is one of the core functions in the ESP8266 program. It is executed only once when the system starts.

✓ **Role:**

- Initialize hardware components (GPIO)
- Start serial communication
- Configure system settings

**Source code**

```
void setup() {
```

[2] Mesquita, J., Guimarães, D., Pereira, C., Santos, F., & Almeida, L. (2018). Assessing the ESP8266 WiFi module for the Internet of Things

```
 Serial.begin(115200);
 pinMode(LED_BUILTIN, OUTPUT);
}
```

This function prepares the system for operation by initializing all required components.

- ### Function loop():

The loop() function runs continuously after the execution of the setup function.

✓ **Role:**

- Read sensor data
- Process information
- Execute system logic

**Source code**

```
void loop() {
 int value = analogRead(A0);
 Serial.println(value);
}
```

It ensures continuous monitoring and real-time operation of the system.

- ### Function readSensor():

This function is used to read data from the connected sensor.

✓ **Role:**

- Acquire sensor data
- Return the measured value

**Source code**

```
int readSensor() {
 return analogRead(A0);
}
```

- ### Function detectSeizure():

This function analyzes the sensor data to detect abnormal conditions.

✓ **Role:**

- Compare values with a threshold

- Identify abnormal patterns

**Source code**

```
bool detectSeizure(int value) {
 if (value > 800) {
  return true;
 }
 return false;
}
```

### ➢ Function sendData():

This function is responsible for sending data to the user or a remote server via Wi-Fi.

✓ **Role:**

- Transmit data
- Display or log results

**Source code**

```
void sendData(int data) {
 Serial.println(data);
}
```

### ➢ Function alert():

This function is used to trigger an alert when an abnormal condition is detected.

✓ **Role:**

- Activate LED or buzzer
- Notify the user

**Source cod**

```
void alert() {
 digitalWrite(LED_BUILTIN, HIGH);
}
```

Through these functions, the program is structured into modular and interconnected units, which improves code readability and ensures efficient system operation for monitoring and responding to critical situations.

➢ **ESP8266 Programming Overview:**

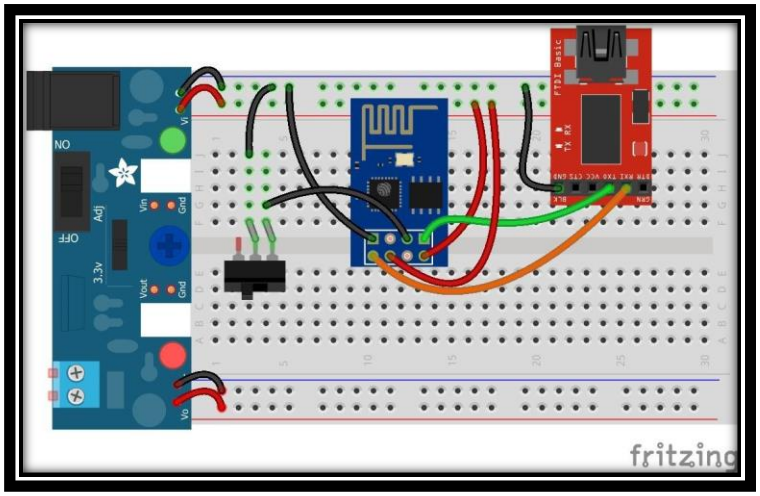

***Figure IV. 3: ESP8266 ESP-01 programming setup with FTDI***

Here is a guide on how to connect and program the ESP8266 module (such as the ESP-01) using an FTDI adapter to interface with your computer. This is the fundamental wiring diagram every developer needs to get started (See Figure IV.3).

➢ **Key Notes for Programming:**

- **Operating Voltage:** The chip operates strictly at 3.3V. Connecting it directly to 5V will likely damage the module.
- **Flash Mode:** To upload code, you must pull the GPIO 0 pin to Ground (GND) during boot-up to put the device into programming mode.
- **Development Environment:** The most popular options are the Arduino IDE (after installing the ESP8266 core) or MicroPython.

## IV.3 Communication with ESP8266 Using AT Commands

The ESP8266 module represents an ideal solution in Internet of Things (IoT) applications due to its high capability in providing wireless connectivity. In this research, the module functions as an interface for transmitting data to monitoring platforms, where communication with the microcontroller is established through the serial port using AT commands. The advantage of this approach lies in the ability to efficiently configure network settings and direct data without the need to engage with the internal programming complexities of the module.

AT commands (Attention Commands) are standardized text-based instructions used to control wireless communication modules, particularly the ESP8266, through a serial communication interface (UART). These commands are sent by the microcontroller in a simple textual format to configure the module and manage its functionalities without requiring complex internal programming. The working principle of AT commands is based on a request/response mechanism, where each command sent by the system is executed by the module, which then returns a response such as “OK” in case of success or “ERROR” in case of failure, allowing reliable monitoring of the execution process.

In this project, AT commands are used to control the ESP8266 module by first initializing and configuring its operating mode, and then connecting it to an available Wi-Fi network to establish a wireless communication channel. Through this channel, the processed data collected from sensors—such as heart rate and motion signals—are transmitted by the microcontroller to a remote monitoring platform for real-time observation of the user’s health condition.

In addition, a GSM communication module SIM900 is integrated into the system to ensure alert reliability in case of network unavailability. In emergency situations, such as abnormal heart rate or unusual movement detection, the system sends SMS notifications to the user or predefined contacts. This combination of Wi-Fi and GSM communication enhances the robustness and reliability of the system under different operating conditions.

The use of AT commands offers several advantages, including simplicity, ease of implementation, and reduced system complexity, as it eliminates the need for advanced firmware development on the communication module. Moreover, it provides efficient control over network configuration and data transmission, making it highly suitable for Internet of Things (IoT) applications, particularly in healthcare monitoring systems that require real-time data transmission and rapid response to critical events.

## IV.4 Seizure Detection Algorithms

The detection algorithms in an epilepsy seizure monitoring system are a core component that enables the transformation of raw data coming from sensors into clear and actionable decisions. These algorithms rely on processing physiological signals collected in real time, such as heart rate, body movement, and sometimes blood oxygen level, in order to determine whether the condition is normal or indicates a possible epileptic seizure. In this project, a simple and effective algorithm based on a threshold-based approach was adopted, where reference values representing the normal state of the human body are defined, such as a specific range for heart rate and normal levels of movement. The measured values from the sensors are then continuously compared to these predefined limits. When these values exceed the set thresholds, the system considers the situation abnormal, especially if an increased heart rate is accompanied by unusual or excessive body movements or strong shaking, which increases the likelihood of a seizure. The system also relies on combining multiple physiological signals instead of depending on a single sensor, a concept known as sensor fusion. The combination of several abnormal indicators at the same time provides a stronger indication of a seizure and reduces the probability of false alarms. After the analysis process, the microcontroller makes the final decision: if all values remain within normal ranges, the condition is considered stable; otherwise, an immediate alert is triggered, which may take the form of sending an SMS message, activating a sound alarm, or vibrating the wearable device. Although this algorithm is relatively simple compared to advanced artificial intelligence techniques, it is highly suitable for practical embedded systems projects because it achieves a good balance between accuracy and ease of implementation. It can also be further improved in the future by integrating machine learning techniques to make the system more intelligent, adaptive to different patients, and capable of reducing error rates more effectively.

## IV.5 Artificial Intelligence(AI)

Artificial Intelligence (AI) is defined as the reproduction of human cognitive abilities and thought processes through computer systems, achieved by developing applications capable of imitating intelligent behavior, drawing on past experiences, and performing reasoning, planning, analysis, and problem-solving. These capabilities are harnessed to accomplish complex tasks with speed and precision, such as medical diagnosis and proposing appropriate therapeutic solutions. AI technologies are considered among the most significant modern innovations, as they embody integration with diverse scientific and technical fields, thereby driving social and scientific progress. This technology has brought about a major transformation in the healthcare sector, where it can rival human capabilities and, in some cases, surpass them. The concept refers to algorithms capable of self-learning from data to perform automated functions without the need for explicit programming of each step, and the World Health Organization recognizes AI as a promising tool for the future of public health and medicine. AI holds the potential to revolutionize healthcare delivery, as it can identify subtle patterns that may escape human observation by analyzing vast amounts of data, leading to more accurate diagnoses and improved treatment plans. Its systems are distinguished by their ability to adapt quickly to new information, enabling them to keep pace with the latest medical developments, while AI-powered decision-support systems assist physicians in making well-informed therapeutic choices, thereby enhancing the quality of healthcare services provided to patients [28].

Artificial intelligence has a wide range of applications in healthcare, as it supports medical diagnosis and enables the analysis of medical images and tests with greater accuracy. It also helps in selecting the most appropriate treatment plans based on large-scale patient data and evidence-based clinical recommendations. Its importance lies in reducing costs and saving time by limiting unnecessary or repeated tests, as well as improving the management of chronic diseases through continuous monitoring and early alerts to prevent medical errors. Moreover, AI enhances the operational efficiency of healthcare institutions, facilitates resource management, and improves the patient experience in terms of treatment quality and effectiveness. In addition, it provides access to digital health services and personalized medical information online, and supports the use of wearable devices to monitor vital signs. It also assists doctors and nurses in choosing the most effective therapeutic interventions. Its impact is not limited to advanced medical centers, but also extends to providing healthcare services in remote areas. Furthermore, AI is used in surgical procedures with the assistance of robotic systems such as the “da Vinci” system, reflecting the integration of intelligent technologies across various aspects of modern medicine [29].

In future developments, the system can be enhanced by integrating Artificial Intelligence to provide intelligent medical report generation and advanced alert management. This would enable the automatic analysis of patient data and the generation of detailed medical reports that can be sent directly to the physician for continuous follow-up. In addition, the system can support multiple levels of smart notifications, including alerts to the patient’s guardian, the responsible doctor, and emergency services such as civil protection in case of severe epileptic seizure detection. This multi-level alert mechanism would improve response time and ensure rapid intervention, thereby increasing patient safety and making the system more reliable and suitable for real-time healthcare monitoring. This concept is illustrated in Figure IV.4.

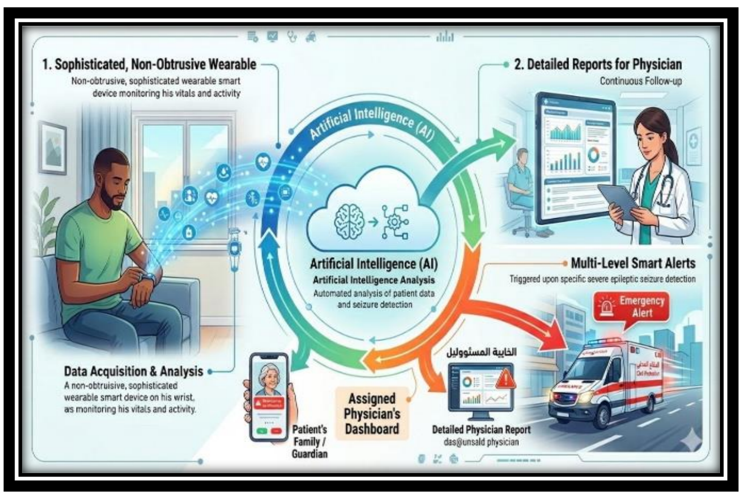


***Figure IV. 4 : Intelligent Wearable Healthcare System for Epilepsy Monitoring***

## IV.6 Conclusion

This chapter presents the different stages involved in the design and development of the proposed epilepsy monitoring system. A successful implementation was achieved based on the ESP8266 module as the main core for control and data processing, due to its simplicity, high efficiency, and strong suitability for embedded healthcare and IoT-based applications. The chapter also covered both the hardware and software architecture of the system, including the key functions responsible for monitoring physiological signals, detecting abnormal conditions, generating alerts, and transmitting data in real time when necessary. In addition, the use of AT commands combined with the SIM900 GSM module improved system reliability and ensured fast communication during emergency situations. The implemented detection algorithm also provided a practical and efficient approach for continuous patient monitoring based on real-time analysis of sensor data. Finally, the chapter highlighted the growing role of Artificial Intelligence in future healthcare systems, where it can support early seizure prediction, intelligent reporting, and enhanced emergency response mechanisms, making the system more accurate, reliable, and effective in smart healthcare applications.

# Chapter V. System Implementation, Results, and Discussion

## V.1 Introduction

In this chapter, we present the practical implementation of the intelligent portable epileptic seizure detection system. The developed prototype aims to ensure continuous monitoring of the patient's physiological parameters and body movements in order to detect abnormal situations associated with epileptic seizures.

The system is based on an embedded architecture using several biomedical sensors connected to an ESP8266 microcontroller. The acquired data are analyzed in real time to identify the characteristic signs of a seizure, after which an emergency alert is automatically sent through a GSM module.

The proposed device represents a portable, lightweight, and low-power solution suitable for medical telemonitoring applications and connected healthcare systems.

## V.2 Prototype Development

### V.2.1 Hardware Components

The developed prototype consists of several hardware components that work together to continuously monitor physiological parameters and detect epileptic seizures. The ESP8266 NodeMCU serves as the central processing unit responsible for sensor management, data acquisition, signal processing, and communication. The MPU9250 sensor measures body movements through its accelerometer, gyroscope, and magnetometer. The MAX30102 sensor continuously monitors the patient's heart rate using photoplethysmography (PPG), while the CJMCU-6701 GSR sensor measures changes in skin conductivity associated with physiological stress. The SIM900 GSM module enables automatic SMS transmission to caregivers during emergencies. A rechargeable battery powers the entire prototype, ensuring portability and continuous operation.

The implemented prototype consists of the following hardware components:

- ESP8266 NodeMCU: central processing unit;

- MPU9250: motion sensor (accelerometer, gyroscope, and magnetometer);
- MAX30102: heart rate sensor;
- CJMCU-6701: galvanic skin response (GSR) sensor;
- SIM900: GSM module for SMS alert transmission;
- Portable rechargeable battery for system power supply.

### V.2.2 Hardware Integration

The integration of all hardware modules was carried out to ensure stable communication and reliable real-time operation. The MPU9250 and MAX30102 sensors communicate with the ESP8266 using the I²C protocol through the SDA and SCL lines. The GSR sensor is connected to the analog input A0, while the SIM900 GSM module communicates with the microcontroller through UART serial communication. All modules share a common ground connection, and the GSM module is powered separately to provide sufficient current during SMS transmission. This configuration guarantees synchronized acquisition of physiological data and efficient communication between all components.

The ESP8266 microcontroller ensures the acquisition and processing of data from the different sensors. The MPU9250 and MAX30102 sensors communicate with the ESP8266 through the I2C protocol, while the GSR sensor provides an analog signal directly acquired by the analog input of the microcontroller. The SIM900 module uses UART serial communication for the transmission of emergency messages

The prototype was assembled as a compact portable system integrating all the required electronic components. Connections between the modules were made using jumper wires and a prototyping board.

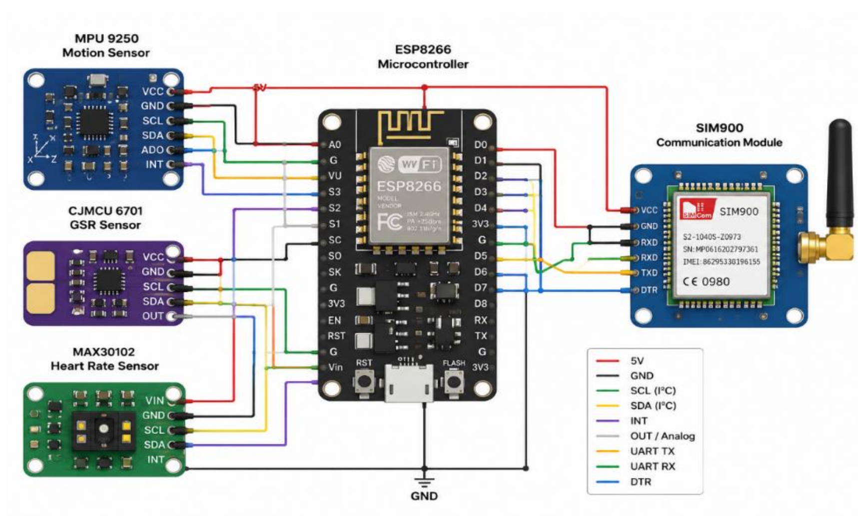


*Figure V. 1: Hardware integration of the proposed wearable seizure detection device*

The hardware architecture of the proposed intelligent epileptic seizure detection system is based on an embedded and portable design integrating several biomedical sensors with an ESP8266 NodeMCU microcontroller. The ESP8266 acts as the central processing unit responsible for sensor management, real-time data acquisition, signal processing, seizure detection, and communication control. The system integrates an MPU9250 motion sensor, a MAX30102 heart rate sensor, a CJMCU-6701 galvanic skin response (GSR) sensor, and a SIM900 GSM communication module. The MPU9250 sensor combines an accelerometer, gyroscope, and magnetometer to detect abnormal body movements, convulsions, and sudden position variations associated with epileptic seizures. The MAX30102 sensor continuously measures the patient's heart rate using photoplethysmography (PPG) technology, allowing the system to identify abnormal cardiac variations during seizure episodes. In addition, the GSR sensor measures changes in skin conductivity related to physiological stress and electrodermal activity, providing complementary physiological indicators that improve detection reliability.

The communication between the ESP8266 and both the MPU9250 and MAX30102 sensors is established through the I2C protocol, which allows multiple devices to share the same communication bus while ensuring fast and stable digital data transmission. In the implemented setup, the SDA pins of the MPU9250 and MAX30102 sensors are connected to the D2 (GPIO4) pin of the ESP8266, while the SCL pins are connected to the D1 (GPIO5) pin. Both sensors are powered through the 3.3V output of the ESP8266 and share a common ground connection. The GSR sensor provides an analog output signal that is directly connected to the analog input pin A0 of the ESP8266, while its VCC and GND pins are connected respectively to the power supply and ground terminals. For emergency communication, the system uses a SIM900 GSM module connected through UART serial communication. The TX pin of the GSM module is connected to the RX pin of the ESP8266, while the RX pin of the module is connected to the TX pin of the microcontroller. The GSM module is externally powered to ensure sufficient current during SMS transmission operations, and all components share a common ground to guarantee stable communication and proper system operation.

The entire prototype is assembled on a breadboard using jumper-wire connections, allowing flexible hardware integration and easy testing during the development phase. A portable rechargeable battery is used to power the system, making the device lightweight, low-power, and suitable for continuous medical monitoring and IoT-based healthcare applications. This hardware configuration enables continuous acquisition of physiological and movement data, real-time processing by the ESP8266, and automatic transmission of SMS alerts whenever epileptic seizure conditions are detected.

In the following sections, the integrated sensors and communication modules are experimentally evaluated in order to verify the reliability, stability, and accuracy of the hardware architecture under different operating conditions.

## V.3 Software Implementation

### V.3.1 Data Acquisition

The operation of the system can be summarized in the following steps (see Figure V.1):

1. Continuous acquisition of physiological data and body movements.
2. Signal processing by the ESP8266.
3. Detection of abnormalities corresponding to epileptic seizures.
4. Automatic activation of the GSM module.
5. Transmission of an SMS alert to relatives or medical personnel.

The detection algorithm combines several parameters in order to improve system reliability and reduce false alerts.

Data acquisition part follows flowchart presented in Figure V.2:

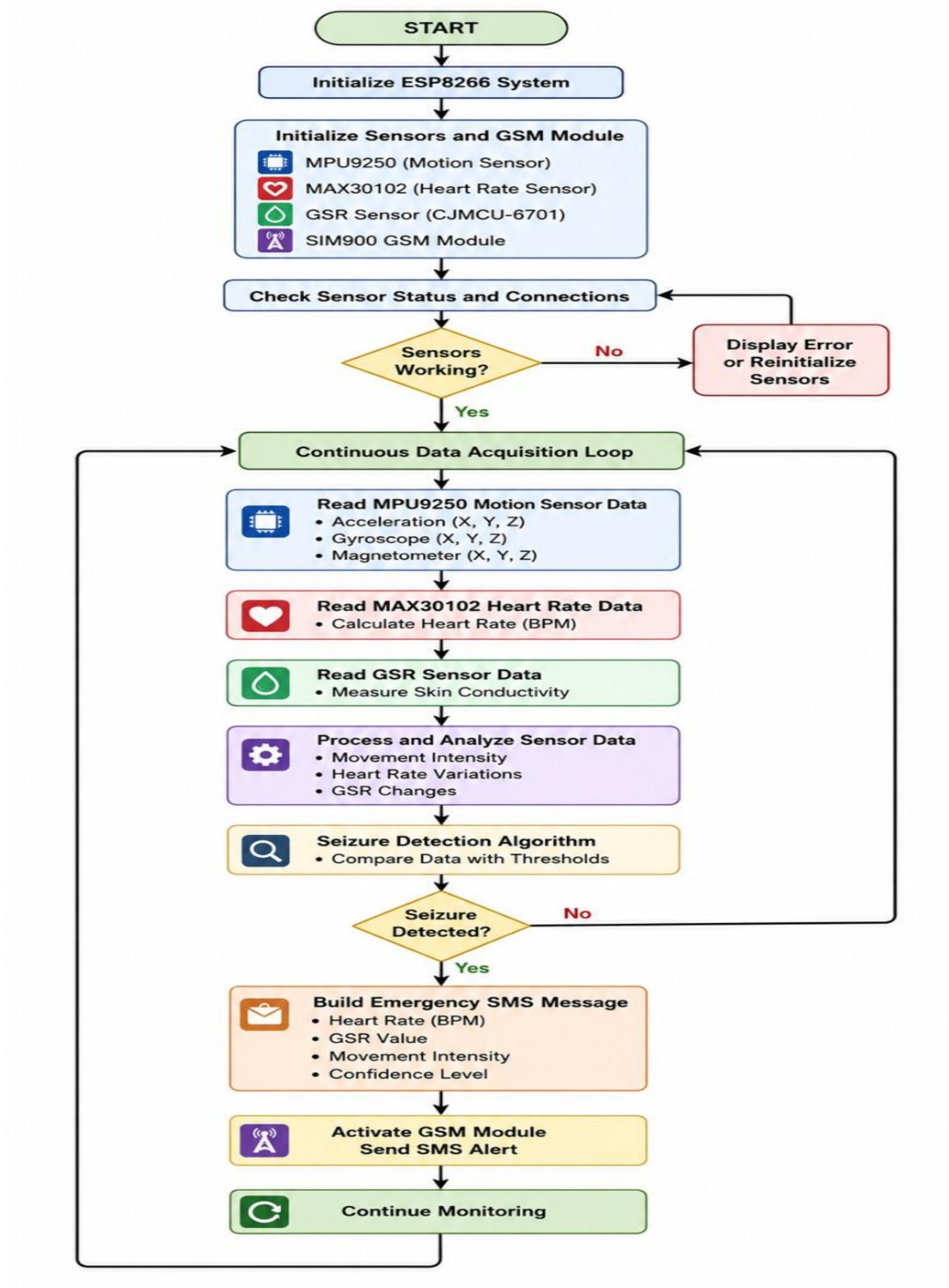


***Figure V. 2: Flowchart of the proposed epileptic seizure detection system***

The main program was developed in the Arduino IDE environment using the C++ programming language. The libraries required for I2C communication, sensor management, and AT command transmission to the GSM module were integrated into the program.

The system performs the following operations:

- Sensor initialization.

- Periodic data acquisition.
- Calculation of detection thresholds.
- Analysis of abnormal movements.
- Heart rate monitoring.
- Measurement of electrodermal response.
- Automatic transmission of SMS alerts.

### V.3.2 Signal Processing

#### V.3.2.1 Function initMPU9250()

- **Function Role**

The **initMPU9250()** function is responsible for initializing and configuring the MPU9250 sensor.

- **Operating Principle**

This function configures the I2C communication between the ESP8266 microcontroller and the MPU9250 sensor. It initializes the three internal modules of the sensor:

- Accelerometer
- Gyroscope
- Magnetometer

The I2C bus frequency is set to 400 kHz to ensure fast and stable communication.

After initialization, the function performs a communication test to verify that the sensor responds correctly.

- **Role in the System**

This function enables:

- Activation of the motion sensor.
- Verification of proper hardware operation.
- Preparation of the system for motion data acquisition.

#### V.3.2.2 Function readMPU9250()

- **Function Role**

The **readMPU9250()** function reads data from the MPU9250 sensor.

- **Operating Principle**

The function retrieves:

- Acceleration measurements along the X, Y, and Z axes.
- Angular velocity data from the gyroscope.
- Magnetometer data.

It also calculates the total acceleration magnitude in order to evaluate the overall intensity of movement.

- **Role in the System**

This function is essential for:

- Detecting abnormal movements.
- Identifying convulsions.
- Measuring rapid movement variations during seizures.

#### V.3.2.3 Function getAccelMagnitude()

- **Function Role**

This function returns the acceleration magnitude value calculated from the MPU9250 data.

- **Operating Principle**

The magnitude is obtained from the acceleration components along the three axes.

- **Role in the System**

It quantifies the intensity of body movements in order to identify sudden movements associated with epileptic seizures.

#### V.3.2.4 Function initMAX30102()

- **Function Role**

The **initMAX30102()** function initializes the MAX30102 sensor.

- **Operating Principle**

The function starts I2C communication with the heart rate sensor and configures the optical parameters of the module, particularly the intensity of the red and infrared LEDs used for photoplethysmography (PPG).

It then verifies the presence of the sensor before confirming its activation.

- **Role in the System**

This function enables:

- Activation of the heart rate sensor.
- Preparation of physiological measurements.
- Verification of proper module operation.

#### V.3.2.5 Function updateHeartRate()

- **Function Role**

The **updateHeartRate()** function continuously updates the heart rate.

- **Operating Principle**

The MAX30102 sensor measures blood flow variations using the infrared signal. When the system detects a heartbeat, it calculates:

- The time interval between two beats.

- The heart rate in beats per minute (BPM).

The function also averages the latest measurements to improve result stability.

- **Role in the System**

This function enables:

- Continuous monitoring of heart rhythm.
- Detection of abnormal variations during seizures.
- Improved detection accuracy.

#### V.3.2.6 Function getHeartRate()

- **Function Role**

This function returns the current average heart rate value.

- **Operating Principle**

It checks whether the cardiac data are valid and then returns the calculated average of the latest measurements.

- **Role in the System**

It provides the cardiac data used by the seizure detection algorithm.

#### V.3.2.7 Function readMAX30102Raw()

- **Function Role**

This function displays the raw data from the MAX30102 sensor.

- **Operating Principle**

It directly reads the infrared and red values measured by the sensor.

- **Role in the System**

It is mainly used for:

- Debugging.
- Calibration.
- Verification of sensor operation.

#### V.3.2.8 Function initGSR()

- **Function Role**

The initGSR() function initializes the GSR sensor.

- **Operating Principle**

It configures the analog pin A0 as an input to enable electrodermal signal acquisition.

- **Role in the System**

This function prepares the system to measure galvanic skin response.

#### V.3.2.9 Function readGSR()

- **Function Role**

The readGSR() function reads data from the GSR sensor

- **Operating Principle**

It reads the analog value from the sensor and calculates the corresponding voltage.

The function also records the minimum and maximum detected values.

- **Role in the System**

This function enables:

- Monitoring of electrodermal activity.
- Detection of abnormal physiological reactions.
- Analysis of physiological stress levels.

#### V.3.2.10 Function getGSRValue()

- **Function Role**

This function returns the current GSR signal value.

- **Operating Principle**

It simply returns the latest measured analog value.

- **Role in the System**

It provides the data used in the seizure detection algorithm.

#### V.3.2.11 Function detectCrisis()

- **Function Role**

The **detectCrisis()** function constitutes the main epileptic seizure detection algorithm.

- **Operating Principle**

This function simultaneously analyzes:

- Heart rate.
- GSR data.
- Body movements.

Each parameter is compared with a predefined threshold:

- High heart rate.
- High skin conductivity.
- Significant abnormal movement.

A confidence score is then calculated according to the detected conditions.

When the score exceeds a certain threshold, the system considers that a seizure has been detected.

- **Role in the System**

This function represents the core of the intelligent system. It enables:

- Automatic seizure detection.
- Reduction of false alerts.

- Real-time decision making.

#### V.3.2.12 Function buildEmergencyMessage()

- **Function Role**

  This function constructs the emergency SMS message.

- **Operating Principle**

  It assembles the different physiological information:

  - Heart rate.
  - GSR value.
  - Movement intensity.
  - Detection confidence level.

- **Role in the System**

  This function enables the transmission of useful medical information during alert notification.

#### V.3.2.13 Function startTestMode()

- **Function Role**

  This function activates the system test mode.

- **Operating Principle**

  It initializes the variables required for epileptic seizure simulation.

- **Role in the System**

  It facilitates:

  - Experimental testing.
  - System validation.
  - Detection performance evaluation.

#### V.3.2.14 Function runTestSimulation()

- **Function Role**

  This function artificially simulates epileptic seizure conditions.

- **Operating Principle**

  It generates:

  - Elevated heart rate.
  - High GSR activity.
  - Significant body movements.

  These simulated data are then transmitted to the detection algorithm.

- **Role in the System**

  This function enables:

  - Testing system behavior.

Verifying alert triggering

- Evaluating algorithm stability.

#### V.3.2.15 Function printSensorStatus()

- **Function Role**

This function displays the status of the different sensors.

- **Operating Principle**

It verifies whether each module is correctly connected and operational.

- **Role in the System**

It facilitates:

- Hardware diagnostics, Maintenance.

Monitoring of system operation.

## V.4 Experimental Methodology

The experimental tests were conducted (using previous described functions) in order to:

- Verify the proper operation of the prototype.
- Evaluate sensor accuracy.
- Test GSM communication stability.
- Validate the seizure detection algorithm.
- Measure system response time.

### V.4.1 Testing Conditions

The experimental evaluation was conducted under controlled laboratory conditions to verify the reliability of the developed prototype. Different physiological situations were simulated, including normal conditions and seizure-like events. All sensors were calibrated before testing, and multiple experiments were performed to ensure repeatability and consistency of the obtained results.

### V.4.2 Functional Tests

Functional tests were performed to verify the correct operation of each hardware and software component. Individual tests evaluated sensor initialization, physiological data acquisition, signal processing, seizure detection, GSM communication, and emergency SMS transmission. Additional integration tests confirmed the correct interaction between all modules during continuous operation.

#### V.4.2.1 MPU9250 Sensor Tests

The MPU9250 sensor was tested to detect sudden movements and abnormal vibrations simulating an epileptic seizure.

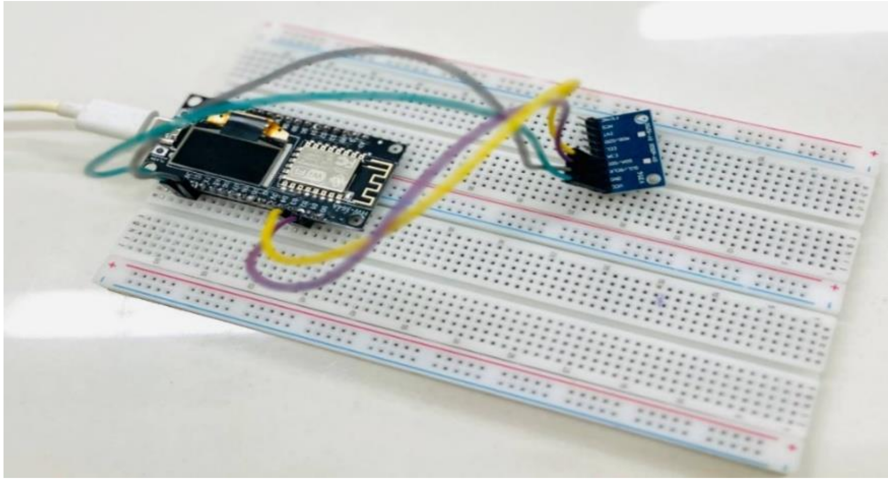

***Figure V. 3: Experimental setup for MPU9250 motion sensor testing during seizure movement simulation***

The obtained results show that

- The sensor correctly detects significant accelerations.
- The gyroscopic data help identify repetitive movements.
- The system reacts rapidly to sudden position changes.

The collected data were used to establish convulsion detection thresholds.

### V.4.2.2 MAX30102 Sensor Tests

The MAX30102 sensor was used to measure heart rate in real time.

The tests verified:

- Stability of heart rate measurements.
- Sensor sensitivity to physiological variations.
- The system's ability to detect abnormal increases in heart rhythm.

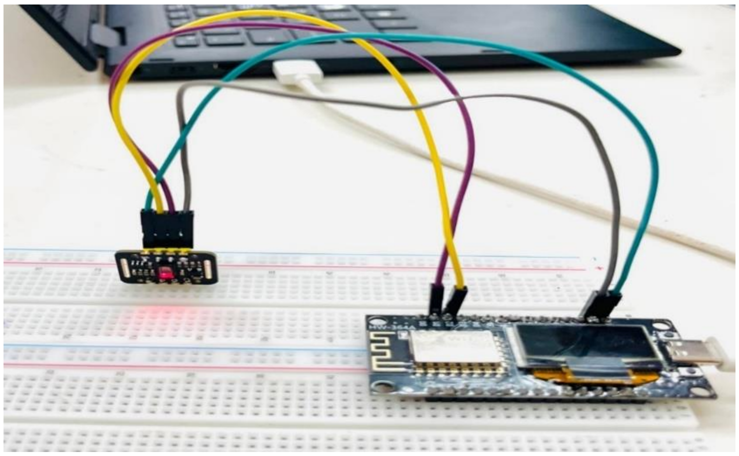

***Figure V. 4: Experimental setup for MAX30102 heart rate sensor validation***

The obtained values were consistent with normal physiological measurements.

#### V.4.2.3 GSR Sensor Tests

The CJMCU-6701 sensor was tested to evaluate variations in skin conductivity.The experiments demonstrated that:

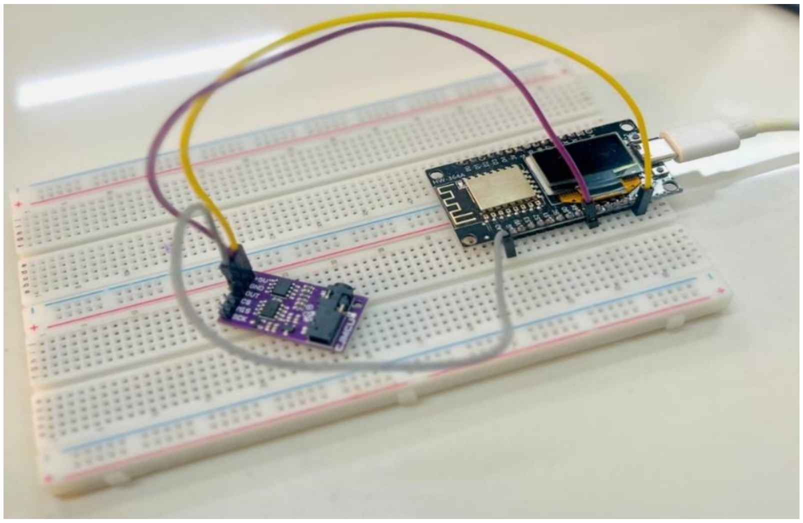

***Figure V. 5: Experimental setup for GSR sensor testing and electrodermal signal acquisition***

- GSR signal variations increase during simulated stress situations.
- The sensor provides usable analog data.
- Electrodermal fluctuations can be used as an additional physiological indicator.

#### V.4.2.4 SIM900 GSM Module Tests

The SIM900 module was tested to ensure SMS alert transmission.

The performed tests confirmed:

- Proper serial communication with the ESP8266.
- Correct transmission of AT commands.
- Rapid transmission of emergency messages.

The average SMS transmission time was a few seconds after anomaly detection.

#### V.4.2.5 Power Consumption Tests

Power consumption tests were conducted to evaluate the energy efficiency of the prototype. The current consumption of each hardware component was measured during normal operation and SMS transmission. The obtained results confirmed that the system consumes relatively low power, making it suitable for wearable healthcare applications requiring continuous monitoring.

## V.5 Experimental results

### V.5.1 Physiological Measurement Results

The measurements obtained from the different sensors demonstrated:

- Stable data acquisition.
- Good synchronization between modules.
- Satisfactory accuracy for medical monitoring applications.

The heart rate sensor made it possible to detect significant heart rhythm variations, while the GSR sensor provided additional indications about the patient's physiological condition.

### V.5.2 Seizure Detection Results

The experiments demonstrated that the combined use of sensors significantly improves detection reliability.

The system is capable of:

- Detecting convulsive movements.
- Identifying abnormal physiological changes.
- Reducing false detections through multi-sensor analysis.

### V.5.3 Communication Results

The GSM communication tests demonstrated:

- Reliable SMS alert transmission.
- Good communication stability.
- Low latency between detection and alert transmission.

### V.5.4 Energy Consumption

The system exhibits relatively low power consumption thanks to the use of the ESP8266 and low-power components.

This characteristic makes the device suitable for portable applications and continuous monitoring systems.

## V.6 Performance Evaluation

The performance of the proposed system was evaluated based on detection reliability, response time, communication efficiency, and energy consumption. Experimental results demonstrated that combining multiple physiological sensors significantly improves seizure detection compared to single-sensor systems. The ESP8266 provided fast processing capabilities, while the SIM900 module ensured reliable emergency message delivery. Overall, the prototype exhibited stable operation, low latency, and satisfactory performance for real-time epileptic seizure monitoring.

## V.7 Discussion

The experimental results obtained during the implementation and testing phases confirm the feasibility and effectiveness of the proposed intelligent epileptic seizure detection system. The developed prototype successfully integrates multiple physiological sensors with an ESP8266 microcontroller to continuously monitor the patient's condition and detect seizure-related abnormalities in real time. Throughout the experiments, the system demonstrated stable operation and reliable communication between the different hardware modules, validating the overall architecture of the proposed solution.

One of the main strengths of the proposed system is the use of multiple physiological indicators instead of relying on a single sensor. The combination of body movement information obtained from the MPU9250 sensor, heart rate measurements acquired through the MAX30102 sensor, and galvanic skin response provided by the CJMCU-6701 sensor significantly improves the reliability of seizure detection. This multi-sensor approach reduces the probability of false alarms because an alert is generated only when several physiological parameters simultaneously indicate abnormal behavior. Consequently, the proposed system provides a more robust monitoring strategy than conventional single-sensor solutions.

The ESP8266 NodeMCU proved to be an appropriate platform for embedded healthcare applications. Its processing capability was sufficient to perform real-time acquisition, signal processing, seizure detection, and communication tasks without noticeable delay. Moreover, its integrated Wi-Fi capability and low cost make it particularly attractive for Internet of Things (IoT) medical applications, where affordability and connectivity are important design requirements.

The communication subsystem based on the SIM900 GSM module also demonstrated satisfactory performance during the experiments. Emergency SMS messages were transmitted within a few seconds after seizure detection, ensuring rapid notification of caregivers or family members. Such rapid communication can significantly reduce response time during emergency situations and may contribute to improving patient safety, especially when seizures occur while the patient is alone.

From an energy perspective, the prototype exhibited relatively low power consumption due to the use of low-power sensors and the ESP8266 microcontroller. This characteristic makes the device suitable for portable and wearable healthcare applications requiring continuous monitoring over extended periods. Nevertheless, the GSM module remains the component with the highest power consumption, particularly during SMS transmission, suggesting that future optimization of power management could further increase battery autonomy.

Despite these encouraging results, several limitations were identified during the experimental evaluation. First, sudden movements unrelated to epileptic seizures may occasionally produce acceleration patterns similar to convulsive movements, which can affect detection accuracy.

Second, physiological parameters such as heart rate and skin conductivity naturally vary from one individual to another according to age, physical activity, emotional state, and medical condition. Therefore, fixed detection thresholds may not be equally effective for all patients. In addition, the performance of the GSM communication module depends on the availability and quality of the mobile network, which may delay alert transmission in areas with poor coverage. To overcome these limitations, future work should focus on improving the intelligence and adaptability of the system. Artificial intelligence and machine learning algorithms could replace fixed thresholds to provide personalized seizure detection models adapted to each patient. Cloud connectivity could also be integrated to enable continuous remote monitoring, secure storage of physiological data, and long-term medical analysis.

Furthermore, miniaturization of the electronic hardware and the design of a custom printed circuit board (PCB) would significantly improve the comfort, reliability, and commercial potential of the wearable device. Finally, a dedicated mobile application offering real-time visualization of physiological signals, GPS location, seizure history, and caregiver notifications would further enhance the usability of the proposed system.

Overall, the obtained results demonstrate that the proposed prototype represents a promising, low-cost, and portable solution for intelligent epileptic seizure detection. By combining wearable sensing technologies, embedded processing, and wireless communication, the developed system contributes to the advancement of connected healthcare and provides a solid foundation for future smart medical monitoring systems.

## V.8 Conclusion

This chapter presented the implementation and experimental validation of the proposed intelligent epileptic seizure detection system. The developed prototype successfully integrates multiple biomedical sensors with an ESP8266 microcontroller to monitor physiological signals and detect seizure-related abnormalities in real time.

Experimental evaluations confirmed the effectiveness of the hardware architecture, software implementation, and GSM communication system. The obtained results demonstrate that the proposed solution is reliable, portable, and suitable for continuous healthcare monitoring, providing a promising foundation for future intelligent medical IoT application.

# Chapter VI. Startup valorization

## VI.1 Introduction:

This chapter shifts the focus from the theoretical and technical aspects of the project toward its practical and economic dimensions, exploring the possibility of transforming the smart bracelet designed for early seizure detection into an innovative project that could be developed as a startup. The aims is to highlight the project's practical value and assess its potential for entering the market within the field of medical technology and wearable smart devices. It also covers a target market analysis, an examination of a suitable business model, an estimation of the prototype cost, and the key aspects related to product marketing and future development. In addition, it explores the possibility of incubating the project within university incubators and innovation centers.

## VI.2 Market Research:

The medical and healthcare field is considered one of the most promising areas for the application of Internet of Things (IoT) technology, as it enables medical applications to provide early intervention for users when needed. It also offers remote monitoring capabilities, which provide significant benefits for patients, especially those with chronic diseases, as their health condition can be continuously monitored by family members or healthcare providers even when they are living alone [30]. In recent years, there has been increasing interest in the design and development of wearable biosensing systems dedicated to health monitoring, both in academic research and in the industrial sector. These technologies are expected to bring a major transformation in the future of healthcare by enabling continuous and proactive monitoring of patients' conditions anytime and anywhere [31].

Wearable technology has gained significant popularity in recent years and has become widely used in the healthcare sector. These devices are useful for smart healthcare and real-time health monitoring systems, allowing the tracking and monitoring of various physiological parameters [32].

Artificial intelligence technologies integrated into wearable devices offer an innovative and promising solution, as they rely on the analysis of physiological signals and the use of machine learning algorithms to detect seizures and predict their occurrence [33].

Epilepsy is a neurological disorder characterized by the occurrence of sudden and unpredictable seizures without prior warning, and this unpredictability represents one of the major challenges associated with the disease. The ability to anticipate a seizure before it occurs and alert the patient in advance may allow timely medical intervention, thereby improving the overall health condition and enhancing quality of life [34].

Approximately one-third of epilepsy patients continue to experience seizures despite regular use of antiepileptic medications. Monitoring their clinical condition requires an accurate estimation of seizure frequency, which is why patients, family members, or caregivers typically rely on paper or digital logs to record seizure episodes. However, many patients fail to notice their seizures as they occur, forget them afterward, or simply neglect to record them for various reasons. As a result, self-reported seizure records remain an unreliable method, both in routine clinical practice and in clinical studies assessing the effectiveness of antiepileptic treatments. In this context, assistive technologies can help improve the reliability of seizure documentation and support more accurate adjustments to treatment plans [35].

For effective telemedicine practice, continuous remote monitoring of patients' physiological data is essential, and this can be achieved using wearable devices. This technology can be defined in the medical field as electronic devices that typically include sensors, microprocessors, and wireless communication systems, aimed at recording medical information in real time. The popularity of these devices has increased in recent years due to technological advancements in sensor miniaturization and other electronic components. In addition, the increasingly widespread healthy lifestyle among people has contributed to the growing adoption of these devices for monitoring physiological parameters and improving physical fitness. Their use has also increased among the elderly, as they allow real-time monitoring of potential health issues such as falls or medical complications, enabling early and rapid medical intervention. Furthermore, these devices provide elderly users with greater confidence in performing daily activities independently and reassure their families during their absence. Overall, the use of wearable devices in telemedicine has experienced rapid growth in recent years, providing numerous benefits across the healthcare system [36].

Epilepsy is the fourth most common neurological disorder across all age groups, affecting approximately 65 million people worldwide. It has a significant impact not only on patients' quality of life but also on their professional careers and social interactions, while also placing a considerable burden on healthcare systems [37].

Globally, about 5 million new cases are recorded annually. In high-income countries, the incidence rate is approximately 49 cases per 100,000 people per year, whereas in low- and middle-income countries it rises significantly to about 139 cases per 100,000 people. This disparity is related to several factors, including the prevalence of infectious and endemic diseases such as malaria and neurocysticercosis, as well as higher rates of road traffic accidents, birth-related complications, and limited access to healthcare services and preventive care. It is also estimated that around 80% of people with epilepsy live in low- and middle-income countries.

Epilepsy represents a significant portion of the global health burden, accounting for more than 0.5% according to indicators based on years of life lost due to premature death or disability. Its impact is not limited to health aspects but also extends to economic and social dimensions, as families bear substantial financial costs related to treatment and healthcare, along with reduced productivity and loss of employment opportunities.

On the other hand, negative perceptions and social stigma associated with epilepsy are among the most difficult challenges faced by patients and may sometimes have an even greater impact than the seizures themselves. Many patients and their families experience exclusion or unfair treatment due to misconceptions that epilepsy is contagious, incurable, or associated with immoral behavior, which often leads to social isolation and reluctance to seek proper medical care. Individuals with epilepsy may face several limitations that affect their life paths, including reduced access to education, difficulties in obtaining a driving license, barriers to employment in certain professions, and limited access to health and life insurance services [38].

The field of smart wearable medical devices has experienced rapid development in recent years, driven by the growing need for solutions that enable continuous and effective remote monitoring of patients' health conditions. This trend is mainly due to the widespread increase in chronic diseases and the need for constant and accurate health supervision. Accordingly, this field is considered one of the most promising sectors, as it combines technological advancement with real medical needs, opening the door to the development of new and improved solutions. On the other hand, the current market includes a range of competing technological solutions based on smart devices for measuring and tracking physiological parameters. However, most of these solutions are not specifically designed for monitoring epilepsy, and many of them suffer either from high cost or from limitations in accuracy and continuity of data collection and analysis. This highlights a clear gap in the field and confirms the need to develop a dedicated device characterized by low cost, high reliability, and effective early seizure detection capability. In this context, the development of wearable systems dedicated to epilepsy monitoring using Internet of Things (IoT) and artificial intelligence technologies represents a real opportunity for innovation and improvement. These technologies contribute to enhancing the quality of medical monitoring and reducing the risks associated with sudden seizures. Moreover, the increasing level of health awareness among individuals, along with the widespread use of smartphones and connected technologies, significantly enhances the acceptance and adoption of such solutions in everyday life.

## VI.3 Business Model

The business model of this project is based on the development of a smart wearable device dedicated to monitoring patients with epilepsy. It is primarily targeted at individuals suffering from this condition, as well as their families and healthcare providers such as doctors, hospitals, and treatment centers. This model aims to provide a practical solution that enables continuous real-time monitoring of the patient's health status, with the ability to detect abnormal indicators that may precede a seizure, thereby sending immediate alerts to allow rapid intervention and reduce potential risks to the patient's life.

From a marketing perspective, the project is based on selling the device as a physical product (hardware) that can be purchased by users or healthcare institutions, either through direct sales or through different distribution channels such as pharmacies, online stores, or partnerships with healthcare organizations. This model allows access to different categories of users, both individuals and institutions, which increases the product's potential for market adoption.

In addition to the physical device, the system is supported by a dedicated mobile application directly connected to it. This application receives data from the sensors, analyzes it, and presents it in a simple and user-friendly way. It also allows the user or physician to monitor the patient's health status in real time, as well as access historical health records and track changes over time, enabling a better understanding of the patient's condition and more accurate medical decision-making.

Furthermore, this digital system provides additional features such as secure health data storage, periodic reporting on the patient's condition, and the possibility of analyzing certain physiological indicators using intelligent algorithms. This integration between the device and the application makes the solution more effective, as it does not only collect data but also analyzes and utilizes it to improve the quality of medical monitoring.

To ensure long-term sustainability of the project, a subscription model can also be adopted, allowing users to access advanced services such as AI-based analysis, early seizure prediction, and secure cloud-based health data storage. This model provides a continuous revenue stream instead of relying solely on device sales.

In a later stage, the project can be expanded through partnerships with hospitals and health insurance companies, aiming to integrate this solution into modern digital healthcare systems, which increases its practical value and enhances its chances of large-scale adoption. Thus, the business model combines the sale of a core product with the provision of intelligent digital services, giving the project strong scalability and long-term sustainability.

## VI.4 Prototype development cost

The economic study of the prototype is an essential step in evaluating the feasibility of the proposed system for practical implementation and industrial development. The success of smart systems does not rely only on technical performance, but also on low cost, ease of manufacturing, and potential for commercialization. With the rapid growth of the Internet of Things (IoT) and wearable devices, it has become necessary to develop smart healthcare solutions that combine efficiency with low cost.

This project aims to design a smart wearable bracelet for monitoring vital signs and early detection of epileptic seizures using biometric sensors and wireless communication technologies. The electronic components were carefully selected to be low-cost and widely available, which allowed the development of a functional prototype without requiring a large budget.

The cost analysis shows that this project is based on economical components, focusing on minimizing expenses while maintaining the essential functions of the system. This makes the prototype significantly low-cost compared to traditional medical devices that perform similar functions but are much more expensive.

The following table presents the electronic components used in building the prototype along with their estimated costs:

| Component | Quantity | Total Cost |
|---|---|---|
| **ESP8266** | 1 | 1500da |
| **SIM900** | 1 | 1200da |
| **MAX30102** | 1 | 585da |
| **GSR Sensor** | 1 | 350da |
| **MPU9250** | 1 | 600da |
| **PCB 7×9** | 1 | 300da |
| **Supports** | 2 | 150da |
| **900mAh Battery** | 3 | 1100da |

***Table 1: The table represents the prototype cost estimation***

- **Total System Cost:**

The total estimated cost of the prototype is approximately 9135 DA, which is considered very low compared to the functionalities provided by the system, such as vital sign monitoring, patient movement tracking, and emergency alert notifications. This confirms that the project is based on cost-effective solutions that enable the development of smart medical devices without requiring large financial resources.

Most of the components used in this project are low-cost and easily accessible, while a small portion of the cost is allocated to communication and power modules due to their essential role in system performance. Nevertheless, the overall cost remains low and affordable compared to similar medical systems.

In general, this prototype demonstrates strong economic potential, making it a promising candidate for future development into a low-cost smart medical product suitable for the healthcare and wearable technology market.

This economic aspect confirms that the selection of components was not random, but rather based on a careful balance between performance and cost. The system relies on widely available and affordable electronic modules while still maintaining the essential functionalities required for reliable operation. Therefore, this prototype demonstrates the feasibility of developing smart medical devices using limited resources, which is particularly important in environments where access to expensive medical technologies is limited.

It is also observed that most of the components used in this project are low-cost and easily accessible, such as biometric sensors and development boards (ESP8266), which significantly contributed to reducing the overall system cost. On the other hand, a relatively larger portion of the cost is concentrated in the communication and power modules due to their crucial role in ensuring system stability, real-time data transmission, and emergency alert functionality, which are essential features in smart healthcare systems.

Nevertheless, the total cost remains low and reasonable when compared to traditional medical systems or similar commercial devices that offer comparable functions at much higher prices. This further supports the idea that IoT-based and smart sensor technologies can provide efficient and affordable alternatives in the healthcare sector without compromising performance or monitoring accuracy.

Overall, this prototype demonstrates strong economic potential and a high degree of scalability. In the future, the design can be further improved by optimizing energy consumption, miniaturizing the system, and integrating components into a single unified circuit board, which would further reduce production costs. This economic advantage also opens the door for transforming the project into a low-cost smart medical product suitable for commercialization, or even developing it as a startup in the digital health field, especially given the growing global demand for wearable devices and intelligent healthcare monitoring solutions for chronic diseases.

## VI.5 Industrial Perspectives

The development of this project opens promising industrial perspectives in the field of smart medical devices and connected healthcare technologies. The main objective is to move from a functional prototype to a reliable industrial product that is certified and suitable for real clinical use.

In a first stage, the device can be improved to ensure greater robustness, higher miniaturization, and improved energy autonomy. The integration of optimized electronic components and high-precision medical sensors will increase system reliability and enable continuous long-term monitoring.

Furthermore, scaling up to mass production requires the adoption of standardized industrial manufacturing processes. This helps reduce production costs while maintaining high quality and safety standards. As a result, the device could be commercialized at an affordable price, especially for developing countries where access to specialized medical equipment remains limited. Another important perspective is the integration of advanced technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT). These technologies would enhance the system's performance by improving early seizure detection and enabling predictive analysis of biomedical data.

Finally, this project can evolve through collaboration with medical companies and research laboratories in order to obtain medical certification and validate the device through clinical trials. This step is essential to ensure the adoption of the product in hospitals and healthcare centers.

## VI.6 University startup incubator

The prospects of the university incubator for this project indicate a real opportunity to transform it from an academic research idea into a viable startup that can be implemented and developed, by benefiting from the support ecosystem provided by university-based business incubators. These incubators play an important role in supporting student innovators throughout the different stages, starting from idea formulation, through prototype development, and up to improvement and testing, by providing the necessary scientific, technical, and managerial guidance.

In this context, the wearable epilepsy monitoring device project can greatly benefit from this support, given its nature which combines both medical and technological aspects, requiring high precision in design, development, and testing. The university incubator also provides a stimulating working environment that enables interaction with professors, researchers, and experts in various fields such as electronics, artificial intelligence, and medicine. This contributes to improving the scientific and technical quality of the project and increases its chances of being developed according to professional standards closer to market requirements.

In addition, these structures provide access to available material and technical resources within the university, such as research laboratories, prototyping workshops, and testing equipment, which helps reduce costs and accelerate the transition from theoretical concept to practical implementation.

At a later stage, incubating this project can serve as a key step toward establishing a startup specialized in developing smart healthcare solutions based on the Internet of Things and artificial intelligence, with the possibility of gradual expansion into local, regional, and international markets. Furthermore, participation in incubation programs opens access to additional support such as seed funding, innovation competitions, and accelerator programs, which enhances the project's chances of success and long-term sustainability.

Thus, the university incubator does not represent merely a temporary support phase, but rather a fundamental pillar in the process of transforming the project into a real industrial and medical product with economic value and practical applicability. (See Figure VI.1)


***Figure VI. 1: The incubator of El Oued University***

# General Conclusion

This work is not merely an academic accomplishment , but rather the culmination of a comprehensive research journey rooted in a deeply held conviction: that when technology is genuinely directed toward service of humanity, it transforms into an unstoppable civilizational force. In a world where healthcare is no longer confined within hospital walls or restricted to scheduled clinic appointments, the door has been flung wide open to a new health paradigm one that accompanies the patient with every heartbeat, vigilantly monitors their condition at every moment, and anticipates critical decisions before the crisis ever strikes.

From this expansive horizon, this project was born, springing from a pressing medical challenge that touches the lives of millions: epilepsy patients who live each day on the edge of the unknown, held hostage by seizures that strike without warning and threaten their lives in the blink of an eye. Science had an obligation to respond, and this work answered with a solution that transcends mere diagnosis to deliver real protection, a smart bracelet that places upon the patient's wrist a guardian that never sleeps and never tires, continuously monitoring vital and motor indicators moment by moment, and instantly firing alerts the instant any anomaly is detected.

The work began by laying a solid theoretical foundation, delving into the full depths of epilepsy across all its medical and human dimensions, before immersing itself in the existing scientific literature to identify critical gaps and map the boundaries between what is currently possible and what is genuinely needed. Upon this firm foundation, the system's electronic architecture was meticulously constructed with precision and craftsmanship, while its programming algorithms were woven with intelligence and exactitude — ultimately yielding an integrated system that harmoniously unites speed, precision, and reliability into a single cohesive whole.

The experimental results came to silence all doubt and cement certainty; the prototype demonstrated remarkable efficiency in detecting the physiological and motor changes that herald seizures, dispatching instant alerts within fractions of a second. The experiments further revealed that the principle of multi-sensor fusion stands as the golden key to elevating system reliability and reducing false alarms to their absolute minimum; a defining distinction that sets this system fundamentally. and irrevocably apart from the inadequacy of traditional monitoring solutions. Ambition did not halt at the technical boundaries alone, but extended to economic viability with a sharp investment eye; this prototype was successfully realized on a relatively modest budget, making it resoundingly clear that innovation is not the exclusive privilege of the wealthy. Market analysis and the developed business model jointly demonstrated that this project carries within it the seeds of a genuine and promising startup in the digital health sector, built upon the triple pillars of innovation, sustainability, and social valu

Yet this achievement is not a final destination, it is a merely launchpad toward broader and deeper horizons. The prospective integrating artificial intelligence and machine learning will propel the system well beyond seizure detection toward something far greater and more transformative: the ability to predict seizures before they occur. Furthermore, connecting the system to smart applications and cloud platforms will transform accumulated data into precise and comprehensive health maps, granting physicians an unprecedented strategic vision for monitoring their patients with greater accuracy, continuity, and clinical insight.

The deepest truth this work embodies lies neither in the precision of its sensors nor in the efficiency of its algorithms, but in the human message it carries: that when technology pulses with the spirit of humanity, it transcends wires and electronic chips to become a shield that protect the vulnerable, and outstretched hands that reaches those whom time has left behind.

In this very meaning resides the true and enduring legacy of this project — not in what it has accomplished today, but in what it will inspire, ignite, and set in motion tomorrow.

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