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IoT Device for Long-Term ECG Monitoring in Collaborative Environment

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Abstract

Ubiquitous electrocardiography (ECG) sensing with wireless connectivity will be a solid alternative to conventional in-hospital healthcare surveillance. This paper presents a prototype for long-term ECG measurement equipment using an IoT environment over a collaborative diagnosis network. We propose a collaborative vision of working on two major paths for designing a device for long-term ECG surveillance: the design path and the decision path. The design path is made from the sensors design, the analog front-end design, the IoT equipment design, the gateway application, to the cloud application. The decision path is from the acquired ECG signal through the software decision at the IoT equipment level and software decision on the gateway level and cloud application level to the highest level represented by the human. We summarized the evolution and performance of Electric Conductive Textiles (ECT) as the primary material for long-term wearable ECG electrodes based on the skin-electrode contact impedance, motion artifacts, signal quality, and skin-electrode chemical interaction. The presented system topology was designed for lower power consumption in a collaborative diagnosis network environment.

Keywords: Electrocardiography (ECG) , Electrode , Collaborative , IoT , Power , Wearable.

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1. INTRODUCTION

The field of wearable electrocardiogram (ECG) technology has witnessed remarkable growth in recent years, driven by advancements in sensor technology, signal processing algorithms, and collaborative efforts across interdisciplinary domains. Wearable ECG devices have emerged as promising tools for continuous monitoring of cardiovascular health in both clinical and ambulatory settings, allowing for a more comprehensive assessment of cardiac health over extended periods. These devices offer the advantage of convenience, enabling users to track their heart activity seamlessly throughout the day. Wearable ECG devices have revolutionized long-term monitoring by enabling continuous data collection in collaborative efforts and have been essential in advancing the capabilities of these devices and translating them into clinical practice. Long-term monitoring of cardiac activity plays a crucial role in the early detection and management of cardiovascular diseases, offering insights into heart rhythm abnormalities, ischemic events, and overall cardiac function.

The collaborative efforts among researchers, engineers, clinicians, and industry stakeholders have been instrumental in driving the development and adoption of wearable ECG technology as a resilient solution for patients' health state.

This paper presents a proof of concept about the structure of a system for the long-term acquisition and surveillance of ECG using an IoT environment over a collaborative diagnosis network. We propose a collaborative vision of working on two major paths: the design and decision paths. IoT provides remote, unconstrained connectivity and services that leverage data and facilitate timely, meaningful, and critical decisions for a better lifestyle. The paper also highlights similar proposed systems and differences between them and ours.

2. STATE OF THE ART IN ECG COLLABORATIVE MONITORING

The paper in [1] presents a comprehensive study of ECG monitoring systems and conducts a systematic review of related literature in view of a deep understanding of the components, contexts, features, and challenges. A generic architectural model for these systems was proposed, and an extensive analysis of the value chain was conducted. The literature is reviewed and classified according to the experts' taxonomy, highlighting challenges and current trends. The paper identifies key challenges and stresses the importance of smart monitoring systems that incorporate technologies like deep learning, AI, Big Data, and IoT to create efficient, cost-effective, and fully connected monitoring solutions.

The authors in [2] addresses the limitations of conventional IoT applications, where data are typically transferred from sensors to the cloud via a gateway, which can be impractical for short-range protocols like Bluetooth Low Energy (BLE) due to the need for multiple gateways. The authors propose an edge-based hybrid network system architecture consisting of hybrid routers and an IoT gateway. These routers support both BLE and LoRa wireless protocols and include a solar energy harvester for extended lifetime. This system extends BLE coverage using LoRa technology and performs basic edge computing tasks. The IoT gateway supports multiple protocols (LoRa, BLE, XBee) and handles advanced edge computing tasks such as data filtering, storage, processing, user interface, and cloud connection. The system's capabilities are demonstrated through three case studies: a wearable safety monitoring sensor network, a healthcare monitoring application, and a smart hospital application. Experimental results show that edge processing minimizes delay to 11.5ms, and the BLE network coverage can be extended to 2.4 km using the hybrid LoRa network.

Advances in wireless technology have enabled the creation of networks of connected devices via the internet, as proposed by the authors of [3]. Their ECG monitoring system uses an AD8382 ECG sensor, Arduino Uno, ESP8266 Wi-Fi module, and the IoT Blynk application. This system allows doctors to remotely monitor patients through the IoT Blynk application on their smartphones, enabling real-time monitoring of ECG signals from anywhere, eliminating the need for hospital visits.

The paper in [4] introduces RAMi, a Fog/Cloud platform for monitoring elderly and convalescent patients by processing medical data in real-time. The proposed system detects anomalies and reduces false positives by considering individual patient characteristics. The adaptable architecture ensures sustainability by allowing alternative software components. Currently, it processes real-time data from sensors but does not handle historical data. Experiments confirm RAMi's effectiveness in processing data streams from ECG and other sensors.

The Internet of Medical Things (IoMT) is increasingly prevalent, employing smart medical devices and cloud computing to monitor patients in various settings. Traditionally, large amounts of health data are analyzed on centralized servers, leading to delays and privacy concerns. To address these issues, the authors of [5] proposes a Federated Learning (FL) based Anomaly Detection (AD) model that processes data locally on edge cloudlets, avoiding the need to share patient data. The hierarchical model allows data aggregation at multiple levels, enhancing collaboration without relying on a single server. A novel disease-based grouping mechanism is introduced to group AD models by specific diseases. Additionally, a Federated Time Distributed (FEDTIMEDIS) Long Short-Term Memory (LSTM) approach is developed for training the AD model. A Remote Patient Monitoring (RPM) use case and a proof-of-concept implementation using Digital Twin (DT) and edge cloudlets demonstrate the model's effectiveness.

In [6] the authors review the current state of IoT-based patient monitoring systems, specifically focusing on their use in healthcare for continuous tracking of vital signs like ECG, heart rate, blood pressure, and more. They discuss various IoT architectures, sensors, data transmission methods, and how these systems enable real-time monitoring, diagnostics, and remote care. The review emphasizes IoT's potential in transforming healthcare by reducing hospitalization needs, enabling remote treatment, and improving patient outcomes. Furthermore, the authors explore how IoT frameworks integrate with cloud and edge computing to handle vast data and support decision-making in collaborative healthcare environments. However there are some limitations and challenges regarding data privacy and security making patient data vulnerable to cyber-attacks during data transmission and storage. The IoT device is battery-powered, leading to limitations in continuous monitoring due to the need for frequent recharging or replacement. Also, continuous monitoring generates vast amounts of data, challenging systems to efficiently process and store it, especially for real-time analytics. Ensuring consistent performance in dynamic, real-world conditions is a limitation, as IoT sensors are often subject to noise, signal interference, and environmental factors.

Paper [7] presents a wearable device design for continuous cardiac monitoring using a system-on-chip architecture. The device captures and processes ECG signals in real-time, aiming to provide an efficient, compact, and low-power solution suitable for long-term use. It features integrated components for data acquisition, processing, and wireless transmission, supporting remote monitoring in healthcare settings. Although, despite improvements, battery life remains a challenge for long-term continuous monitoring. Furthermore, real-time data transmission could affect both maintaining reliable ECG signal quality in dynamic environments (during movement) and security breaches, posing risks to patient privacy.

In [8] it is proposing a wearable ECG system that uses IoT and cloud technologies to enable real-time cardiac monitoring and remote healthcare. The device captures ECG data and sends it via an IoT platform to a cloud server, where it can be stored, analyzed, and accessed by healthcare providers. This setup allows for continuous monitoring and early detection of cardiac events, with the potential to improve patient outcomes and healthcare efficiency. However, there are latency issues since real-time data transmission to the cloud may face delays, impacting timely intervention and power consumption remains a challenge, particularly for continuous ECG monitoring over extended periods. The experiments were carried out on healthy volunteers showing that data privacy and security remains a major challenge and an impediment in scalability of the solution.

A wearable ECG device integrated with machine learning algorithms to enhance real-time heart health monitoring is introducing in paper [9]. The system captures ECG signals, which are analyzed by machine learning models to detect arrhythmias and other cardiac anomalies accurately and efficiently. This approach aims to improve early detection of heart conditions, providing patients with continuous, proactive monitoring and potentially reducing the need for frequent in-person check-ups. However, the effectiveness of anomaly detection depends on the quality and diversity of training data, which limit accuracy. Besides the disadvantages in the previously mentioned solutions regarding processing power, in this case, it is limited because of machine learning algorithms are running on wearable devices with limited computational resources. In addition, sensitive health data processed by machine learning models needs robust encryption to prevent unauthorized access.

In [10] the authors review recent progress in wearable sensors designed for detecting cardiovascular diseases. They explore various sensor technologies—such as ECG, or PPG (photoplethysmography), and blood pressure sensors—and their integration into wearable devices to continuously monitor cardiovascular health. The paper highlights how advancements in sensor accuracy, miniaturization, and connectivity contribute to early detection and preventive care for patients with such diseases. Besides the limitations mentioned to other similar works, sensor accuracy and reliability, and interoperability between different wearable devices and health platforms remains challenges to be solved.

In [11] an IoT-based system designed for continuous maternal health monitoring is presented. The system uses wearable sensors to track vital maternal parameters—such as heart rate, blood pressure, and fetal activity—over extended periods. The collected data is transmitted to a central database where healthcare providers can monitor maternal health remotely, aiming to improve outcomes for expectant mothers, especially those in remote or high-risk scenarios. Limitations are related both to the necessity of stable connectivity for real-time data transmission, which can suffer in remote areas, and to the privacy and security of requested sensitive data from mothers and fetus.

These limitations suggest further research needed to enhance connectivity, power efficiency, data security, and signal accuracy in wearable IoT healthcare devices, enabling reliable, continuous monitoring across diverse health applications. Our article tries to answer some of these shortcomings.

3. IOT EQUIPMENT STRUCTURE AND CONCEPT

Our IoT system presents a patient-centric solution that generates real-time data and might extend patient monitoring and virtual care to long-term treatment improvements using predictive analytics. We have adopted a classic structure for the long-term ECG measurement equipment in an IoT environment over a collaborative diagnosis network, as depicted in FIGURE 1.

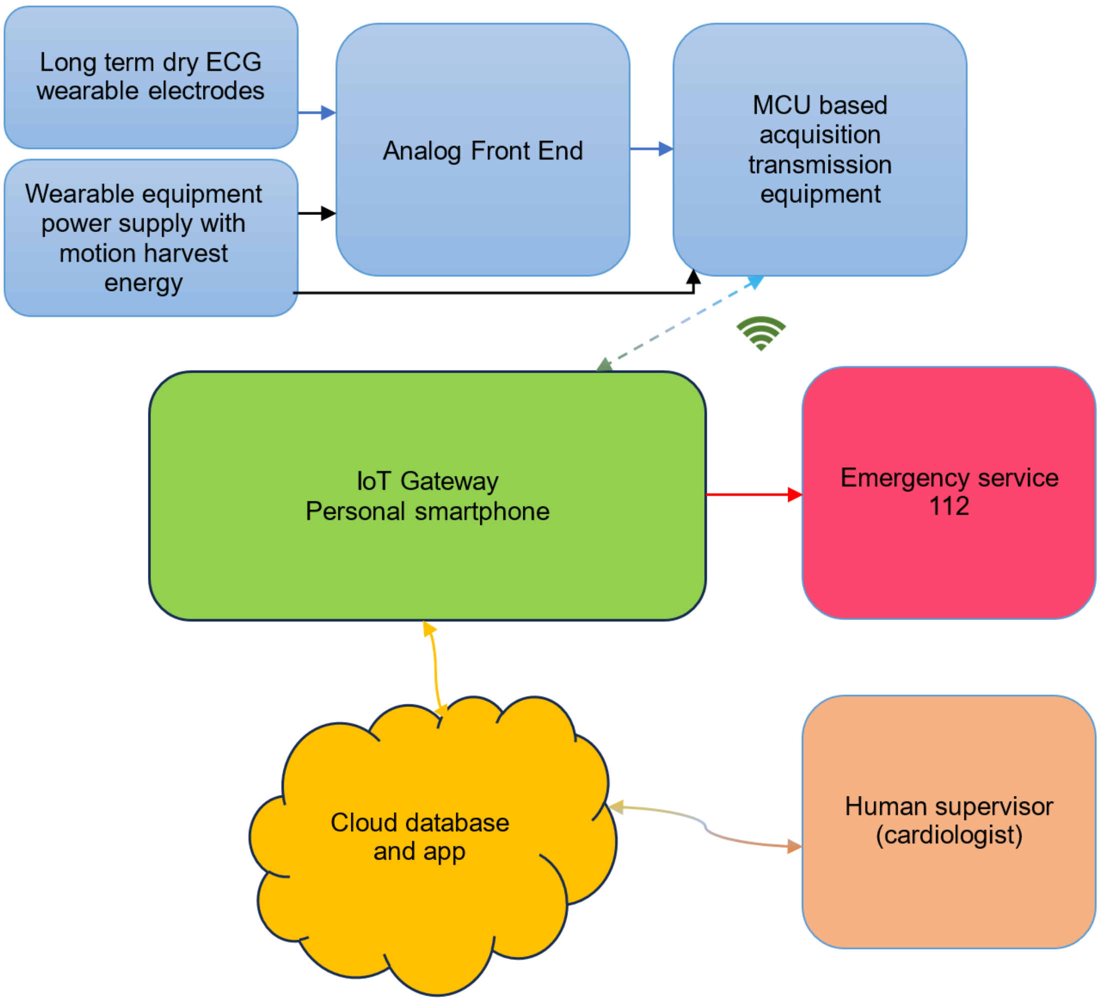

Figure 1: IoT device for long-term ECG structure.

The structure is organized into layers, from the hardware and software local layer to the highest collaborative layer between the cloud application and human supervisor. The first level can be local, on the analog front-end IC, as MAX3000x series, and the second level can also be local, at the MCU-based acquisition/transmission equipment. In our vision, local is the hardware-level wire connected to the electrodes applied to the human chest. Local analysis of the data from electrodes will have advantages, such as a very low data transmission rate between local hardware and the IoT gateway and extremely low power consumption. The major drawback is the limited computing power in these stages, and the analysis type will be reduced to heart rate anomalies.

The second level will be the IoT Gateway, typically a smartphone, with the advantage of being able to do heart rate analysis and ECG form analysis, and the disadvantage of the need for continuous transmission between local equipment and IoT gateway, involving a higher power consumption in the local equipment. Depending on the type of monitoring we want to perform, we can choose the equipment structure.

The alarms and warnings generated at the local level or in the IoT gateway must be sent to the cloud application and, in the case of unknown or uncategorized warnings and alarms, further communicated via the cloud app to the physician–human decision level. If the alarms categorized by the IoT gateway or the decision path described above are severe, the IoT gateway will perform an automatic call for the emergency number 112. There is also the possibility to query the first-level equipment at the request or at a set time for a complete monitoring signal. Each functional block in FIGURE 1, will be described in the following sections.

3.1 ECG Wearable Sensor

Advancements in sensor technology have been pivotal in enhancing the capabilities of wearable ECG devices. Collaborative research efforts have led to the development of miniaturized sensors capable of capturing high-fidelity ECG signals with minimal interference from motion artifacts and environmental noise and reducing power consumption. Interdisciplinary collaborations between materials scientists, engineers, and physiologists have led to the exploration of novel sensor materials, such as graphene and conductive textiles, for improved signal acquisition and wearer comfort. Furthermore, collaborative initiatives have explored novel sensor configurations, such as textile-based electrodes and flexible substrates, to improve comfort and wearability.

Traditional Ag/AgCl gel electrodes, while effective in many scenarios, are unsuitable for prolonged monitoring due to their inconvenience and discomfort. Thus, there has been a surge in efforts to develop flexible dry textile electrodes integrated into everyday garments.

An illustrative instance is exemplified by wires crafted from synthetic and metallic fibers developed by DuPont, designed to facilitate electricity conduction. Aracon fibers, comprising a Kevlar core coated with silver, nickel, copper, gold, or tin, capitalize on the core's exceptional mechanical prowess, which surpasses steel by a factor of five when considering the equivalent weight. These fibers amalgamate the core's strength with the metal's conductivity, resulting in a material stronger than steel, more pliable than copper, and lighter in weight while retaining excellent electrical conductivity. These yarns can be interwoven or knitted alongside cotton or polyester in e-textiles. In striving to integrate qualities such as flexibility, user comfort, and the potential for device miniaturization and stylish design, designers employ various solutions such as carbon nanotubes, graphene, polymers, elastomers, and dielectric composites, tailoring their selection to meet specific application requirements and responsiveness to diverse stimuli.

Electric Conductive Textiles (ECT) represent materials comprised of glass fibers coated with ultra-thin layers of carbon, enabling integration into woven or knitted fabrics alongside various types of yarns or glass fibers. The carbon coating confers electrical conductivity and resistance, with the latter capable of serving as a source of electric heating.

Figure 2: Textile electrode for ECG measurements (Source: [12]).

The study presented in [13] is a standardized testing procedure and framework for measuring skin-electrode impedance, which is essential for the development of novel dry textile electrodes. Various electrode materials were screen-printed on textile substrates, and their performance was evaluated through impedance measurements on an agar skin model using consistent frequency and pressure. Additionally, the electrodes were tested for ECG signal acquisition, comparing favorably with conventional gel electrodes.

The results indicate that dry textile electrodes exhibit similar impedance regardless of their structure (raised or flat), and variations in pressure have minimal impact on impedance. Interestingly, despite impedance variations, no significant effects on ECG signal performance metrics were observed. This suggests that impedance alone may not be the primary indicator of signal quality.

The review [14] presents the mechanisms by which textile electrodes function, whether through direct skin contact or non-contact capacitive coupling [15]. Finally, the review highlights current research aimed at developing textile-based ECG electrodes with enhanced comfort and signal quality, drawing from interdisciplinary fields including textile, material, medical, and electrical engineering, presenting a promising outlook for future advancements in wearable ECG monitoring technology.

3.2 Local Layer Hardware

The local layer consists of the “Long-term dry ECG electrodes” at level one, the “Analogue front end” at level two, and the “MCU-based acquisition transmission equipment” at level three, together with the local power supply. The development of reliable and unobtrusive sensors is fundamental to the success of long-term wearable ECG monitoring. Collaborative research initiatives have focused on miniaturizing sensors while maintaining high signal quality and reducing power consumption. Explore energy harvesting techniques such as solar power or motion harvesting to supplement or recharge the device’s battery. This can help extend the device’s operational lifespan without the need for frequent battery replacements. This is a wearable device built with regard to very low power consumption and long-time use. Advancements in sensor technology have been pivotal in enhancing the capabilities of wearable ECG devices [16, 17].

The long-term dry ECG electrodes are designed to be interchangeable and comfortable. Our concept for long-term ECG contradicts with energy consumption of the wearable device. We will, therefore, put the energy source in the wearable electrodes' unit, so the wearable electrodes will be changed together with the power supply because, in the time needed for change, the wearable electrodes will have no ECG signal.

For the analog front end, we considered the following specialized ICs: MAX 30001, MAX 30001G, MAX 30002, MAX 30004, MAX 30005/MAX86176, and MAX86178 from Analog Devices [18], and AFE49I30 and ADS1194 from Texas Instruments [19], due to their low power consumption and advanced capabilities. First, we will consider the input stage with a fully differential signal with CMRR greater than 100 dB at 50 Hz, an impedance greater than 1GΩ, a DC-differential input range greater than +/-1000mV, and ENOB greater than 15 bits.

Considering the values from the table below (TABLE 1) we will continue our development with MAX30001G and MAX30005. The big advantage of the MAX30005 is the more extensive input range and lower noise. The MAX86176/MAX30005 are designed to meet IEC 60601-2-47 ambulatory ECG systems monitoring compliance for even the most challenging dry electrode applications. The standard applications are Single-Lead Event Monitors for Atrial Fibrillation (A-Fib) and other Arrhythmia Detection, Single-Lead Wireless Patches for At-Home/In-Hospital Monitoring, Chest-Band Heart-Rate Monitors for Fitness Applications, Biometric Authentication and ECG-on-Demand Applications. For the MCU, we chose the STM32WB09TE Ultra-low-power, Arm Cortex-M0+ MCU 64 MHz with 512 Kbytes of Flash memory, Bluetooth LE 5.3 from ST Microelectronics Company [20].

Table 1: Analog Front End comparison.

AFE IC	ECG input CMRR	Impedance	ENOB	Noise uV	DC-diff range mV	AC dyn range mVpp	Additional functions	Consumption power uW
MAX 30001	100	1G	15.9	3.1	650	65	BioZ	85
MAX 30001G	100	1G	15.9	3.1	650	65	GSR, EDA	85
MAX 30003	100	500M	15.5	5	650	65		85
MAX 30004	100	500M	15.5	5	650	65		85
MAX 30005	110	1G	15.6	0.6	1300	90		NA
MAX 86176	110	1G	15.6	0.6	1300	90	PPG, Sync	NA
MAX 86178	110	1G	15.3	0.72	1000	200	PPG, BioZ, Sync	NA
ADS 1194	105	1G		12				3000

The STM32WB09TE is an ultra-low power programmable Bluetooth® Low Energy wireless SoC solution. It embeds STMicroelectronics' state-of-the-art 2.4 GHz RF radio peripherals, optimized for ultra-low-power consumption and excellent radio performance for unparalleled battery lifetime. It is compliant with Bluetooth® Low Energy SIG core specification version 5.3, addressing point-to-point connectivity and Bluetooth® Mesh networking, and allows large-scale device networks to be established reliably. The STM32WB09xE is also suitable for 2.4 GHz proprietary radio wireless communication to address ultra-low latency applications. The STM32WB09xE embeds an Arm® Cortex®-M0+ microprocessor that can operate up to 64 MHz and the radio core coprocessor

(DMA based) for Bluetooth® Low Energy timing critical operations [20]. For using most of these ultra-low power characteristics, we developed optimized firmware, with particular attention to code efficiency, minimizing wake-ups, and utilizing hardware peripherals effectively.

We developed a 4-layer PCB with the dimensions 27x14mm, with all the features described above. The PCB contains the analog front end MAX30005, the MCU STM32WB09KEV6TR, the connector for the dry sensor, the connector for the battery, the Antenna for Bluetooth communication, and all components required. The complete design of the PCB for this sensor is shown in FIGURE 3.

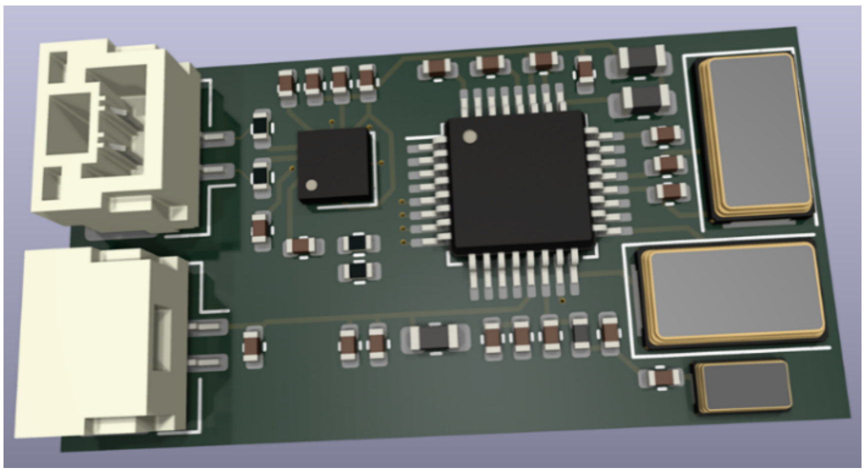

Figure 3: PCB for ECG sensor.

The dry ECG electrodes are connected to the MAX30005 ECG inputs via two resistors. These two resistors are useful when a defibrillator is used on the patient and limit the current on inputs due to the clamping diodes existing in the MAX 30005 input stage. We do not use the third electrode (RLD). The ECG analog signal is converted into a digital signal and transmitted to the STM MCU via an SPI interface. The STM32 MCU internal switching power supply unit generates the MAX power supply of 1.8V. The STM32 MCU performs several tasks to transmit a good-quality ECG signal to the gateway. The first is to acquire the ECG signal data from MAX30005 via the SPI interface, the second is to perform basic signal processing for detecting ECG signal anomalies. The third task is to compress the ECG signal, and the fourth is to transmit over the Bluetooth interface the compressed signal and warnings. The STM has a built-in Bluetooth front-end interface and transceivers. The schematics are not available due to the non-disclosure agreement (NDA) signed with Analog Devices.

Another issue is the power supply management to maximize the battery life. Even if it is a little noisier than an LDO, we chose to make the development with STM32WB09xE MCU to reduce the power loss, using an on-chip feature. In the future, we plan to test the possibility of using a specialized power controller, like BQ25504 from Texas Instruments [21]. The main advantage of this IC is the possibility to harvest the motion energy to supplement the wearable system battery. To further assist the system in the strict management of the energy budgets, the BQ25504 toggles the battery good flag to signal the STM32WB09xE microcontroller when the voltage on an energy storage battery or capacitor has dropped below a pre-set critical level. This warning should trigger the shedding of load currents to prevent the system from entering an under voltage condition. The OV, UV, and battery reasonable thresholds are programmed independently.

3.3 Algorithms for ECG Analysis

We also need to implement efficient signal processing algorithms to minimize computational load and, consequently, power consumption. In our development, these algorithms cannot be located at the analog front-end IC MAX30005 due to the need for an internal monitoring system. In this case, the algorithms reside in the STM32 MCU software. First, we perform a digital filter to reject motion-related noise and sensor noise. Then, we detect the QRS complex (the combination of three of the graphical deflections seen on a typical ECG) [22] and calculate the heart rate (HR). Then, we decide if the HR is normal and within the desired limits.

We continue analyzing the most critical data registered during cardiac monitorization (heart rhythm and conductance disturbances, ECG waves' morphology change). Data analysis will include:

- Heart rate values: minimum, maximum, median
- Heart rhythm changes: sinus tachycardia, atrial fibrillation, ventricular and supraventricular extrasystole, or life-threatening arrhythmias such as ventricular tachycardia or ventricular fibrillation
- Heart conduction disturbances: atrioventricular blocks type I, II, III, pauses
- ST segment changes: segment subdenivelation and elevation

Analysis algorithms will identify such events by analyzing each ECG wave to estimate the type of disturbance in rhythm, conduction, or morphology. This involves assessing the ST segment (the portion of the ECG that starts at the end of the S wave and ends at the beginning of the T wave) and following the ST-elevation myocardial infarction (STEMI - the most severe type of acute coronary syndrome) first criteria:

- New ST-segment elevation at the J point in 2 contiguous leads with the cut-off point as greater than 0.1 mV in all leads other than V2 or V3

The immediate importance of ECG monitoring is in identifying heart rhythms that cause syncope or cardiac arrest in high risk patients, especially in those patients in which the standard ECG Holter monitoring over 24 h did not identify any changes. The advantage of our monitoring system over the Holter monitorization is that it can be performed over more extended periods having unlimited data storage.

We will use a lossless compression algorithm to send an ECG signal to the IoT Gateway via Bluetooth low energy signal (BLE).

Another approach is to minimize the data processing at the MCU level and transmit all time the ECG signal with lossless compression. Then, the signal is processed at the IoT Gateway level, and estimate the results. In this stage of our pilot project, we are in discussion with the medical experts to analyze and decide how it is more convenient (in what format) to save data in the cloud so that it can be retrieved later and even subjected to data analysis algorithms based on Artificial Intelligence. Unlike some stand-alone commercial solutions, the IoT system proposed by us offers unlimited storage of all ECG and health data in a secure cloud platform.

4. THE HUMAN COLLABORATIVE NETWORK

In addition to the two collaborative networks paths, the design path and the decision path, the proposed solution involves the development of a collaborative healthcare network with hospitals, labs from academia, engineers, and medical institutions. In this collaborative ecosystem (FIGURE 4) the actors - authors of this article, cooperate in tasks, share knowledge, and combine different and complementary skills to anticipate changes in patient status, providing a resilient innovative IoT solution focused on the human person:

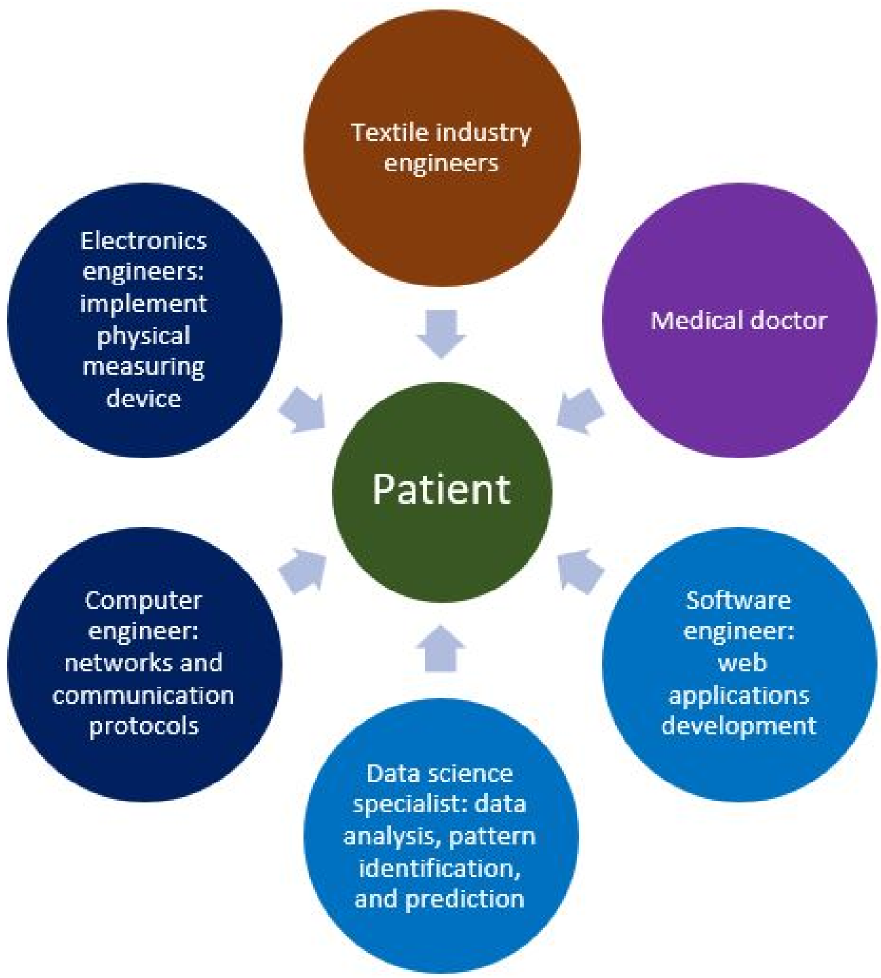

Figure 4: The human collaborative network for developing the healthcare IoT solution.

- Engineers from the field of the textile industry for the design and development of "wearable" systems or clothes that incorporate the created monitoring system.
- Electronics engineers to implement the physical measuring device - the sensing layer based on electrodes of the IoT system for data collection and measurement, the microcontroller, heart rate measurement/elevation metrics, etc.

- Computer engineer specialist in networks and communication protocols for implementing the communication layer of the IoT system, Bluetooth low energy communication (for patients), and Wi-Fi (for doctors).
- Software engineer expert in web applications development (Android, C#, ASP.NET, etc.) to implement the graphical user-friendly interface available online on any electronic medium (laptop, mobile phone, etc.) for real-time illustration of metrics and vital parameters of the patient, etc.
- Data science specialist in data analysis, pattern identification, and prediction, such that the app is able to predict the appearance of unpleasant events in a short time, critical conditions and automatically warn and alarm the cardiologist and the emergency system (“112”).
- The patient (end-user) is the primary beneficiary of the implemented monitoring system and will ultimately prolong his well-being, health, and life; the patient knows/visualizes his state of health permanently.
- The medical doctor (decision maker level) - who can be automatically notified of critical cases, spikes, etc., and can transmit a decision to the patient for immediate treatment or to initiate rescue of the patient. The medical doctor can benefit from the identification of different appearance patterns by analyzing several patients and the publication of scientific solutions. The medical system as a whole is improving by offering real-time services not only for diagnosis but also for treatment.

The decision path starts from the acquired ECG signal through the software decision at the IoT equipment level and software decision on the gateway level and cloud application level to the highest level represented by the human. This is very important especially in case when a quick decision should be taken. The data are collected in real time and stored in the cloud. If their values are under specified thresholds recommended by doctor then the human supervisor or emergency call should not be alert (used). The thresholds will be set by doctor because could depend from person to person. In the later stage, prediction algorithms implemented at software level in cloud could decide when to alarm the doctor.

The alarms and warnings generated at the local level or in the IoT gateway will be sent to the cloud application and, in the case of unknown or uncategorized warnings and alarms, further communicated via the cloud app to the physician–human decision level. If the alarms categorized by the IoT gateway or the decision path described above are severe, the IoT gateway will perform an automatic call for the emergency number 112. There is also the possibility to query the first-level equipment at the request or at a set time for a complete monitoring signal.

5. CONCLUSIONS AND FURTHER WORK

The IoT system developed represents a pilot project for ECG monitoring focusing on reduced power consumption in a collaborative diagnosis network environment and embedded in a wearable accessorize. Our system is a strong and cheap alternative to conventional in-hospital healthcare surveillance under conditions of a limited number of beds or doctors. The application also has educational value because it could be used by clinicians or professors in medicine to exemplify arrhythmia studies or other cardiovascular diseases, myocardial dysfunction, etc.

In further studies, we would like to implement a web application available both on the computer and on smartphones to receive real-time information in graphical form, beneficial for patients, and that can be sent to board-certified cardiologists for analysis. Using patients' historical data, our team will implement prediction algorithms (predictors by partial matching, artificial neural networks and time series) to determine in advance potential crises or heart attacks for preventive healthcare and support the detection of patients' unusual medical problems or a change in behavioral patterns.

5.1 Limitations

The system is in the concept development phase, and we still need to get a lot of data. Our interest, for the moment, is the functioning of the system as a whole; in addition, the data sets we have are confidential.

In addition, we only tested a few algorithms for ECG analysis to decide which are more appropriate, and neither did we set the frequency of data transmission to not send irrelevant data in the cloud.

6. ACKNOWLEDGEMENTS

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References

[1] Serhani MA, T. El Kassabi H, Ismail H, Nujum Navaz A. ECG Monitoring Systems: Review, Architecture, Processes, and Key Challenges. Sensors. 2020;20:1796.

[2] Wu F, Qiu C, Wu T, Yuce MR. Edge-Based Hybrid System Implementation for Long-Range Safety and Healthcare IoT Applications. IEEE Internet Things J. 2021;8:9970-9980.

[3] Hasan D, Ismaeel A. Designing ECG Monitoring Healthcare System Based on Internet of Things Blynk Application. Journal of applied science and technology trends (JASTT). 2020;1:106-111.

[4] Debauche O, Nkamla Penka JB, Mahmoudi S, Lessage X, Hani M, Manneback P, Lufuluabu UK, Bert N, Messaoudi D, Guttadauria A. RAMi: A New Real-Time Internet of Medical Things Architecture for Elderly Patient Monitoring. Information. 2022; 13(9):423

[5] Gupta D, Kayode O, Bhatt S, Gupta M, Tosun AS. Hierarchical Federated Learning Based Anomaly Detection Using Digital Twins for Smart Healthcare. In 2021 IEEE 7th international conference on collaboration and internet computing (CIC) .2021:16-25. IEEE.

[6] Mahmmod BM, Naser MA, Al-Sudani AH, Alsabah M, Mohammed HJ, et al. Patient Monitoring System Based on Internet of Things: A Review and Related Challenges with Open Research Issues.IEEE Access. 2024.

[7] Jain A, Singh M, Singh B. Real Time System on Chip Based Wearable Cardiac Activity Monitoring Sensor. Measurement: Sensors. 2022;24:100523.

[8] Yang Z, Zhou Q, Lei L, Zheng K, Xiang W. An IoT-Cloud Based Wearable ECG Monitoring System for Smart Healthcare. J. Med. Syst. 2016;40.

[9] Alimbayeva Z, Alimbayev C, Ozhikenov K, Bayanbay N, Ozhikenova A. Wearable ECG Device and Machine Learning for Heart Monitoring. Sensors. 2024;24:4201.

[10] Khan B, Riaz Z, Khoo BL. Advancements in Wearable Sensors for Cardiovascular Disease Detection for Health Monitoring. Mater. Sci. Eng. R Rep.2024;159:100804.

[11] Sarhaddi F, Azimi I, Labbaf S, Niela-Vilén H, Dutt N, et al. Long-Term IoT-Based Maternal Monitoring: System Design and Evaluation. Sensors. 2021;21:2281.

[12] https://www.nuubo.com/en-us/health-professionals/nuubo-system

[13] Alizadeh-Meghrazi M, Ying B, Schlums A, Lam E, Eskandarian L, et al. Evaluation of Dry Textile Electrodes for Long-Term Electrocardiographic Monitoring. Biomed. Eng. Online. 2021;20:1-20.

[14] Nigusse AB, Mengistie DA, Malengier B, Tseghai GB, Langenhove LV. Wearable Smart Textiles for Long-Term Electrocardiography Monitoring—a Review. Sensors. 2021;21:4174.

[15] https://www.amazon.co.uk/Weartech-T-Shirt-Intergrated-Cardiac-Sensors/dp/B00DM8A7EG?th=1

[16] Camós-Vidal R, Rosell-Ferrer J. Ultra-High Input Impedance Buffer for Dry or Capacitive Electrodes: Design and Characterization for Industry. IEEE access. 2023.

[17] Zompanti A, Sabatini A, Grasso S, Pennazza G, Ferri G, et al. Development and Test of a Portable ECG Device with Dry Capacitive Electrodes and Driven Right Leg Circuit. Sensors. 2021;21:2777.

[18] https://www.analog.com/en/products/max30005.html

[19] https://www.ti.com/product/ADS1194

[20] https://www.st.com/en/microcontrollers-microprocessors/stm32wb0-series/documentation.html

[21] https://www.ti.com/product/BQ25504

[22] Serhani MA, T. El Kassabi H, Ismail H, Nujum Navaz A. ECG Monitoring Systems: Review, Architecture, Processes, and Key Challenges. Sensors. 2020;20:1796.