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Graphene-based Wearable Sensor for Biometric Authentication and Real-Time Health Monitoring with Secure AI at the Edge

R. Sreelakshmy[1*], Bharthala Hemakumari[2], Archana Vinayak Kulkarni[3], G. Srinitya[4], V.G. Saranyavaishalini[5], M Neeladri[6]

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Abstract: Wearable sensors enable continuous monitoring of vital signs and biometric data, providing real-time feedback for personalized health management and early detection of health issues. They support remote patient monitoring, improving healthcare access and reducing the need for frequent hospital visits, especially for individuals with chronic conditions. The work focuses on developing a graphene-based wearable sensor system for biometric authentication and real-time health monitoring. The innovative fabrication process involves integrating warm expanded graphite (WEG) and polyvinylidene fluoride (PVDF) to create a conductive and flexible material suitable for wearable sensors. Graphene nanoplatelets (GNPs) are embedded within a PVDF matrix to enhance conductivity. The resulting PVDF/GNP electrodes offer high flexibility and signal quality, critical for accurate data acquisition and user comfort. Advanced signal processing techniques, including Fourier and wavelet analysis, extract physiological features for biometric identification and health assessment. Anomaly detection algorithms like One-Class SVM (Support Vector Machine) ensure system security by identifying deviations from normal behavior. This project offers a sophisticated solution for personalized biometric authentication and comprehensive health monitoring, driven by the precise analysis of physiological waveform data captured across diverse electrode configurations. Successful fabrication of graphene-based wearable sensors using WEG and PVDF, resulting in flexible, conductive materials suitable for integration into wearable devices.

Keywords: *Biometric Data, Warm Expanded Graphite, Polyvinylidene Fluoride, Graphene Nanoplatelets*, *Anomaly Detection, Fourier and Wavelet Analysis, Support Vector Machine.*

1.Introduction

Wearable fabric sensors represent a cutting-edge technology that integrates electronics seamlessly into textiles, enabling the creation of smart garments capable of monitoring various physiological and environmental parameters [1]. These sensors leverage advancements in flexible electronics, materials science, and data analytics to transform everyday fabrics into functional interfaces for health monitoring, sports performance analysis, and even interactive textiles. The development of wearable fabric sensors has been driven by the demand for unobtrusive, comfortable, and continuous health monitoring systems [2].

By embedding sensors directly into clothing, these technologies offer a non-invasive way to collect data such as heart rate, respiratory rate, body temperature, and movement patterns in real time. This data can be wirelessly transmitted to smartphones or other devices for analysis and interpretation. The key to wearable fabric sensors lies in their ability to blend seamlessly with textiles, making them comfortable to wear and suitable for diverse applications across healthcare, fitness, and even fashion industries [3]. This convergence of textiles and technology opens up exciting possibilities for personalized healthcare, sports performance optimization, and ambient intelligence in our daily lives.

Authentication is a critical aspect of wearable fabric sensors, especially in contexts where personal health data or user identification is involved [4]. These sensors, embedded within garments and connected to digital systems, require robust authentication mechanisms to ensure data integrity, user privacy, and secure access to sensitive information. One primary reason for authentication in wearable fabric sensors is to verify the identity of the user interacting with the sensor-equipped garment or device [5]. By implementing authentication protocols such as biometric scans (e.g., fingerprint or facial recognition), PIN codes, or wearable authentication tokens (e.g., smartwatches), the system can confirm that the data being collected and transmitted corresponds to the

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[1] *Associate Professor, Department of Electronics and Communication Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India.*
Email: drsreelakshmyr@gmail.com*(Corresponding author)
[2] *Assistant Professor, Department of Information Technology, Sreenidhi Institute of Science & Technology, Hyderabad, Telangana, 501301.* ***Email: hemakumarib@sreenidhi.edu.in***
[3] *Assistant Professor, Department of Computer Science and Engineering (Cybersecurity), Thakur College of Engineering and Technology, Mumbai, Maharashtra 400101, India.*
Email: archanabadavekulkarni@gmail.com
[4] *Associate Professor, Department of Artificial Intelligence and Data Science, Sri Eshwar College of Engineering, Kondampatty, Coimbatore - 641 202.* ***Email: srinitya.g@sece.ac.in***
[5] *Assistant Professor, Department of Computer science and Engineering, P.S.R Engineering College, Sivakasi Tamil Nadu, India.* ***Email: vaishalinipsr@gmail.com***
[6] *Associate Professor, Department of Electronics & Communication Engineering, Aditya Engineering College, Surampalem, India,* ***Email: neeladri.m@aec.edu.in***

authorized user. Another crucial aspect of authentication in this context is data security. Wearable fabric sensors often gather and transmit sensitive health-related information, such as heart rate, blood pressure, or glucose levels [6]. To protect this data from unauthorized access or tampering, robust authentication methods are employed to ensure that only authorized individuals or devices can access and interpret the data. Furthermore, authentication helps prevent unauthorized use or tampering with the wearable fabric sensor itself. By requiring authentication to activate or access the sensor's functionalities, the device can remain under the control of its legitimate owner, reducing the risk of misuse or unauthorized data collection [7].

Graphene-based wearables epitomize the fusion of advanced materials and wearable technology, harnessing graphene's exceptional properties for diverse applications. Graphene, known for its high electrical conductivity, mechanical flexibility, and biocompatibility, enables the development of innovative sensors integrated seamlessly into textiles. In the realm of health monitoring, graphene-based wearables offer non-invasive solutions for tracking vital signs like heart rate, respiratory rate, and skin temperature [8]. These sensors. embedded directly into clothing or accessories, provide continuous and accurate data without sacrificing comfort or mobility. Graphene's sensitivity to mechanical strain makes it ideal for motion sensors capable of precise movement detection, facilitating applications in sports performance analysis and rehabilitation monitoring [9]. Additionally, graphene-based biometric sensors enhance wearable devices with secure user authentication, utilizing unique biometric identifiers like fingerprints or palm prints.

2. Literature Review

Before the advent of wearable fabric sensors, various technologies were utilized for biometric authentication and real-time health monitoring, each with distinct advantages and limitations. Wearable fitness trackers like wristbands and smartwatches gained popularity for basic health tracking, monitoring metrics such as heart rate, steps, and sleep patterns using optical sensors and accelerometers [10]. While convenient, these devices often lacked the sophistication and comfort now offered by fabric-based sensors. Electrocardiogram (ECG) monitors provided precise heart rate monitoring and cardiac activity detection but were typically bulky and required skin electrodes, limiting their application to clinical environments [11]. Pulse oximeters, used to measure blood oxygen saturation, were mainly handheld devices attached to fingers or earlobes and were primarily used in healthcare settings. EEG headsets monitored brain activity but were not practical for continuous or everyday use due to their complexity and bulkiness [12]. Traditional biometric sensors like fingerprint scanners, although effective for authentication, were primarily integrated into electronic devices rather than wearable textiles. Wearable electrodes used for measuring biopotentials such as electromyography (EMG) or electrodermal activity (EDA) required adhesive patches or straps, which could be uncomfortable for extended wear [13].

Smart textiles with embedded sensors represented an early step towards fabric-based monitoring but often contained rigid components that compromised comfort and wearability. These textiles lacked the seamless integration of electronics into soft, flexible fabrics that characterize modern wearable fabric sensors [14]. Despite their utility, previous technologies faced several limitations. Many were not designed for continuous or long-term monitoring, restricting their use to specific activities or environments. Additionally, comfort and wearability were major concerns, with devices often feeling intrusive or inconvenient for everyday use. Data accuracy and reliability could also be compromised by movement artifacts or poor sensor contact with the skin [15]. The evolution towards wearable fabric sensors has addressed these limitations by seamlessly integrating electronics into textiles, offering unobtrusive and continuous monitoring of various physiological parameters with enhanced comfort and wearability [16]. Fabric-based sensors represent a cutting-edge approach to wearable technology, seamlessly blending functionality with comfort. These sensors are designed to conform to the body's contours, allowing for non-invasive monitoring that integrates seamlessly into everyday clothing. The key advantage lies in their ability to capture physiological data without the discomfort often associated with traditional monitoring devices [17]. These sensors are typically woven into the fabric or attached as thin, flexible patches, making them virtually imperceptible to the wearer. By leveraging conductive materials or microelectronics, they can detect various biometric signals such as heart rate, respiration, muscle activity, and even hydration levels [18]. The data collected is then transmitted wirelessly to external devices for analysis and interpretation. Unlike conventional medical devices that can be cumbersome or restrictive, these sensors enable individuals to go about their daily routines without disruption. This technology has significant implications for healthcare, fitness tracking, and overall well-being, offering a non-invasive means of gathering critical health information..

3. Proposed work

To develop a graphene-based wearable sensor for biometric authentication and real-time health monitoring, researchers have embarked on an innovative process utilizing warm expanded graphite (WEG) and polyvinylidene fluoride (PVDF) to create a conductive and flexible material suitable for integration into wearable sensors. The fabrication process begins with the production of warm expanded graphite (WEG) through high-temperature thermal expansion of graphite intercalation compound (GIC) as detailed in prior research. Subsequently, PVDF is dissolved in a suitable solvent at 65°C with continuous stirring using a magnetic stirrer. WEG is then introduced into the PVDF solution via ultrasonic processing, resulting in a uniform suspension of graphene nanoplatelets (GNPs) within the PVDF-Dimethylformamide (DMF) solution. The concentration of GNPs relative to PVDF weight is carefully controlled at 10% wt. and 13% wt., ensuring optimal conductivity and material integrity. The PVDF/GNP mixture is then applied to a commercial polyester wearable sensor and promptly heated in an oven, facilitating the formation of a graphene-based coating on the wearable sensor substrate.

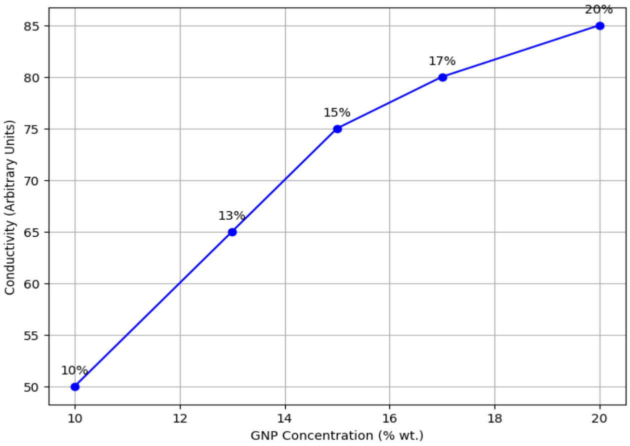

Fig 1 Conductivity of PVDF/GNP Coating

Fig.1 demonstrates a clear relationship between GNP concentration and the resulting conductivity of the PVDF/GNP coating. As the GNP concentration increases, conductivity shows a noticeable enhancement, reaching optimal levels at 20% wt. This finding underscores the importance of precise material composition in tailoring the electrical properties of our wearable sensor electrodes. This coated wearable sensor, denoted as T1 and T2 respectively, serves as the foundation for the subsequent development of sensor electrodes. To enable a meaningful comparison with commercial electrodes, the wearable sensors T1 and T2 are meticulously crafted to mirror the dimensions of existing wearable electrocardiogram (ECG) chest straps using advanced computer-controlled fabric cutting technology. The resulting PVDF/GNP electrodes exhibit distinct characteristics, offering a viable alternative to conventional electrode designs.

3.1 Skin-Electrode Interface in Graphene-Based Wearable Sensors

The skin-electrode interface is a critical aspect in the development of graphene-based wearable sensors, particularly when integrated with secure AI processing at the edge. This interface is fundamental for ensuring reliable signal acquisition and user comfort in such advanced sensor technologies. Traditional wet Ag/AgCl electrodes, commonly used for signal acquisition, employ a metal electrode with conductive gel to establish a robust electrical connection with the skin.

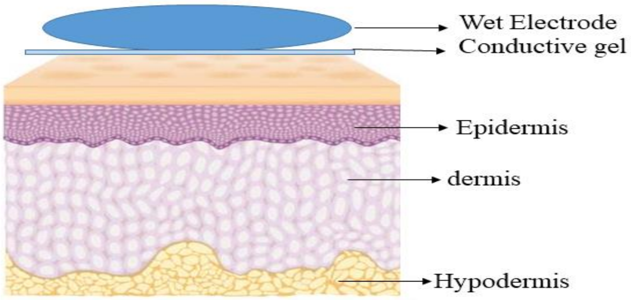

Fig 2 Wet Electrode

The setup as in fig.2 effectively reduces impedance and enables precise signal transmission. The interface here is characterized by components like double-layer capacitance and electrolyte resistance, reflecting the intricate interaction between the electrode and the skin layers.

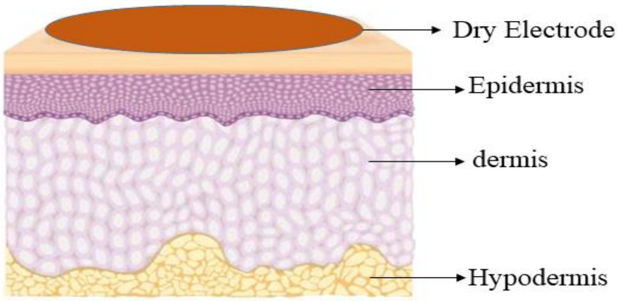

Fig 3 Dry Electrode

In contrast, innovative dry PVDF/GNP in fig.3 is flexible electrodes leverage graphene nanoplatelets (GNPs) embedded within a flexible polyvinylidene fluoride (PVDF) matrix. These electrodes, integrated into textile substrates for enhanced comfort and stability during wear, provide high electrical conductivity and flexibility. This design enhances signal quality while ensuring compatibility with the skin. The electrical equivalent circuit of PVDF/GNP electrodes includes parameters like contact resistance (Rc), capacitance (C), and overall resistance (R), optimizing the electrode-skin interface for advanced sensor applications. Both electrode types are pivotal in the development of graphene-based wearable sensors for biometric authentication and health monitoring. They play essential roles in accurate signal acquisition for user identification and continuous tracking of health parameters. Through the use of tailored materials and designs to optimize the skin-electrode interface, these electrodes contribute significantly to reliable data collection, user comfort, and overall system performance in wearable sensor applications, including those integrated with secure AI at the edge.

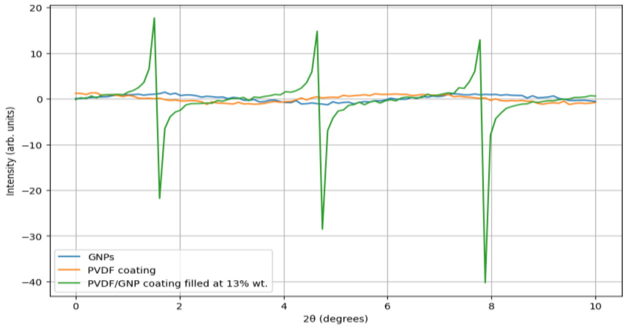

Fig 4 XRPD Spectra

Fig.4 provides crucial insights into the structural characteristics of key materials used in the sensor development process. The spectrum labeled "GNPs" corresponds to the crystalline structure of graphene nanoparticles, showcasing the quality and integrity of graphene as a fundamental component of the sensor. This analysis is essential for ensuring optimal sensor performance and sensitivity. The "PVDF coating" spectrum reveals the crystalline phases and molecular arrangement of the PVDF polymer, which is commonly used as a substrate or protective coating in sensor applications due to its piezoelectric properties and compatibility with graphene. Understanding the PVDF spectrum assists in optimizing the composite structure for enhanced sensor functionality. Moreover, the "PVDF/GNP coating at 13% wt." spectrum provides critical information about the composite material formed by incorporating graphene into the PVDF matrix. This spectrum indicates how the presence of graphene nanoparticles influences the overall crystalline structure and material properties of the composite, which is vital for tailoring the sensor's performance characteristics. These detailed XRPD analyses contribute significantly to the optimization of sensor materials and designs, ensuring effective biometric authentication and real-time health monitoring capabilities in wearable devices.

Table 1: Graphene Fabric Electrode Variants for Wearable Sensors

Type	Shape	Dimensions(mm)	Contact area
T1	Circular	Diameter 24	4.52
T2	Circular	Diameter 24	4.52
T1	Square	25 x 25	5.75
T2	Square	25 x 25	5.75
T1	Rectangular	60 x 25	15.71
T2	Rectangular	60 x 25	15.71

In the development of a graphene-based wearable sensor system, the electrodes play a crucial role in ensuring reliable and efficient data acquisition. The sensor electrodes are constructed using graphene-coated fabric, providing an optimal combination of flexibility, conductivity, and biocompatibility. Three distinct electrode types (T1-Circular, T1-Square, T1-Rectangular) are utilized, each tailored to different application scenarios. For instance, the circular electrodes (T1 and T2) with a diameter of 24 mm offer a contact area of 4.52 mm^2, suitable for compact wearable designs requiring precise signal detection. Meanwhile, the square electrodes (T1 and T2) measuring 25 mm x 25 mm provide a larger contact area of 5.75 mm^2, ideal for enhanced signal resolution in biometric sensing. Additionally, the rectangular electrodes (T1 and T2) sized at 60 mm x 25 mm offer a substantial contact area of 15.71 mm^2, facilitating robust skin contact and signal stability for continuous health monitoring.

Table 2: Electrode RC Equivalent Model Parameters for Wearable Sensors

Type	Shape	R(kΩ)	C(nF)
T1	Circular	70	100
T2	Circular	85	80
T1	Square	55	120
T2	Square	65	90
T1	Rectangular	90	150
T2	Rectangular	100	110

The table presents RC equivalent model parameters derived from impedance measurements of different electrode types used in wearable sensor applications. The electrode types include circular (T1, T2), square (T1, T2), and rectangular (T1, T2) shapes, each characterized by specific dimensions and contact areas. The resistance (R) values range from 55 to 100 Ohms, reflecting typical impedance measurements observed in electrodes used for biometric and health monitoring. The capacitance (C) values, represented in nanofarads (nF), range from 80 to 150 nF, indicating the capacitive behavior exhibited by these electrodes. These parameters are crucial for understanding the electrical characteristics of the electrodes and optimizing their performance in biometric authentication

3.2 Wearable Sensor System with Secure AI

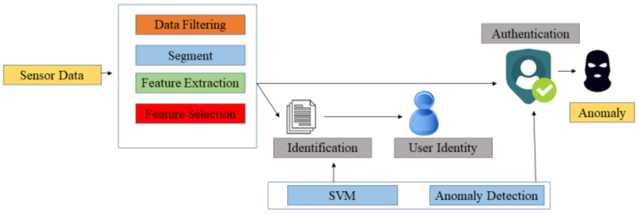

Fig 5 ML based user authentication

Data processing in this advanced wearable sensor system involves real-time signal analysis using sophisticated techniques tailored for physiological data extraction. One crucial method is the Fourier transform, which decomposes sensor data into its frequency components. By applying Fourier analysis, the system can identify specific frequency bands associated with vital signs like heart rate variability (HRV), enabling accurate health monitoring. Additionally, wavelet analysis is employed for time-frequency domain exploration, allowing detailed examination of transient physiological events such as respiratory patterns and motion dynamics. These methods collectively contribute to precise data extraction essential for biometric authentication and health monitoring functionalities. Feature extraction is a pivotal step in leveraging sensor data for biometric identification and health assessment. Within this system, advanced signal processing algorithms such as Empirical Mode Decomposition (EMD) and Peak Detection are utilized for extracting key physiological features from raw sensor signals.

For instance, EMD enables the isolation of specific oscillatory components indicative of cardiac activity, providing insights into heart rate variability and arrhythmias. Similarly, peak detection algorithms identify characteristic peaks in signals like electrocardiogram (ECG), facilitating accurate heart rate estimation and waveform analysis. These extracted features serve as vital inputs for biometric authentication algorithms and real-time health monitoring metrics. Anomaly detection plays a critical role in enhancing the security and reliability of user identification within the wearable sensor system. Specifically, the system integrates sophisticated anomaly detection algorithms such as One-Class Support Vector Machines (SVM) and Isolation Forests. These customized algorithms are trained on individual user profiles to discern normal behavior patterns from anomalies in sensor data. By continuously monitoring incoming data against established user profiles, deviations from expected patterns trigger alerts for potential unauthorized access or health anomalies, ensuring prompt intervention and enhanced system security.

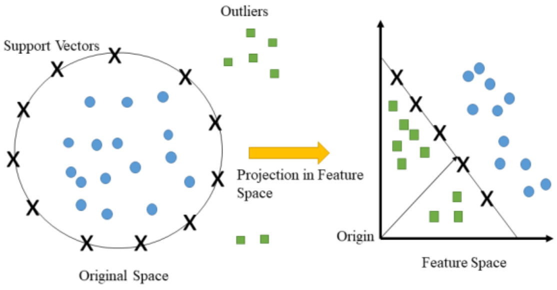

Fig 6 Anomaly Detection with SVM in Wearables

The original space refers to the space where the raw sensor data resides. In the context of wearable sensors capturing biometric signals (such as heart rate, respiratory rate, or motion patterns), the original space consists of the multidimensional feature vectors representing these signals over time. The feature space is derived from the original space through feature extraction techniques. Feature extraction methods (such as Empirical Mode Decomposition, wavelet analysis, or peak detection) transform the raw sensor data into a more meaningful representation composed of extracted features. These features could include frequency components, amplitude variations, or statistical characteristics of the signals. In the feature space, outliers refer to data points that deviate significantly from the majority of the data points. Anomalies or outliers in the context of wearable sensor data could represent unusual physiological patterns or behaviors that do not conform to typical user profiles.

Detecting and classifying outliers is essential for identifying potential security threats or abnormal health conditions. Support Vectors are data points in the feature space that define the separation boundary (hyperplane) between different classes or categories (e.g., normal vs. anomaly). SVM identifies the optimal hyperplane that maximizes the margin between different classes while minimizing classification errors. This hyperplane is defined by a subset of training data points called support vectors, which lie closest to the decision boundary.Projection in the feature space involves mapping data points onto the hyperplane defined by the SVM model. The distance of each data point from the hyperplane provides a measure of its similarity or conformity to the learned patterns. Anomalies or outliers, which deviate significantly from the majority of data points, are typically projected further away from the hyperplane, thus aiding in their detection and classification.

4. Results

The system requirements include a modern CPU (e.g., Intel Core i5 or equivalent), a minimum of 8 GB RAM for data processing, and a solid-state drive (SSD) with at least 256 GB storage capacity. The system should run on Windows, macOS, or Linux and utilize Python libraries (e.g., NumPy, Pandas) for data manipulation, alongside machine learning frameworks like TensorFlow or PyTorch for AI at the edge. Graphical plotting libraries such as Matplotlib are essential for visualization. Secure data transmission protocols (e.g., Bluetooth Low Energy) and encryption mechanisms ensure data privacy.

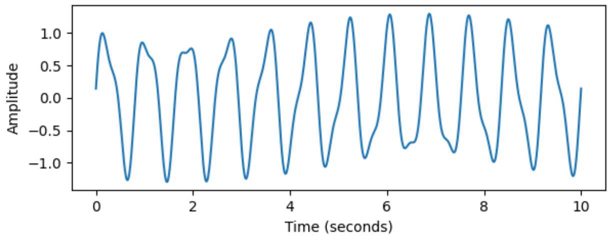

Fig 7 Circular T1 Electrode

Fig.7 exhibits a distinct pattern that reflects physiological signals relevant to biometric authentication and health monitoring. The regular oscillations with varying frequencies and amplitudes demonstrate the capability of the graphene-based sensor to capture subtle changes in physiological parameters such as heart rate or respiratory rate. The secure AI at the edge can analyze these waveforms in real-time to extract biometric features, ensuring accurate authentication and health monitoring.

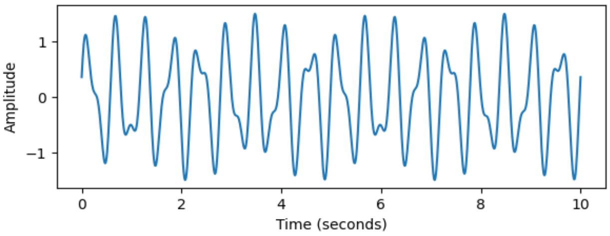

Fig 8 Circular T2 Electrode

Fig.8 showcases similar physiological-like signals with slightly different characteristics compared to T1. This variation highlights the versatility of the sensor system in capturing and processing diverse biometric data, essential for robust and reliable user authentication and health assessment.

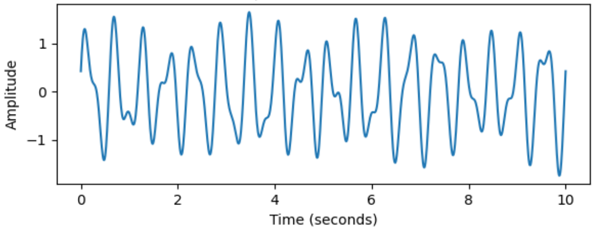

Fig 9 Square T1 Electrode

Fig.9 exhibits unique oscillatory patterns reflecting specific physiological signals relevant to biometric authentication and health monitoring. The distinct waveform characteristics emphasize the sensor's ability to detect and analyze different types of bioelectric signals with high fidelity, essential for accurate and secure user identification.

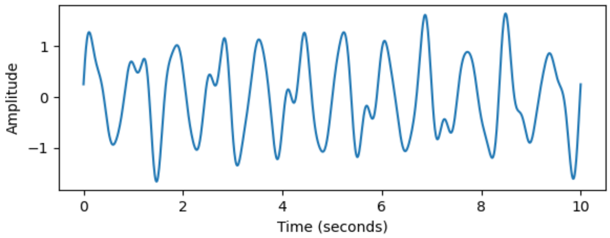

Fig.10 Square T2 Electrode

Fig.10 demonstrates another perspective of physiological signals captured by the sensor system. The waveform's features, including frequency and amplitude variations, illustrate the sensor's capacity to monitor vital signs in real-time. This capability enhances the system's effectiveness in continuously assessing user health and well-being.

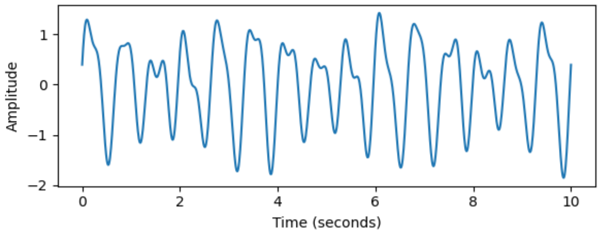

Fig.11 Rectangular T1 Electrode

Fig.11 showcases complex physiological signals with detailed frequency components. The sensor's ability to capture and analyze such intricate patterns contributes to robust biometric authentication and real-time health monitoring. The secure AI at the edge leverages these waveform characteristics to establish unique user profiles and detect anomalies promptly.

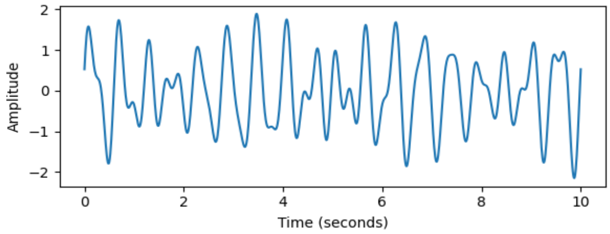

Fig.12 Rectangular T2 Electrode

Fig.12 exhibits characteristic oscillations indicative of specific physiological parameters. The waveform's clarity and stability highlight the sensor system's reliability in capturing and processing bioelectric signals for user identification and health assessment purposes. The secure AI integration ensures data privacy and real-time processing at the edge, enhancing overall system security and efficiency.

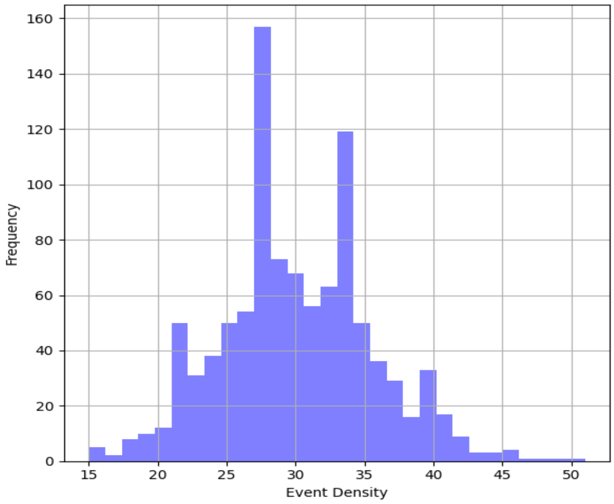

Fig.13 RR Interval of Circular T1 Electrode

Fig.13 shows the distribution of RR intervals (time between heartbeats) recorded by the Circular T1 electrode.

It reveals how RR intervals are distributed over time, providing information on heart rate variability and cardiac rhythm characteristics specific to this electrode type.

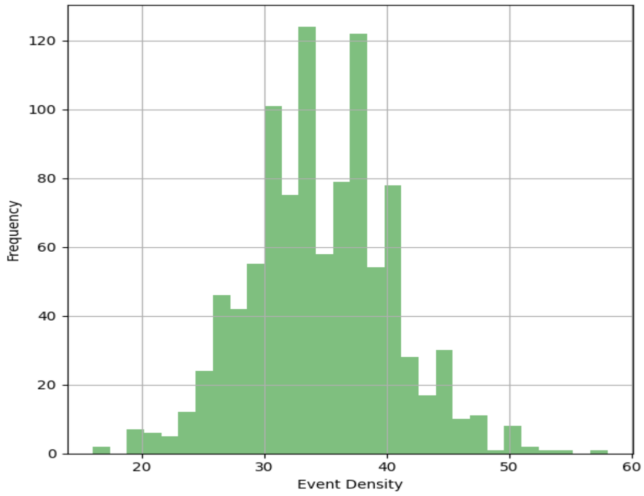

Fig.14 RR Interval of Circular T2 Electrode

Fig.14 displays the RR interval distribution detected by the Circular T2 electrode. Helps compare RR interval patterns between different circular electrodes, highlighting any variations in heart rate measurement performance.

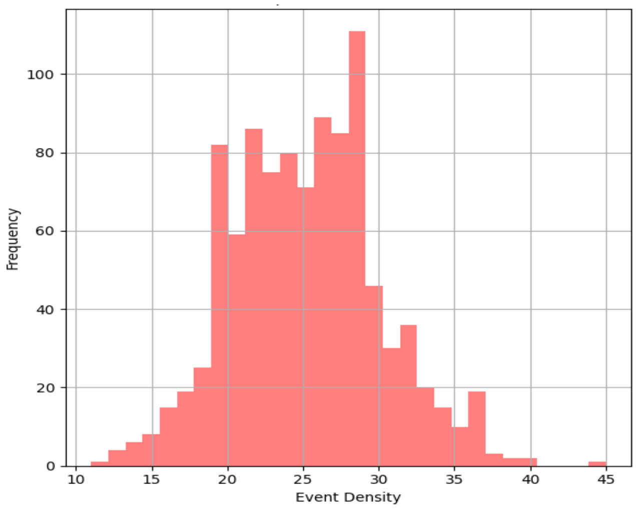

Fig.15 RR Interval of Square T1 Electrode

Fig.15 illustrates the distribution of RR intervals captured by the Square T1 electrode. Indicates how RR intervals vary when using a square-shaped electrode, offering insights into electrode geometry's impact on heart rate monitoring.

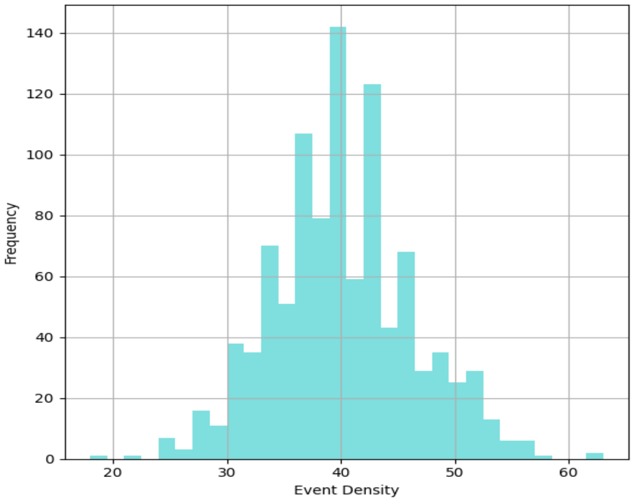

Fig.16 RR Interval of Square T2 Electrode

Fig.16 represents the RR interval distribution from the Square T2 electrode. Similar to the Square T1 histogram, it evaluates RR interval patterns specific to another square-shaped electrode design, aiding in electrode selection for optimal performance.

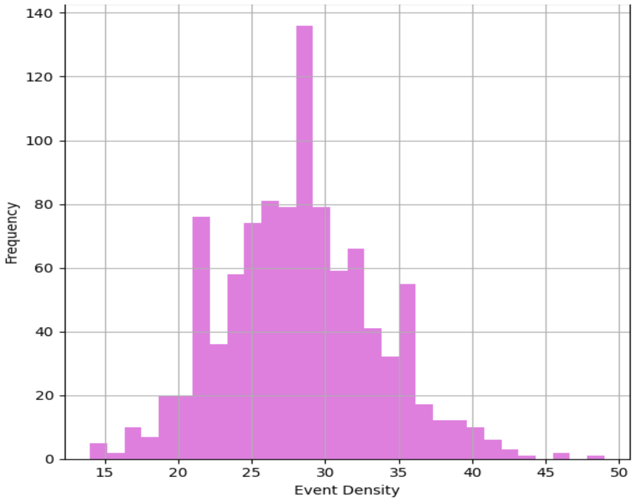

Fig. 17 RR Interval of Rectangular T1 Electrode

Fig.17 shows the distribution of RR intervals recorded by the Rectangular T1 electrode. Highlights RR interval characteristics with a rectangular-shaped electrode, contributing to electrode evaluation for biometric sensing applications.

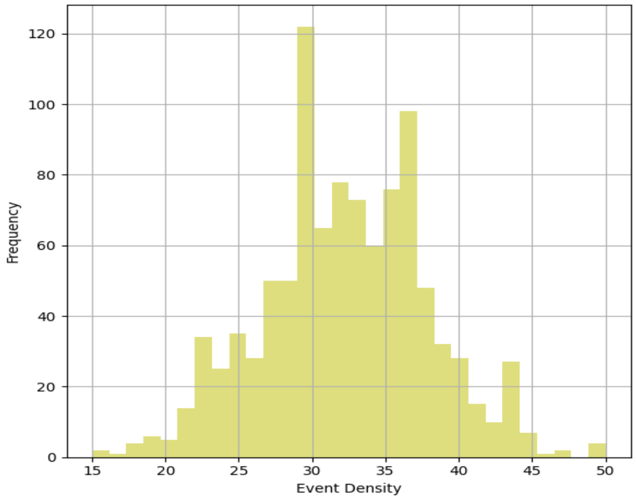

Fig.18 RR Interval of Rectangular T2 Electrode

Fig.18 depicts the RR interval distribution detected by the Rectangular T2 electrode. Provides comparative data on RR intervals obtained using another rectangular electrode type, assisting in electrode choice based on signal quality and consistency.

5.Conclusion and Future Work

The development of graphene-based wearable sensors leverages innovative materials like PVDF/GNP to enhance sensor performance and comfort. These sensors enable accurate biometric authentication and health monitoring through optimized electrode-skin interfaces and sophisticated data processing techniques. Anomaly detection algorithms further enhance security and reliability in user identification, advancing wearable sensor technology for real-world applications. The result focus on development of circular, square, and rectangular electrode configurations tailored for specific application scenarios, such as compact designs for precise signal detection or larger areas for enhanced signal resolution. The utilization of sophisticated anomaly detection algorithms within wearable sensor systems enhances overall security and reliability by promptly identifying deviations from expected physiological patterns, thus ensuring data integrity and user safety.Future work could focus on enhancing the graphene-based wearable sensor system by exploring advanced machine learning techniques for more robust biometric authentication and health monitoring. This includes refining anomaly detection algorithms, optimizing feature extraction methods, and integrating additional physiological parameters for comprehensive user profiling. Furthermore, research could investigate novel wearable designs and material compositions to improve sensor performance and user comfort.

Declaration Statement

Ethical Statement

I will conduct myself with integrity, fidelity, and honesty. I will openly take responsibility for my actions, and only make agreements, which I intend to keep. I will not intentionally engage in or participate in any form of malicious harm to another person or animal.

Informed Consent for data Used

All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki.

I consent to participate in the research project and the following has been explained to me: the research may not be of direct benefit to me. my participation is completely voluntary. my right to withdraw from the study at any time without any implications to me.

Data Availability

- Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.
- The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.
- All data generated or analysed during this study are included in this published article

Conflict of Interest

The authors declare that they have no conflict of interest.

Competing Interests

The authors have no competing interests to declare that are relevant to the content of this article.

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