

DESIGN OF A WI-FI-ENABLED ECG DEVICE FOR TELEMEDICINE AND AMBULATORY MONITORING IN A ROBOTIC PLATFORM

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Abstract: *This article presents a robotic platform integrated with a Wi-Fi-enabled ECG device designed for telemedicine and ambulatory monitoring. The advancement of portable and wearable ECG monitoring systems remains a key focus in the development of health-related technologies. An ECG device is a critical medical tool used to record the electrical activity of the heart over a specified period, playing a vital role in diagnosing heart diseases and monitoring cardiovascular health. Our objective is to develop a new generation of robotic tools that enhance healthcare and patient management. Specifically, we aim to design an innovative Wi-Fi-enabled ECG device for non-invasive heart rhythm monitoring, capable of receiving, storing, visualizing, and transmitting high-quality electrocardiographic signals remotely. This device enables comprehensive ECG analysis and continuous patient monitoring while seamlessly integrating with other diagnostic and therapeutic functions within the robotic platform's operational framework. A key feature of the proposed device is its ability to detect and promptly alert users to abnormal heart rhythms, making it highly effective for telemedicine and ambulatory care. One of its most notable innovations is the incorporation of the MAX30003 chipset, which facilitates real-time ECG monitoring in portable and wearable systems suitable for both remote medical consultations and personal health tracking. Looking ahead, the system is designed to evolve toward autonomous functionality. Unlike other similar devices, innovative solutions related to the construction and connections of the ECG with the Robotic System are presented here. The research team has extensive experience in surgical robotics, and this development builds upon previous work in the field.*

Key words: *Wireless ECG Device, Portable Monitoring Devices, Robotics, Surgical Robotics, Health Monitoring.*

1. INTRODUCTION

Healthcare systems are currently grappling with a range of emerging challenges. These include meeting the demands of an aging population, addressing patients' growing interest in actively monitoring their health, and ensuring access to appropriate medical services for those living in remote areas. Remote health monitoring presents a valuable solution, particularly for individuals who do not require constant medical supervision but could benefit from enhanced self-management support. This group includes people with diabetes, obesity, cardiovascular conditions, chronic obstructive pulmonary disease (COPD), hypertension, and the elderly. Developing cost-effective, user-friendly, and accessible healthcare technologies is therefore essential – not only to improve patient comfort and autonomy but also to reduce the frequency of outpatient visits. One promising example of such a solution is ECG monitoring.

An ECG device is a medical instrument designed to record the heart's electrical activity over a specific period. By capturing the heart's electrical signals, it delivers crucial insights into heart rate, rhythm, and overall cardiac function. This information is vital for diagnosing a wide range of heart conditions and plays a key role in monitoring cardiovascular health, including during surgical procedures.

Recording and interpreting an electrocardiogram (ECG) is a cornerstone of modern clinical practice and plays a crucial role in the diagnosis of cardiovascular diseases. Cardiologists analyze ECG waveforms—examining the presence or absence of specific waves and measuring intervals—to detect cardiac abnormalities, evaluate the effects of medications, and monitor the performance of implanted pacemakers. ECGs are also widely used in prehospital settings, such as by emergency medical personnel to assess a patient's condition on-site. In sports, ECG monitoring supports the evaluation of athletes' cardiac performance. Additionally, a range of signal processing algorithms has been developed to enable automated ECG monitoring for both patients and healthcare professionals, facilitating continuous assessment in clinical and non-clinical environments.

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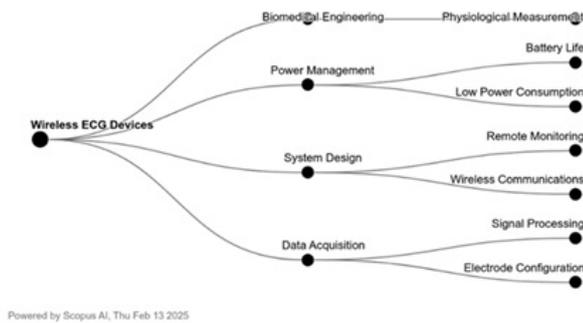


Fig. 1. Wireless ECG Devices and their branches.

Wireless ECG Devices include Biomedical Engineering, Power Management, System Design, and Data Acquisition. Figure 1 shows the main branches of Wireless ECG Devices.

Biomedical engineering (BME) is a dynamic and interdisciplinary field that combines engineering principles with medical and biological sciences to advance healthcare, both in diagnostics and therapy. Key applications of BME include the design and development of biocompatible prosthetics, medical diagnostic and therapeutic devices, clinical instrumentation, microimplants, and advanced imaging technologies such as MRI and ECG/EKG systems:

- Power Management – it is important to consider Low power consumption and Battery life;
- Wireless transmission technologies - Bluetooth, ZigBee, radio frequency identification (RFID) and Wi-Fi have been used for providing wireless communications in healthcare monitoring applications. Bluetooth transceivers surpass Wi-Fi radios in terms of power consumption, making Bluetooth-based wireless solutions more efficient in battery usage. They also provide advantages such as efficient and low-power data transmission;
- The system may include a local storage module to minimize power consumption by reducing the need for constant data transmission [1]. If the device is mobile, it should also include a battery power supply;
- System Design – Modern ECG monitoring devices have evolved significantly in recent years, and clinicians rely on technical innovations to improve their work. The presence of cables often hinders the free movement of the user, along with the routine operations of clinicians. Therefore, wireless ECG devices are preferred; that is, for the system design of such devices, remote control is of essential importance. In addition, the system design of electrocardiographic (ECG) devices is directed towards wearable and/or wireless systems, which are combined with modern computer technologies and artificial intelligence (AI), to provide good healthcare services. Since cardiovascular diseases are common, therefore monitoring of cardiac function is of paramount importance and application in a wide range of areas: System design related to remote monitoring solutions using sensor electrodes distributed on furniture in the residential environment try to reduce healthcare costs, with a key role played by wireless communication systems allowing data

transfer to the hospital/health server or, more generally, to a specific base station or a smartphone application;

- Data Acquisition - Integration of a microcontroller, which controls the initial acquisition and pre-processing of ECG data. This data is then transmitted via a wireless protocol (uMAC, ZigBee, Bluetooth, etc.) to a higher-level computer or mobile device for further analysis and display [1];
- Data Transmission: Recommended protocols (ZigBee, Bluetooth 5.0 BLE protocol stack uMAC, etc.) are used to provide the system with efficient and low-power data transmission, which is crucial for long periods of monitoring [1].

The device should include a display for data visualization and a printer.

1.1. Portable and wearable ECG monitoring systems

The development and innovation of portable and wearable ECG monitoring systems represent a rapidly growing area in the field of health technologies. These systems are designed to enable continuous, real-time monitoring of cardiac activity, playing a vital role in the early detection and timely treatment of heart diseases.

The integration of Internet of Things (IoT), artificial intelligence (AI), and advanced signal processing techniques has greatly enhanced the precision, reliability, and capabilities of these devices. As a result, they offer significant potential for identifying cardiac abnormalities at an early stage [2].

Moreover, wearable ECG devices equipped with sophisticated signal analysis can reduce the need for frequent hospital visits, offering heart patients greater convenience and improved quality of care.

Researchers are focusing on developing low-cost and affordable solutions for ECG monitoring and telemedicine. These innovations aim to make cardiac monitoring more widely available and easy, especially in remote or underserved areas. The use of low-power wireless technologies and integration with smartphones and other portable devices are key aspects of this trend.

The development of medical equipment, particularly ECG devices, must adhere to stringent safety and performance standards. These include not only core functional and safety requirements but also essential characteristics such as autonomy, efficiency, and reliability. To ensure compliance, specialized hardware design standards have been established and are widely implemented.

At the same time, users – especially developers and integrators – have the flexibility to configure the device interface based on specific application needs. This includes optimizing parameters such as the number of channels, noise levels, and power consumption to achieve the best balance between performance and resource efficiency for the intended use.

Our objective is to develop a new generation of robotic tools aimed at enhancing healthcare delivery and patient care. As part of this effort, we are focused on designing an innovative Wi-Fi-enabled ECG device for non-invasive heart rate monitoring. This device will be capable of remotely receiving, storing, visualizing, and transmitting high-quality electrocardiographic signals.

The structure of the paper is as follows: Section I Introduction, Section II Application of MAX30003 for ECG monitoring, Section IV Sensors and electrodes for data collection, Section IV Decisions and finally Section V is Conclusion.

2. APPLICATION OF MAX30003 FOR ECG MONITORING

The Analog Devices MAX30003 Biopotential Analog Front End (AFE) is a clinical-grade ECG component featuring a high-resolution data converter. It delivers excellent performance across clinical, educational, and fitness applications, while maintaining ultra-low power consumption – ideal for extending battery life in portable devices.

The MAX30003 supports a single biopotential channel for capturing ECG waveforms and detecting heart rate. It is specifically designed for ECG monitoring, making it an optimal choice for integration into portable and wearable health monitoring systems that require reliable, real-time cardiac signal acquisition.

The wireless ECG system, based on the MAX30003 chip, offers a highly portable, low-power, and accurate solution for continuous cardiac monitoring, making it suitable for a wide range of applications from telemedicine to sports. The integration of BLE (Bluetooth Low Energy) technology further improves its usability and efficiency [1, 3].

Key features and functionality are listed further:

- **Low Power Consumption:** The MAX30003 is designed to operate with minimal power consumption, making it ideal for portable and wearable devices.
- **High Accuracy:** The MAX30003 provides high accuracy in acquiring and processing ECG signals. With a root mean square error of up to 10% in the worst-case scenario (signal with power line and noise) and an average of 2.5% in the best-case scenario (no noise) [3].
- **Noise Management:** The device performs well in a variety of noise conditions, maintaining high detection rates for P, R, and S peaks and accurate segmentation for the QRS complex even in noisy environments [3].
- **Signal Quality:** The system demonstrates high signal quality with a 95% detection rate for P, R, and S peaks in noise-free conditions [4].
- **Portability:** The wireless nature of the system eliminates the need for cumbersome cables, allowing for greater mobility and comfort for the user [1].

System design and implementation are as follows:

- **Microcontroller Integration:** The MAX30003 is typically integrated with a microcontroller (MCU) that controls the initial acquisition and preprocessing of ECG data. This data is then transmitted to a higher-level computer or mobile device for further analysis and visualization [1, 5, 6];
- **Bluetooth Transmission:** Using the Bluetooth 5.0 BLE protocol stack, the system provides efficient and low-power data transmission, which is critical for long-term monitoring [1];

- **ZigBee (µMAC) transmission:** the communication concept used is based on the wireless network stack uMAC [7, 5, 6];
- **Local storage:** The system may include a local storage module (e.g. W25Q128FV) to minimize power consumption by reducing the need for constant data transmission [1].
- **Performance and applications:**
- **Clinical validation:** The MAX30003 has been evaluated for its effectiveness in monitoring various cardiac conditions, showing promising results in terms of accuracy and reliability. It achieves a 95% detection rate for P, R, and S peaks and 98% accurate segmentation for the QRS complex in noise-free conditions [3]. High detection and segmentation rates for various cardiac conditions [3].
- **Wearable devices:** The MAX30003 is suitable for integration into wearable devices, providing continuous real-time ECG monitoring. This makes it valuable for telemedicine and home healthcare applications, allowing patients to monitor their health [3].
- **Local storage –** reduces power consumption by minimizing constant data transmission [1].

Table 1 shows the main characteristics of the MAX30003.

The MAX30003 is suitable for continuous and real-time ECG monitoring in portable devices [3].

It can be concluded that the MAX30003 is a highly efficient and effective solution for ECG monitoring, especially in portable and wearable health monitoring systems. Its low power consumption, high accuracy, and stable performance under various conditions make it a valuable tool for continuous monitoring of heart health. The MAX30003 monitors multiple cardiac conditions, including ventricular and atrial tachycardia, hyper- and hypocalcemia, and hyper- and hypokalemia, proving to be versatile for various cardiovascular applications.

Table 1

Key Features of the MAX30003

Characteristics	Description	Reference
Low energy consumption	Efficient power management for portable devices	[1]
High accuracy	Normalized root mean square error < 10% (worst case), 2.5% (best case)	[3]
Noise management	High detection rate and precise segmentation even in noisy environments	[3]
Microcontroller integration	Oversees initial data collection and pre-processing	[1]
Bluetooth transmission	Uses Bluetooth 5.0 BLE for efficient data transmission	[1]
Local storage	Reduces power consumption by minimizing constant data transmission	[1]
Clinical validation	High levels of detection and segmentation of various cardiac conditions	[3]
Portable devices	Suitable for continuous and real-time ECG monitoring in portable devices	[3]

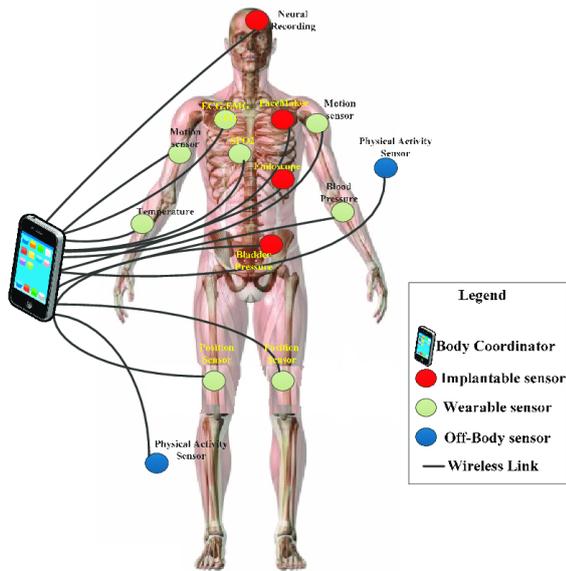


Fig. 2. Typical example of biomedical sensors and its applications [7].

3. SENSORS AND ELECTRODES FOR INFORMATION COLLECTION

Sensors Typical example of biomedical sensors and its applications [7] are shown in Fig 2.

Biomedical sensors based on microwave technology for specific applications in both diagnosis and monitoring of disease states, for example, microwave sensors can be used as a complementary technique to X-ray examination for monitoring [8]. The sensor monitors the dielectric properties and thus can detect changes in the measurement at different times.

An operating system controls the operation of the biosensors, performing data transfer between the converter and the memory, formatting and encryption of the data, and transmitting the data via the RF transmitter [9].

When choosing sensors for continuous cardiac monitoring, they must be. small single lead wearable

Furthermore, the determining factors of a wearable sensor are the location of the device placement, the choice of inter-electrode spacing, the orientation of the device, and the choice of electrode materials, which can have a significant effect on the signal quality and morphology of specific cardiac signals.

For example, some sensors use electrodes placed at small intervals and in a non-standard location, unlike commercial ECG electrodes attached to established locations on the patient's body.

There is a difference in the location of the electrodes, the materials and geometry of the electrodes, the movement of the electrode towards the body, the induced electrical charges due to changes in the contact surface, the distance between the electrodes, the ionic current, the frequency response of the electrodes, etc., which respectively lead to a decrease in the differences in ECG measurements [10].

A block diagram [11] for data transmission with an ECG sensor with dry electrodes is shown in Fig. 3.

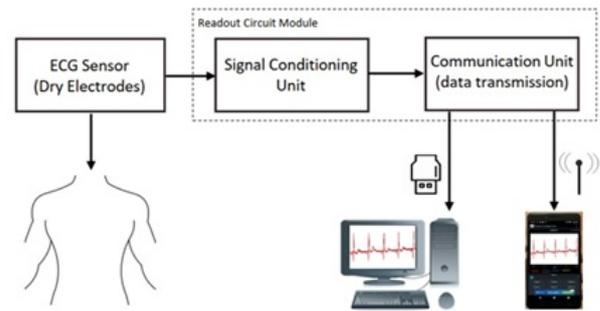


Fig. 3. EKG Sensor with Dry Electrodes [11].

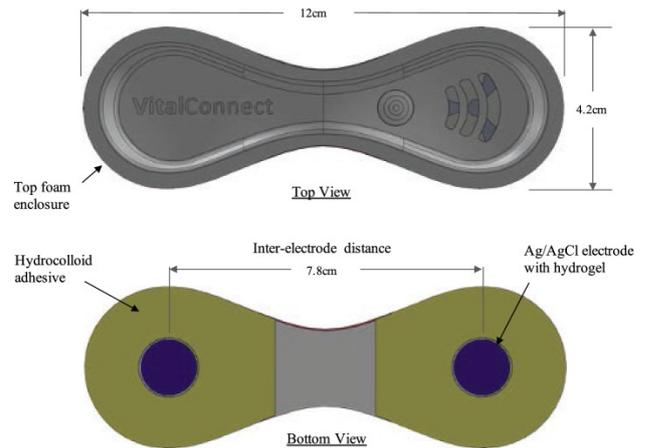


Fig. 4. Views of a VitalPatch Biosensor [12].

3.1. VitalPatch Biosensor

VitalPatch Biosensor (Fig. 4) is a disposable chest patch sensor with a 7-day battery life. The patch uses a built-in processor and Bluetooth Low Energy (BLE) transceiver to process and transmit the ECG signal continuously in real time. In addition to ECG, the VitalPatch also measures and transmits heart rate, respiratory rate, skin temperature, body temperature, steps, posture, and fall detection.

The mechanical design of the VitalPatch electrodes uses a construction similar to standard ECG electrodes [12].

3.2. Biopotential Analog Front-End (AFE) Sensor

For the single-lead ECG and heart rate acquisition, the MAX30003 Biopotential Analog Front-End (AFE) Sensor (by Maxim Integrated®) was selected due to having CVz features such as 32-Word FIFO memory, high-speed SPI Interface and low power consumption. Figure 5 shows the functional diagram of the ECG wireless sensor system.

3.3. Electrodes

The choice of electrodes is crucial. Any improper placement of electrodes can greatly affect the quality of the signal, and movement of the electrode leads can cause noise in the signal. Options include disposable electrodes, wet/dry electrodes, and insulated electrodes [4]. The design should provide minimal motion artifacts, which can be achieved by using high-quality electrodes and proper placement [11].

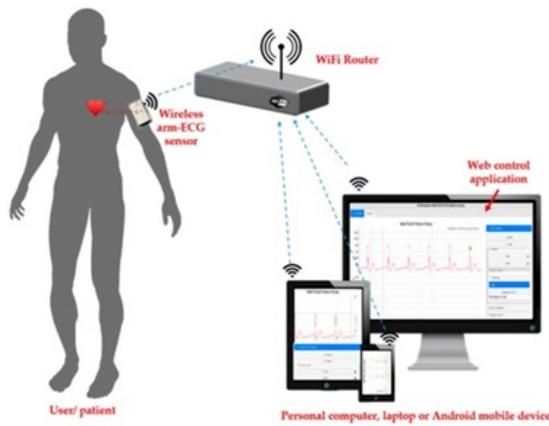


Fig. 5. Functional diagram of the ECG wireless sensor system [13].



Fig. 6. Disposable pregelled electrodes [14].

Possible materials used for dry electrode systems in wearable long-term ECG devices include textile and flexible electrodes, non-contact capacitive electrodes, and traditional biocompatible metal disc electrodes. ECG acquisition systems rely on the impedance stability of the skin-electrode interface for proper operation. Silver-silver chloride (Ag-AgCl) dry electrodes have shown good performance in the frequency range of 0.05 to 150 Hz and are suitable for the hand ECG recording device.

Another electrode solution for EKG devices is disposable pregelled electrodes that may be applied with MAX30003. They are fast, easy and come with a snap connector with cloth and foam.

Disposable pregelled electrodes are shown in Fig. 6.

4. DECISIONS

A patient monitoring device to a robot platform was developed to analyze, process and display data in digital and graphical form. The threshold values of parameter abnormalities [15, 16]. Unlike other similar devices, innovative solutions related to the construction and connection of the ECG with the Robotic System are presented here. It is possible to install several such devices with different placement of probes that are connected to the patient's body, thus obtaining a comprehensive picture of his condition.

Block diagram of the EKG device and its communication with RMLI is shown in Fig. 7.

ECG device is designed to work as part of the Robotic System (RMLI), and as an autonomous device.

The device consists of two modules:

- Control, developed based on JN5168-001-M00 [15];

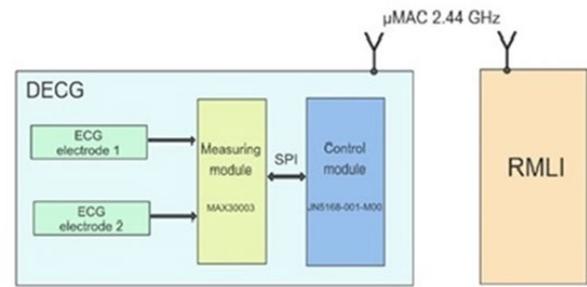


Fig. 7. Block diagram of the EKG device and its communication with RMLI.

- Measuring, developed based on MAX30003 [16].

The power supply of the device is provided by the control module based on 5VDC, received via USB cable from a USB interface or from a 220V AC to USB converter.

The control module controls the operation of the measuring device and provides communication of the device via a wireless interface - uMac or wired - USB. The measuring module generates the patient's ECG through two serviced electrodes and sends the information via an internal SPI interface to the control module Fig. 8.

The proposed device to a robotic platform is designed to meet basic requirements such as accuracy, sensitivity, processing, display, real-time data transmission, automatic signaling, generation and identification of threshold values of information.

Also, the device is tailored to compatibility, comfort, low power consumption and cost, small size and suitability for outpatient applications and telemedicine.

4.1. How to use the wireless ECG device

In Fig. 9, it is shown the method of connecting the wireless ECG device to the patient's body, its connection to the robotic platform software, and the transmission of the information to a remote medical server.

A block diagram of the robotic system and its connection to the ECG device are shown in Fig. 10.

Wireless ECG Device Software

The following software modules have been developed:

- System software;
- User software (GUI);
- uMAC software.

The software was developed in the Tcl scripting language using the Tk graphical library (Tcl/Tk) [17]. Local Operator Station is a software package that provides a graphical user interface for the operator/emergency medical technician. It is designed as a Windows application using the Tcl/Tk programming environment. Tcl/Tk is a programming environment in Windows that uses the resources of the operating system to create user projects. The name Tcl/Tk stands for: Tools Common Language / Tools Kit. Tcl/Tk is a set of program libraries of functions written and pre-compiled in C++. To implement the database in the Local Operator Station, an application for working with and processing databases - MetaKit for Tcl (Mk4Tcl) was used).

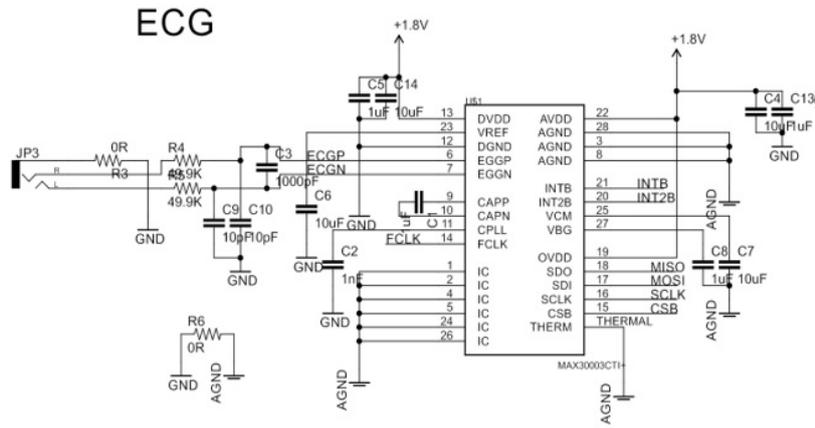


Fig. 8. Control and measurement module for ECG device.

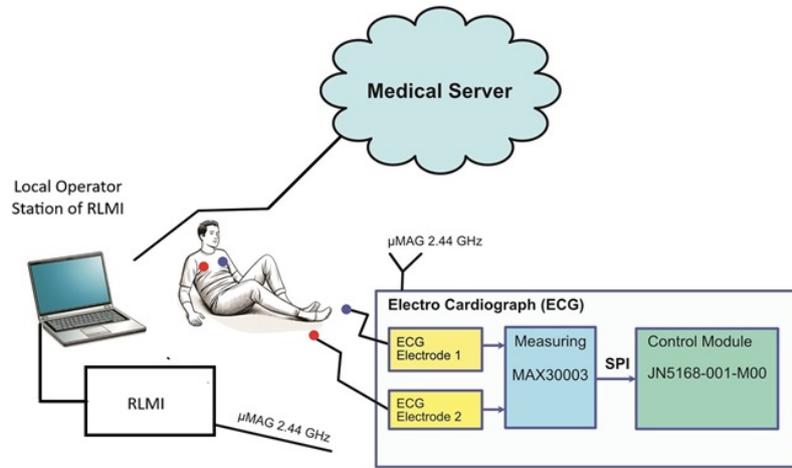


Fig. 9. Connecting the wireless ECG device to the patient's body, its connection to the robotic platform software, and the transmission of the information to a remote medical server.

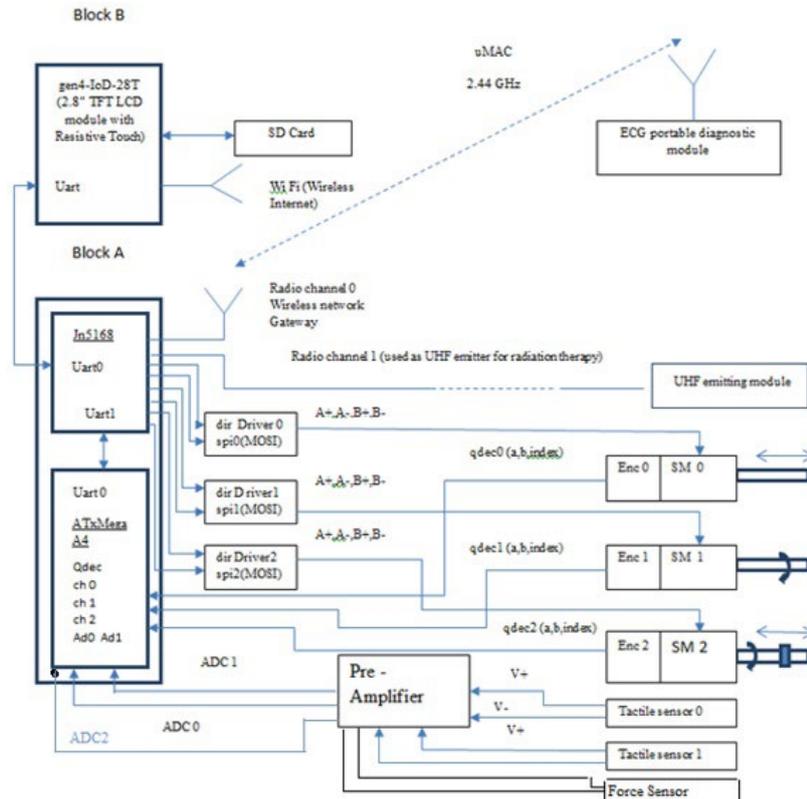


Fig.10. A block diagram of the robotic system and its connection to the ECG device.



Fig. 11. A system architecture of connection between patient, Wi-Fi module, data transmission network, doctors [19].

The work used the measuring module based on MAX30003 for two-wire measurements.

The information is fed to the measuring module based on MAX30003 (Measuring MAX30003), from it to a specialized controller based on JN5168-001-M00 [15, 16] (Control Module JN5168-001-M00). The conversion of the filtered and amplified analogue micro voltages is also performed within the MAX30003 through its internal ADC, and this converted digital information is transmitted to an external specialized controller via SPI connection. Via a wireless connection μ MAC (2.44 GHz), it is sent to the software of the Robotic System for Laparoscopic Surgery (Local Operating Station of Robot Modular Laparoscopic Instruments). This software can be installed on a laptop, tablet or mobile device. The information is visualized on the screen of the local operator station and is recorded in the local database, and from there it can be transmitted wirelessly to a medical server (Medical Server). Once recorded in the server, the information becomes available to all medical centers or universities, depending on what the device is used for – monitoring the vital signs of an operated patient or for training students or surgical staff in how to use the device [18]. A system architecture of connection between the patient, Wi-Fi module, the data transmission network, and doctors is shown in Fig. 11 [19].

5. CONCLUSION

This work aims to enhance healthcare services for elderly individuals living alone and for people residing in remote areas with limited access to medical care. It presented a robotic platform integrated with a Wi-Fi-enabled ECG device, designed for telemedicine and ambulatory monitoring. A patient monitoring device was developed to analyze, process and display data in digital and graphical form. the threshold values of parameter abnormalities.

Unlike other similar devices, innovative solutions related to the construction and connection of the ECG with the Robotic System are presented here. The device consists of two modules: Control, developed based on JN5168-001-M00 and Measuring, developed based on MAX30003.

The components selected for the device are compact and lightweight, ensuring that the ECG unit remains portable, user-friendly, and easy to handle. Acquired data is transmitted to an application – accessible via PC, laptop, tablet, or smartphone – using Bluetooth Low

Energy (BLE), ZigBee (μ MAC), or other suitable communication protocols.

Future research anticipates the development of simulation software to support the training of medical personnel and students in the effective use of the wireless ECG device.

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