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Design of a Low-Cost, Energy-Efficient Telemedicine Platform: An Innovative Solution for Medical Consultations in Remote Areas

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ABSTRACT: In response to the growing demand for healthcare in remote areas, healthcare professionals are compelled to seek innovative solutions. Telemedicine emerges as an effective answer, enhancing access to care and optimizing the use of medical resources. It strengthens interactions between patients and healthcare providers without requiring physical travel and facilitates the remote monitoring of vital signs.This paper presents the design of a low-cost, energy-efficient telemedicine platform for medical consultations in remote areas. The system enables real-time collection and visualization of vital parameters such as ECG, SpO2, heart rate, blood pressure, and body temperature. It leverages low-power sensors and commercially available modules, integrating data processing algorithms to improve diagnostic accuracy. The solution includes an acquisition unit, a communication unit, a management platform, and visualization interfaces tailored to the challenges of remote locations.

KEYWORDS: Telemedicine, Low-cost, Energy-efficient, Vital signs, Remote consultation

I. INTRODUCTION

Madagascar, with a population of over 25 million, faces a major healthcare challenge, particularly in rural areas where nearly 80% of the population resides[1]. The limited attractiveness of practicing medicine in these isolated regions results in inadequate healthcare coverage. The national average ratio of public doctors to inhabitants is 1:10,500, far below the WHO-recommended ratio of 1:10,000[2]. However, this figure conceals significant territorial disparities: urban areas have better healthcare coverage, while rural regions suffer from limited access due to poor infrastructure, transportation issues, and insecurity.

Moreover, distance remains a critical barrier to healthcare access. In Madagascar, more than half of the population lives over 10 km from the nearest healthcare center, exceeding the acceptable distance of 5 to 10 km[3]. This situation forces patients to travel long distances, often resorting to self-medication or illegal traditional practices. A prospective study also predicts an 8% decrease in the number of doctors by 2030, while the population is expected to grow by 30%, resulting in a 30% reduction in medical density [4].

In this context, telemedicine emerges as an innovative solution to reduce healthcare access disparities. By leveraging telecommunication technologies, healthcare professionals can provide remote medical services, addressing inequalities, improving the uneven distribution of healthcare providers, and enhancing the efficiency and quality of care [5].

This study focuses on the design and development of a real-time telemedicine system to improve healthcare access in Madagascar's isolated areas. The primary objectives are:

Reducing healthcare access disparities for isolated populations.

Providing a technical response to epidemiological and demographic challenges related to the unequal distribution of healthcare professionals.

Enhancing the efficiency and quality of care in a context of scarce medical resources.

This thesis, titled "Design of a Low-Cost, Energy-Efficient Telemedicine Platform: An Innovative Solution for Medical Consultations in Remote Areas", proposes a system capable of collecting, visualizing, and transmitting vital signs such as ECG, oxygen saturation (SpO_2), heart rate, bloodpressure, and body temperature in real time. The project consists of the following components:

- Design of a low-power consumption acquisition system
- Development of vital signs processing algorithms
- Design of a data transmission system to the host computer
- Development of a user interface for real-time data visualization

II. MATERIALS AND METHODS

II.I TOOLS FOR FUNCTIONAL NEEDS ANALYSIS

II.1.1 The Horned Beast Diagram Diagram[6], [7]

This tool provides a graphical expression of the need by answering the following questions:

- Who benefits from the product?
- What does the product act upon?
- What is the purpose of the product?

Figure 1: The « Horned Beast Diagram » diagram

II.1.2 TheOctopus Diagram Diagram (or Interaction Graph)[6], [8]

This diagram consists of the product at the center, surrounded by elements from its environment (external context). It is used for expressing functions and allows for a graphical representation of part of the specifications. It helps identify the environment in which the system evolves, determines the precise and concise relationships between the system and surrounding elements, and the relationships between pairs of external elements.It illustrates the relationships (functions) between the product and the external environment. These relationships correspond to the services provided by the product and help in developing the specifications.

Two types of functions are involved [9]:

Main functions: These are the functions for which the product is developed, meaning those that would fulfill the user's requirements. They are represented by links between two elements in the

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environment, with the links passing through the system.

Constraint functions: These are links between the product and an element of the environment. They arise from a constraint imposed by an external element, the existence of an already existing product, a specific user requirement, or the presence of standards and regulations.

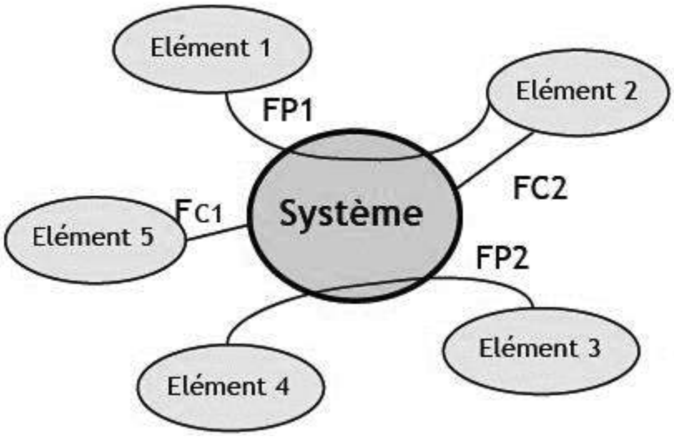

Figure 2: II.1.2.The Octopus Diagram Diagram

II.2 STRATEGIC ANALYSIS METHOD FOR THE PROJECT - SWOT MATRIX[7], [10]

II.2.1 Definition

SWOT is a business strategy tool invented by a group of Harvard professors: Learned, Christensen, Andrews, and Guth, aimed at identifying strategic options for a project. It helps define objectives by focusing on both internal and external factors that can help achieve them.

Conducting a SWOT analysis is a process that involves identifying the Strengths, Weaknesses, Opportunities, and Threats of a project (in English: Strengths, Weaknesses, Opportunities, and Threats – SWOT) [11].

Figure 3: The SWOT Matrix

II.2.2 The 2 Axes of SWOT Analysis

Internal Axis:

- **Strengths:** The first element to analyze in the SWOT matrix is "S" for Strengths. The goal is to identify and assess the strengths the project has to develop its activity. This includes all aspects of the activity: business, management, administration, etc.
- **Weaknesses:** After analyzing strengths, it is time to reflect critically on the weaknesses of

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the project. Trusted advisors, whether personal or professional, can help identify these. What is hindering or limiting the project? This may involve constraints (financial, technical, geographical, regulatory, etc.) or organizational difficulties (logistics, training, recruitment of qualified personnel, etc.).

External Axis

- **Opportunities:** Opportunities refer to anything that can be done to develop the project, boost business activities, or improve sales. It includes all actions aimed at growing the business.
- **Threats:** Threats are anything that poses a risk to the project's development, chances of success, or commercial growth. This encompasses a wide range of factors such as the emergence of newcompetitors, changes in regulations, external financial risks (e.g., financial or real estate bubbles), and anything that could jeopardize the future of the project.

II.3 DATA MODELING METHOD – UML LANGUAGE[12], [13], [14], [15]

II.3.1 Definition

Unified Modeling Language (UML) is a graphical modeling language based on pictograms, designed as a standardized method for visualization in software development and object-oriented design[11]. The current version, UML 2.5, includes 14 types of diagrams: seven structural and seven behavioral. UML is not a methodology, but rather a set of tools where the use of diagrams is at the discretion of the user. The class diagram is generally considered the central element of UML.

II.3.2 Diagrams [10]

a. Structure Diagrams (Static Diagrams)

- Class Diagram: Representation of the classes involved in the system.
- Object Diagram: Representation of instances of classes (objects) used in the system.
- Component Diagram: Representation of the system components from a physical perspective, such as files, libraries, databases, etc.
- Deployment Diagram: Representation of hardware elements (computers, peripherals, networks, storage systems, etc.) and how system components are distributed across these hardware elements and interact with each other.
- Package Diagram: Representation of dependencies between packages (a package being a logical container used to group and organize elements in the UML model), i.e., between sets of definitions.
- Composite Structure Diagram: Representation, in the form of a white-box, of relationships between class components (since UML 2.x).
- Profile Diagram: Specialization and customization for a particular domain of an UML meta-model reference (since UML 2.2).

b. Behavioral Diagrams

- Use-Case Diagram: Representation of possible interactions between the system and external actors, i.e., all functionalities the system must provide.
- State Machine Diagram: Representation of the system's or its components' behavior in the form of a finite state machine.
- Activity Diagram: Representation of the system's or its components' behavior as a flow or sequence of activities.

c. Interaction or Dynamic Diagrams

- Sequence Diagram: Sequential representation of the processing and interactions between system elements and/or actors.
- Communication Diagram: Simplified representation of a sequence diagram focusing on the message exchanges between objects (since UML 2.x).
- Interaction Overview Diagram: Representation of possible sequences between previously identified scenarios in the form of sequence diagrams (a variant of the activity diagram) (since UML 2.x).
- Timing Diagram: Representation of data variations over time (since UML 2.3).

II.4 SOFTWARE DESIGN LANGUAGE AND MICROCONTROLLER PROGRAMMING

II.4.1 HTML [16]

HyperText Markup Language (HTML) is the data format designed to represent web pages. It is a markup language used to write hypertext. HTML also allows semantic and logical structuring of content, formatting web pages, embedding multimedia resources such as images, input forms, and computer programs. It enables the creation of interoperable documents with a variety of devices while conforming to web accessibility standards. HTML is often used alongside JavaScript and Cascading Style Sheets (CSS). It was initially derived from the Standard Generalized Markup Language (SGML).

II.4.2 CSS [16], [17]
Cascading Style Sheets (CSS) is a programming language used to style web pages (HTML or XML).

II.4.3.Bootstrap [18]
Bootstrap is a collection of tools used for creating the design (graphics, animations, and interactions with the page in the browser) of websites and web applications. It includes HTML and CSS code, forms, buttons, navigation tools, and other interactive elements, along with optional JavaScript extensions.

II.4.4 PHP [19], [20]
Hypertext Preprocessor (PHP) is a programming language mainly used to produce dynamic web pages through an HTTP server, but it can also run as any interpreted language locally. PHP is an imperative, object-oriented scripting language. It is most commonly used server-side: in this architecture, the server interprets the PHP code from the requested web pages and generates code (HTML, XHTML, CSS, etc.) and data (JPEG, GIF, PNG, etc.) that can be interpreted and rendered by a web browser. PHP can also generate other formats such as WML, SVG, and PDF. It is designed for creating dynamic applications, often developed for the web.

II.4.5 MySQL [19], [20]
MySQL is a relational database server developed for high-performance reading, meaning it is more suited for serving pre-existing data than frequent updates and highly secure modifications. In practice, the MySQL server can be seen as a storage location for data, whether encrypted or not. Information can then be retrieved quickly from the server via SQL queries.

II.4.6 JavaScript [20], [21]
JavaScript is a scripting language primarily used for interactive web pages, making it an essential part of web applications. Alongside HTML and CSS, JavaScript is sometimes considered one of the core technologies of the World Wide Web. A large majority of websites use it, and most web browsers have a dedicated JavaScript engine to interpret it, regardless of security considerations.

II.4.7 jQuery [20], [22]
jQuery is a free, cross-platform JavaScript library designed to simplify the writing of client-side scripts in HTML web pages. Its main goal is to traverse and manipulate the DOM (including support for CSS selectors and basic XPath), providing numerous features such as animations, manipulation of cascading style sheets (CSS), event management, etc. It also facilitates the use of Ajax and includes many plugins.

II.4.8 AJAX [22], [23], [23]
AJAX (Asynchronous JavaScript and XML) is a method using various technologies in web browsers that enables the sending of requests to the web server and consequently the partial modification of a displayed web page without reloading it completely. This architecture allows the creation of dynamic, interactive web applications and websites.

II.4.9 JSON[20], [23], [24]
JavaScript Object Notation (JSON) is a text-based data format derived from JavaScript's object notation. It allows the representation of structured information, similar to XML.

II.4.10 C++ [25], [26], [27]
C++ is a compiled programming language supporting multiple programming paradigms, including procedural, object-oriented, and generic programming. Its high performance and compatibility with C make it one of the most widely used programming languages in applications where performance is critical.

III. RESULTS

III.1 Modeling of Needs
As part of its analysis publication on 25 telemedicine experiences, [28] ANAP identified the key success factors for a telemedicine project. Among these factors is the necessary definition of a medical project that must be based on the needs of the patients and the involved medical actors.

III.1.1 Expression of the Need with the " Horned Beast Diagram"
Following the analysis of existing solutions,we established a standardized graphicalrepresentation.

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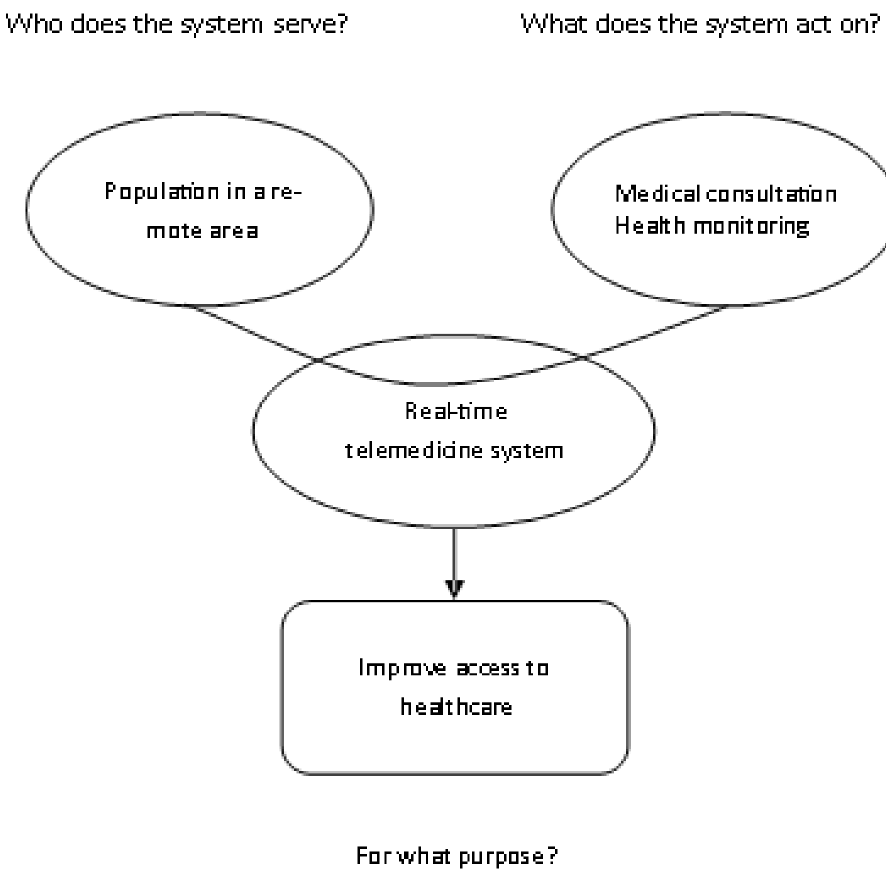

Figure 4: Expression of the need using the Horned Beast Diagram diagram

The system serves the population in remote areas by addressing medical consultation and health monitoring to improve access to care.

It should be noted that the determination of needs to be met will depend on the characteristics of the target population and must account for its evolution over time, influenced by various factors such as demographic, medical, or economic.

III.1.2 Validity Check

This is a systematic questioning aimed at testing the validity of the need and the relevance of its formulation. The validity check is carried out by answering two questions:

- Cause of the need: Why is this system needed?
- Purpose of this need: For what purpose?

Table 1:Validity Check

Why do we need this system? The system serves the population in isolated areas.	**For what purpose?** The system addresses medical consultation and health monitoring of the population.
→ Health is the greatest wealth, and this system is one of the means to provide medical consultation in remote areas.	→ The consultation, conducted by certified doctors, ensures quality care, which helps improve access to healthcare for the population.

The disappearance of the cause and purpose of this need is not currently foreseeable. Therefore, the system deserves further study.

III.1.3 Functional Analysis with the Octopus Diagram Diagram

Functional analysis is a tool for building quality in design (total quality strategy), as detailed in the AFNOR standard NF X50-151. It aims to

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clarify the client's request through a functional analysis of the need (A.F.B.), which allows the precise identification, in terms of functions, of the needs to be met or the services to be provided. This is carried out using the Octopus Diagram Diagram.

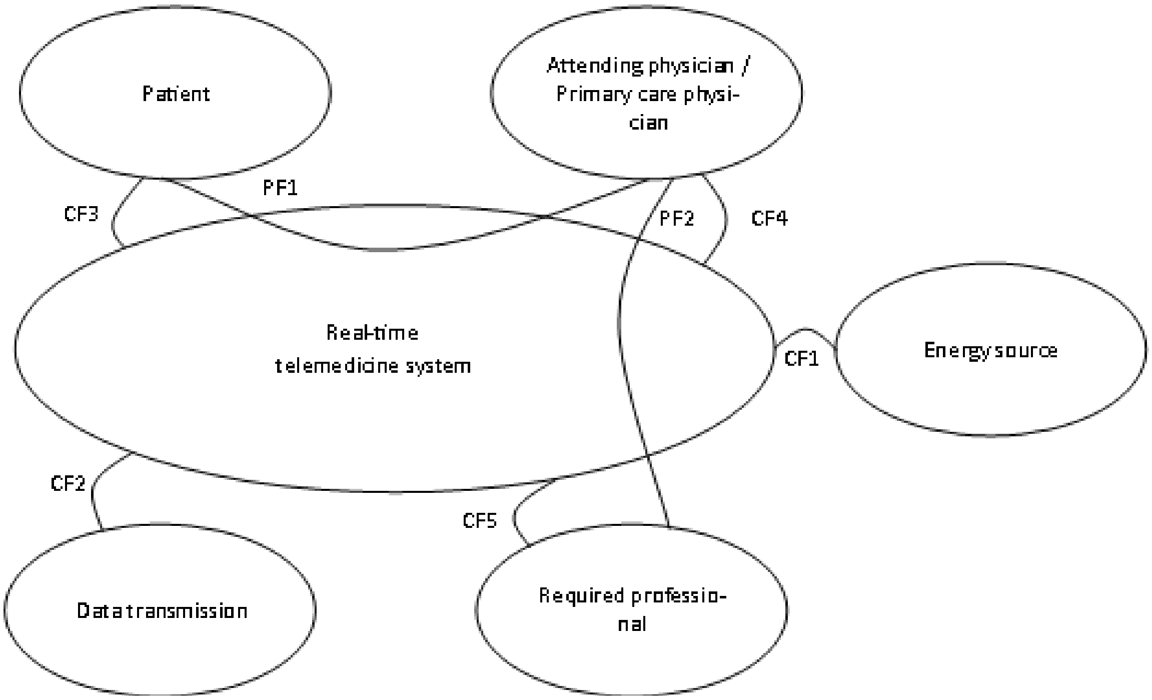

Figure 5: Functional Analysis with the Octopus Diagram Diagram

Table 2: Expression of Service Functions

Function	Description
PF1	Enable doctors to conduct remote consultations/monitoring
PF 2	Enable doctors to provide remote assistance/expertise
CF1	Power the system with renewable energy – consume less energy
CF 2	Be capable of transmitting information in isolated areas
CF 3	Be ergonomic
CF 4	Provide doctors with accurate parameters – Facilitate diagnosis
CF 5	Be easy to handle

III.2 Organizational Model of the System and Technical Feasibility Study of the Device

III.2.1 Organizational Protocol of the System

The project's objective is translated into specific actions for coverage. Indeed, a telemedicine organization defining the telemedicine links to be established can be combined to form organizational models, thereby addressing all the constraints within a given scope.

Identifying the medical procedures that can be performed via telemedicine leads to considering telemedicine connections between the various stakeholders. The combination of these connections can follow different models depending on the type of care intended.

Defining the organizational model involves identifying the stakeholders involved in each telemedicine procedure, the locations where these procedures will be carried out, and describing how these links are organized.

The definition of the organizational protocol and its dissemination to the concerned parties are essential for the effective functioning and adoption of the system.

Table 3 outlines, as an example, the minimal process for implementing a medical teleconsultation project:

Table 3: Process for Implementing a Medical Teleconsultation Project

Stage	Details
Request for Telemedicine Act	• Preparation of the telemedicine file • Request for telemedicine consultation with the remote expert (medical specialist) • Validation of the request (reservation of a consultation time slot) • Notification of the referring doctor
Preparation before the Telemedicine Session	• Informing the patient • Obtaining patient consent (or that of their legal representative if unable) • Preparing the medical file • Informing the family • Informing the staff • Preparing the room at the requesting site • Making the patient's medical file available • Patient's arrival • Verifying internet connections • Setting up participants • Starting the telemedicine software • Turning on the computer, verifying proper alignment • Gathering in the teleconsultation room • Starting the teleconsultation session
Telemedicine Session	• Introduction of all participants (from both sides) • The consulting specialist addresses the patient directly (interview) • The specialist may request additional examinations (conducted, depending on responsibilities, skills, and type of teleconsultation, by the attending healthcare professional) • Discussion between the healthcare team at the requesting site and the consulting doctor (+/- patient +/- family) • If the patient (and/or family) is not involved in the therapeutic discussion, they are escorted out of the room (by the referring nurse or healthcare provider from the requesting site) • The consulting doctor concludes the consultation and closes the telemedicine session
After the Telemedicine Session	• Possible debriefing • Consultation report • Telemedicine session report • Quality assessment

III.3 System Architecture

III.3.1 Global Diagram

The overall system architecture is first explained, followed by an analysis of the various components. This diagram includes a data acquisition unit, a data processing unit, a data transmission unit, and a host computer for data management and user interactions. The data acquisition unit is responsible for collecting data from sensors. All sensors are connected to a central node in a star topology. These data are then processed in the processing unit before being transmitted to a local HTTP server via an Ethernet Shield. The Shield can be connected directly to the computer via a crossover RJ45 cable or through a router and a Wi-Fi device. In this case, data is transmitted to the computer via a Wi-Fi network. Real-time visualization of results and data management are performed via a web platform on the host computer. Communication between the requesting station and the destination site is established via satellite link. Satellite communication consists of two essential components: a space segment and a ground segment. The space segment consists of the satellite itself, equipped with radio transmission and reception devices, antennas, and high-gain broadband amplifiers. The ground segment includes fixed or mobile transmission equipment located on the Earth's surface, as well as auxiliary equipment. Ground receivers include direct satellite reception equipment (DTH, Direct To the Home, or Direct-broadcast satellite) and mobile reception devices in the system.

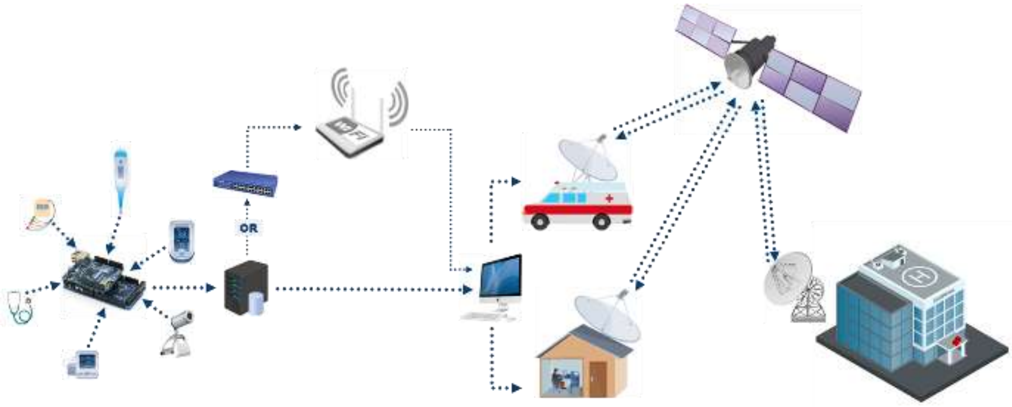

Figure 6: System Architecture

III.3.2 Energy Consumption

Table4 shows the power and energy consumption of each unit over a period of 8 hours.

Table 4: System Energy Consumption

Unit	Estimated Power	Energy Consumption / 8 hours
Data Acquisition Unit	9 W	72 Wh
Data Processing Unit	2.5 W	20 Wh
Data Transmission Unit	1.2 W	9.6 Wh
Host Computer	35 W	280 Wh

Figure 7 highlights that the majority of energy is consumed by the host computer.

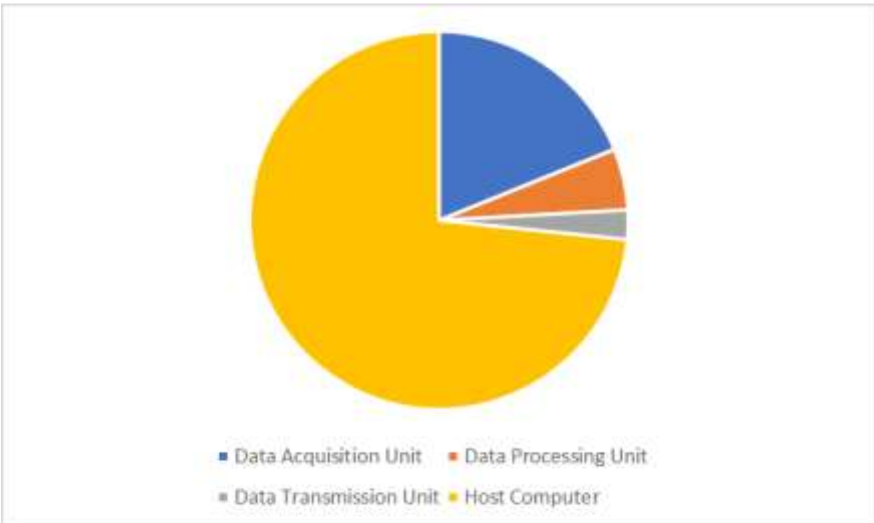

Figure 7: Energy Consumption of Each Unit

In summary, the device can operate with a 12V integrated lithium battery with a capacity of 8000 mAh and can function continuously for at least 8 hours. It can also be powered directly with a 12V DC supply. Since this project is designed for remote areas, the system should consume as little energy as possible, and solar energy is the ideal power source to implement for its operation.

III.4 Data Acquisition Unit

III.4.1 Electrocardiograph

a. Electrodes

The electrodes capture the electrical impulses that initiate cardiac contractions. In our prototype, three frontal electrodes are used to record the variations in the heart's electrical potential in the frontal plane between the leads located on the limbs (Frontal Leads).

Figure 8: Frontal Electrodes

b. Description of the AD8232 Module[29], [30]

The AD8232 is an integrated signal conditioning block for ECG applications and other biopotential measurements. It is designed to extract, amplify, and filter small biopotential signals in the presence of noisy conditions, such as those caused by movement or the placement of electrodes at a distance. This design enables an analog-to-digital converter (ADC) with very low power consumption or an integrated microcontroller to easily acquire the output signal.

This module implements a bipolar high-pass filter to eliminate movement artifacts and electrode half-cell potential. This filter is closely coupled with the amplifier's instrumentation architecture to allow both significant gain and high-pass filtering in a single stage, saving space and reducing costs. An uncommitted operational amplifier allows the AD8232 to create a three-pole low-pass filter to eliminate additional noise. The user can select the cutoff frequency of all filters to adapt to different applications.

The AD8232 includes a fast restoration function that reduces the stabilization time of high-pass filters. This feature allows the system to quickly recover, providing valid measurements shortly after the electrodes are connected to the subject.

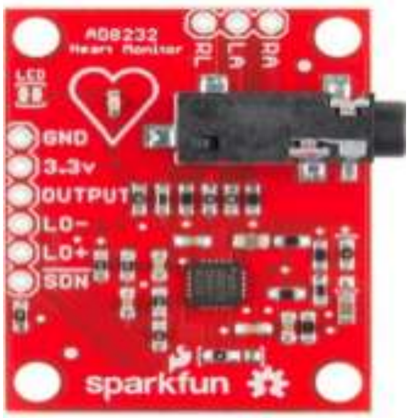

Figure 9: AD8232 Module

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c. Diagram

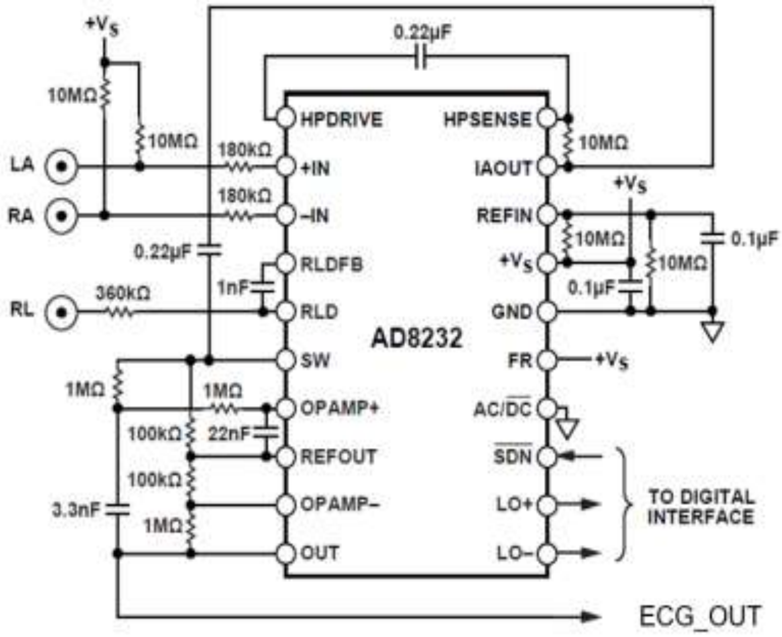

Figure 10: ECG Module

3.4.2 Stethoscope

a. Chest Piece

The chest piece is the part of the stethoscope that is placed on the body to listen to sounds. A membrane within the chest piece captures and transmits sound vibrations to the tubing, which in turn transmits the sound to the acoustic sensor.

Figure 11: Stethoscope Chest Piece

b. Description of the KY-038 Module[29]

The KY-038 module consists of three functional elements. The acoustic sensor located at the front measures sound. The analog signal is then sent to the amplifier, which amplifies the signal based on the gain determined by the potentiometer and sends the signal to the module's analog output.

It is important to note that the signal is inverted: the higher the value measured by the sensor, the lower the output voltage. The third component is a comparator that switches the output and LED when the signal drops below a certain threshold. Sensitivity can be adjusted with the potentiometer. The LED D2 indicates that thesensor is powered, while D1 indicates that a sound has been detected.

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Figure 12: KY-038 module

c. Diagram

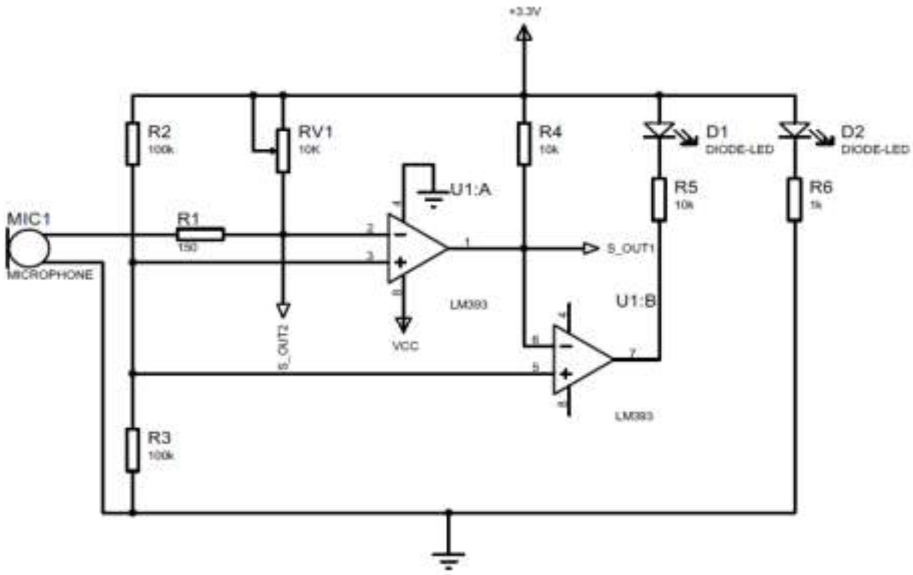

Figure 13: Stethoscope Module

3.4.3 Thermometer

a. Description of the LM35 Sensor[29]

The LM35CAZ temperature sensor is an analog temperature sensor manufactured by Texas Instruments. It can measure temperatures ranging from -40°C to +110°C with a tolerance of ±1°C. The sensor’s analog output is proportional to the temperature. By measuring the voltage at the sensor's output, the temperature can be determined. Each degree Celsius corresponds to a voltage change of +10mV (cf. Appendix D).

Figure 14: LM35CAZ Sensor

b. Schematic Diagram

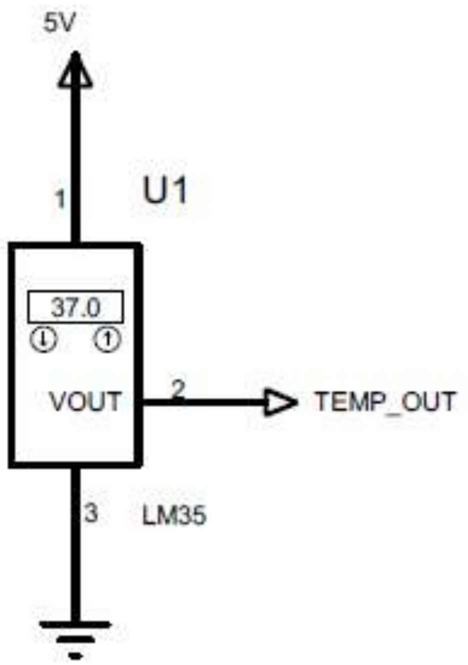

Figure 15: Thermometer Module

3.4.4 Heart Rate

a. Description of the XD58C Module[30]

The XD58C module is a heart rate photodetector combined with an amplifier and noise suppression circuit. The sensor operates by emitting green light via an LED into a finger (or another part of the body, such as an earlobe) and detecting the amount of light reflected using a photodetector tuned to the green light spectrum.

As blood is pumped through the finger with each heartbeat, the amount of light reflected changes, creating a waveform at the sensor's output that is representative of the heart rate. This signal is then processed through an RC filter network, amplified using an operational amplifier, and sent to the microcontroller's analog port.

Figure 16: XD58C Module

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b. Diagram

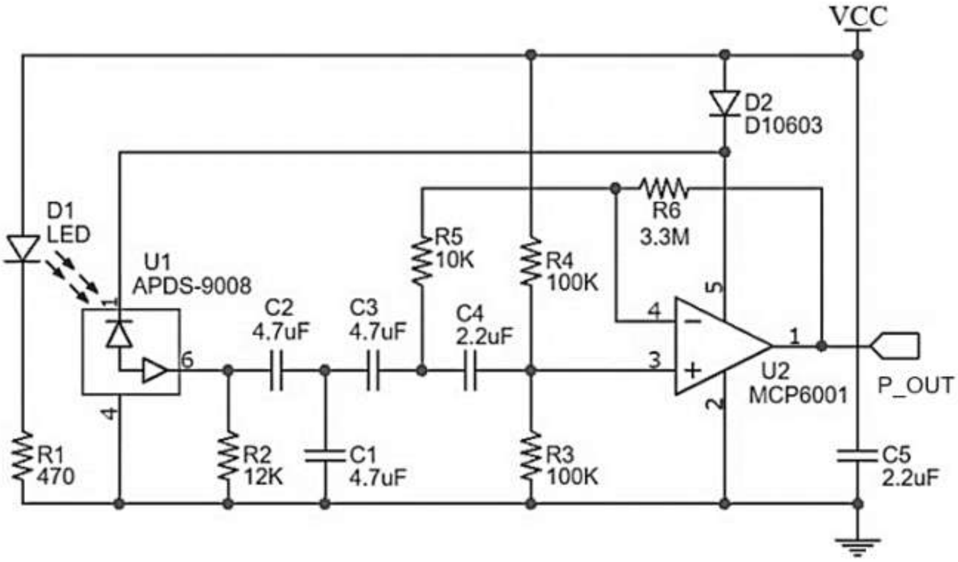

Figure 17: Heart Rate Module

3.4.5 Pulse Oximeter

a. Description of the MAX30100 Module[30]

The MAX30100 module is an integrated solution for pulse oximetry. It combines two light emitters, a photodetector, an optimized optical system, and an analog signal processing system.

The SpO2 subsystem of the MAX30100 includes an ambient light cancellation (ALC) system, a 16-bit sigma-delta analog-to-digital converter (ADC), and a filter.

The SpO2 ADC is a continuous-time oversampling sigma-delta converter with a resolution of up to 16 bits. The output data rate can be programmed from 50 Hz to 1 kHz. The MAX30100 includes a discrete-time filter to reject 50Hz/60Hz interference and residual low-frequency ambient noise.

It also features an integrated temperature sensor to calibrate the SpO2 subsystem's temperature dependence. The SpO2 algorithm is relatively insensitive to the LED's IR wavelength, but the red LED wavelength significantly impacts data interpretation. The temperature sensor data can be used to compensate for SpO2 errors caused by ambient temperature changes.

The module integrates red and IR LED drivers to generate pulses during SpO2 measurements. The LED current can be programmed from 0mA to 50mA, with appropriate supply voltage. The LED pulse width can be programmed from 200µs to 1.6ms to optimize measurement accuracy.

Figure 18: MAX30100 Module

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b. Diagram

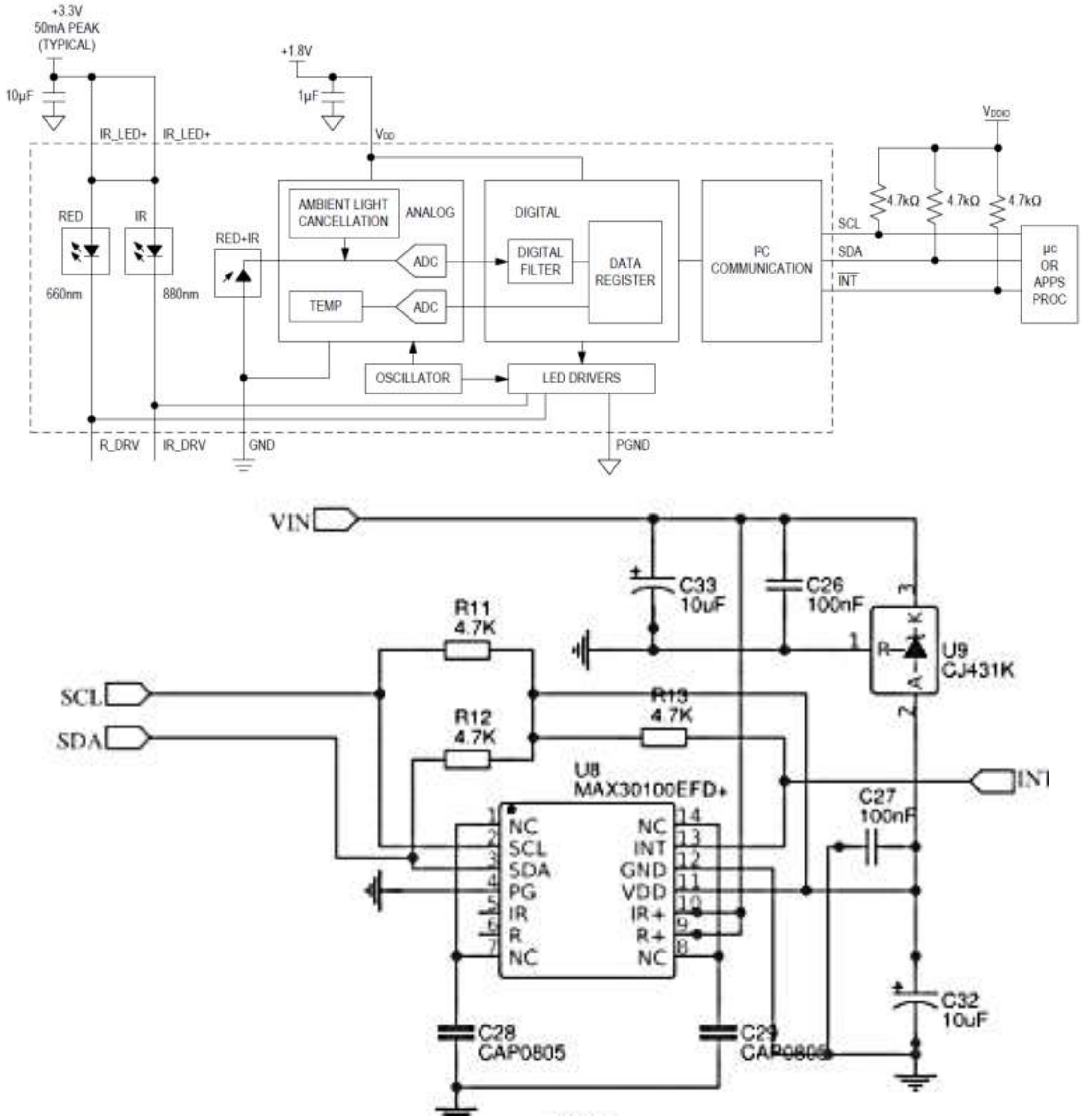

Figure 19: Pulse Oximeter Module

3.4.6 Blood Pressure Monitor

a. Pneumatic Unit

The cuff applies counter-pressure by inflating it using an electric pump to a value higher than the systolic pressure to block arterial blood flow in the arm. The cuff pressure is then gradually released by opening the electrovalve until it reaches a threshold, at which point the blood pressure is sufficient to allow blood to flow again through the artery. This marks the systolic pressure. As the deflation continues, the cuff pressure reaches a value at which there is no longer any obstruction to arterial flow, even when the heart is in diastole. This corresponds to the diastolic pressure.

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Figure 20: Cuff

Figure 21: Rolling pump

Figure 22: Micro electrovalve

b. Blood Pressure Module Description

This module consists of a pressure sensor (MPX2010DP) along with its electrical conditioning circuit (Amplification and Filtering) and a control system for the pneumatic system described above. The analog circuit amplifies both the DC and AC components of the sensor's output signal, allowing it to be processed by the system. The cuff is inflated up to 180 mm Hg, which corresponds to an output voltage of 3.98 mV (see Appendix C). To achieve this, the voltage is amplified from 0 to 4V. The DC amplifier's output is then passed through two cascade band-pass filters.

The DC amplifier enhances both the DC and AC components of the signal. The filter is designed to provide significant gain for frequencies between 0.3 and 19 Hz while attenuating signals outside this range.

The AC component from the band-pass filter is crucial for determining the systolic and diastolic pressures.

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c. Schematic

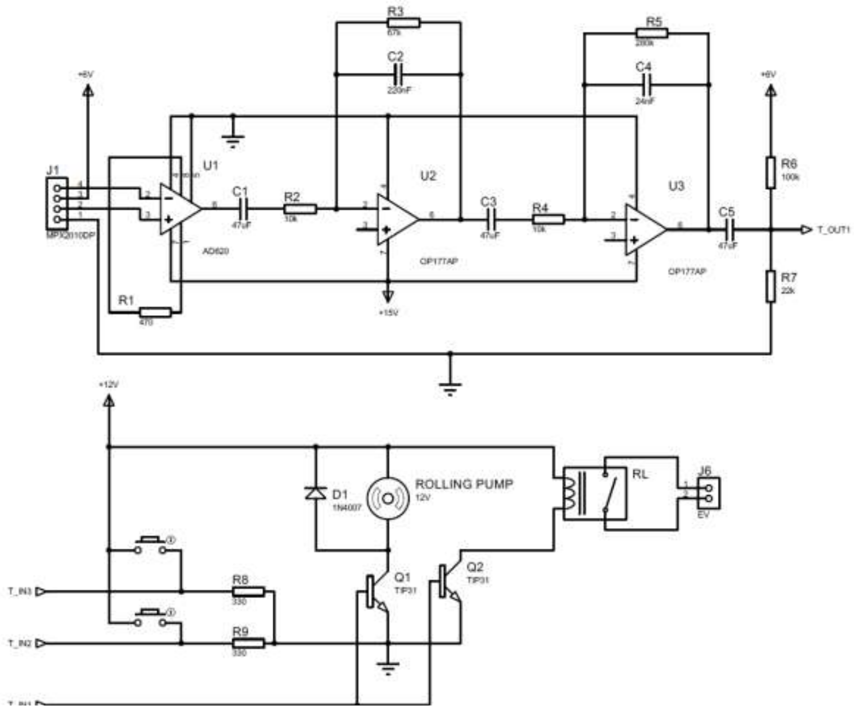

Figure 23: Blood Pressure Module

d. Printed Circuit Board

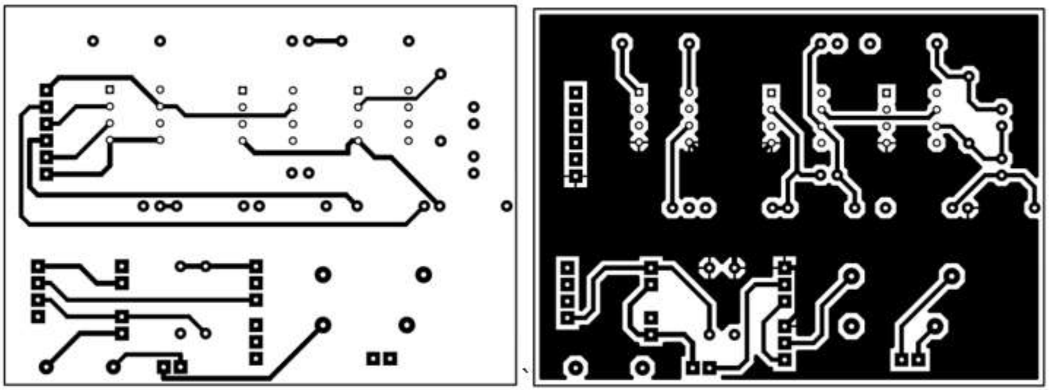

Figure 24: Blood Pressure Module PCB

3.5 DATA PROCESSING UNIT

3.5.1 Module Description[31]

To analyze the data from the various sensors, a data processing circuit has been developed. It facilitates the star topology of different sensors with the Arduino MEGA 2560 development board.

The Arduino MEGA 2560 is a module based on the ATMega2560, running at 16 MHz. It has 54 I/O pins, including 14 PWM outputs, 16 analog inputs, and 4 UARTs. The ATMega2560 microcontroller includes a bootloader that allows program updates without requiring an external programmer.

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Figure 25: Arduino MEGA 2560

3.5.2 Connection Diagram Between Acquisition and Processing Units

The following figure illustrates the connection between the modules presented in section III-4 and the data processing unit.

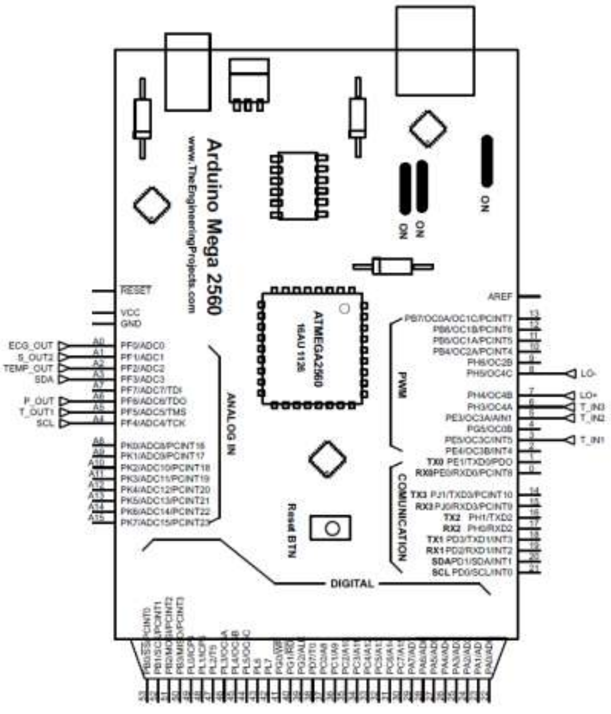

Figure 26: Connection Between Modules and Processing Unit

3.5.3 Data Processing Algorithm

The following flowchart depicts the algorithm for acquiring and processing information from each module until the data is sent to the server.

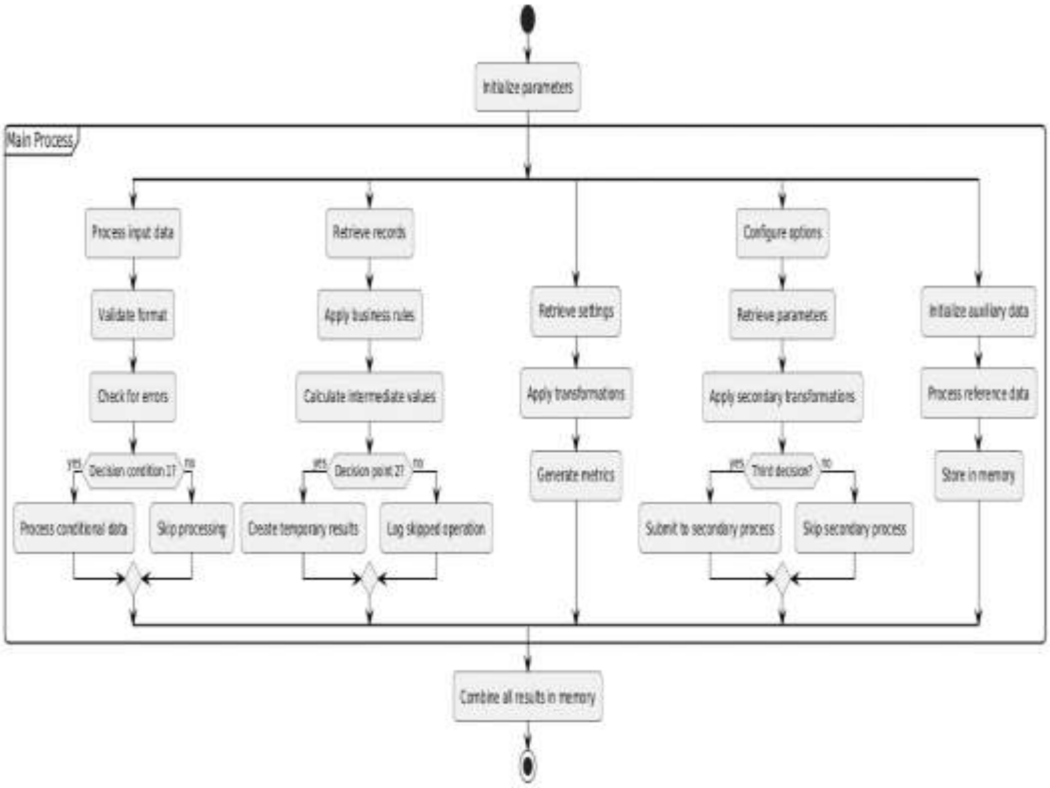

Figure 27: Data Processing Algorithm

3.6 INFORMATION TRANSFER UNIT BETWEEN EQUIPMENT AND HOST COMPUTER

3.6.1 Module Description[27], [31], [32]

The Ethernet Shield module allows the Arduino board to communicate over a wired Ethernet network. This enables the creation of a Human-Machine Interface (HMI) to control or visualize the system's status.

This module includes:

- An Ethernet port (10BaseT/100BaseTX)
- A Wiznet W5100 integrated circuit supporting TCP/IP protocol and 4 simultaneous connections
- A MicroSD card slot for data storage or transmission
- 7 LEDs to display various information:

- **TX**: Lights up during data transmission
- **RX**: Lights up during data reception
- **COLL**: Lights up when there's a network collision
- **FULLD**: Lights up when the network connection is in full-duplex mode
- **LINK**: Lights up when connected to a network, blinks during data exchange
- **100M**: Lights up when the connection speed is 100Mbps
- **PWR**: Lights up when the board is powered

Figure 28: Ethernet Shield module

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3.6.2 Configuring the Module as an HTTP Server for a Local Network

To connect the Shield directly to the computer without a router, a bridge between the WiFi and Ethernet connections needs to be created. First, retrieve the IP addresses used on the network, then configure the module as an HTTP server. The steps are as follows:

- Connect the Ethernet Shield to the Arduino board
- Set the IP address and subnet mask of the host computer
- Connect the Ethernet Shield directly to the computer via a crossover RJ45 cable or through a router using a straight RJ45 cable
- Configure the module as an HTTP server using the algorithm below:

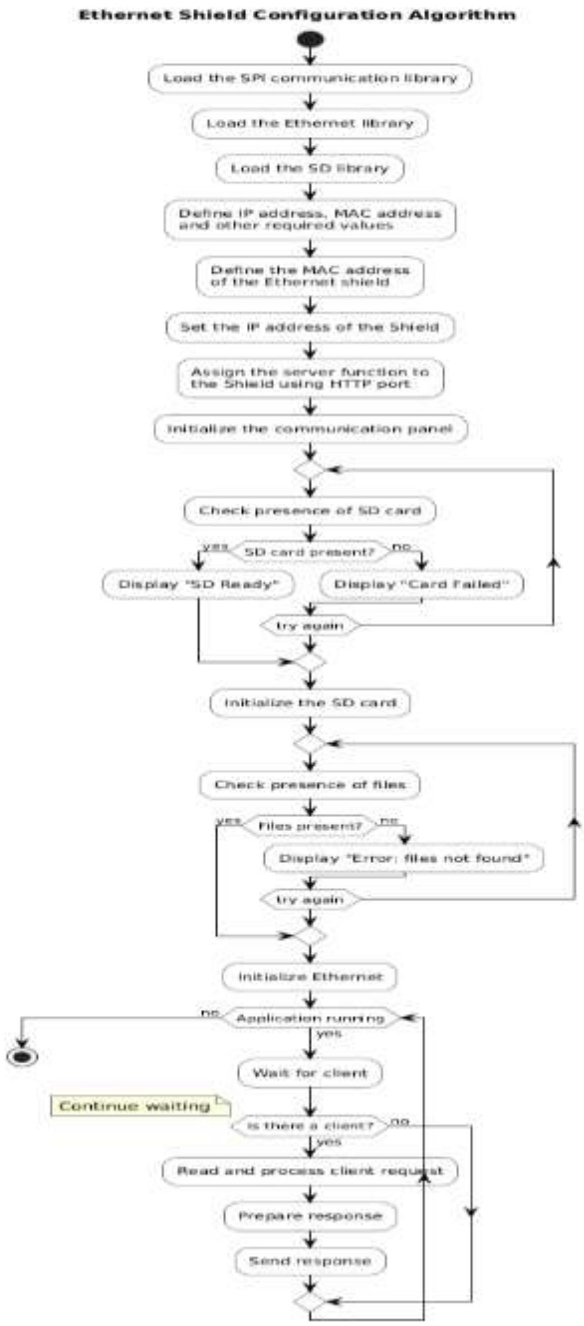

Figure 29: Ethernet Shield Configuration Algorithm as an HTTP Server

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3.7 DATABASE AND USER INTERFACE

3.7.1 Data Modeling with UML

a. Use Case Diagrams

This diagram represents the functional behavior of the software. It shows discrete units of interaction
between users and the system.

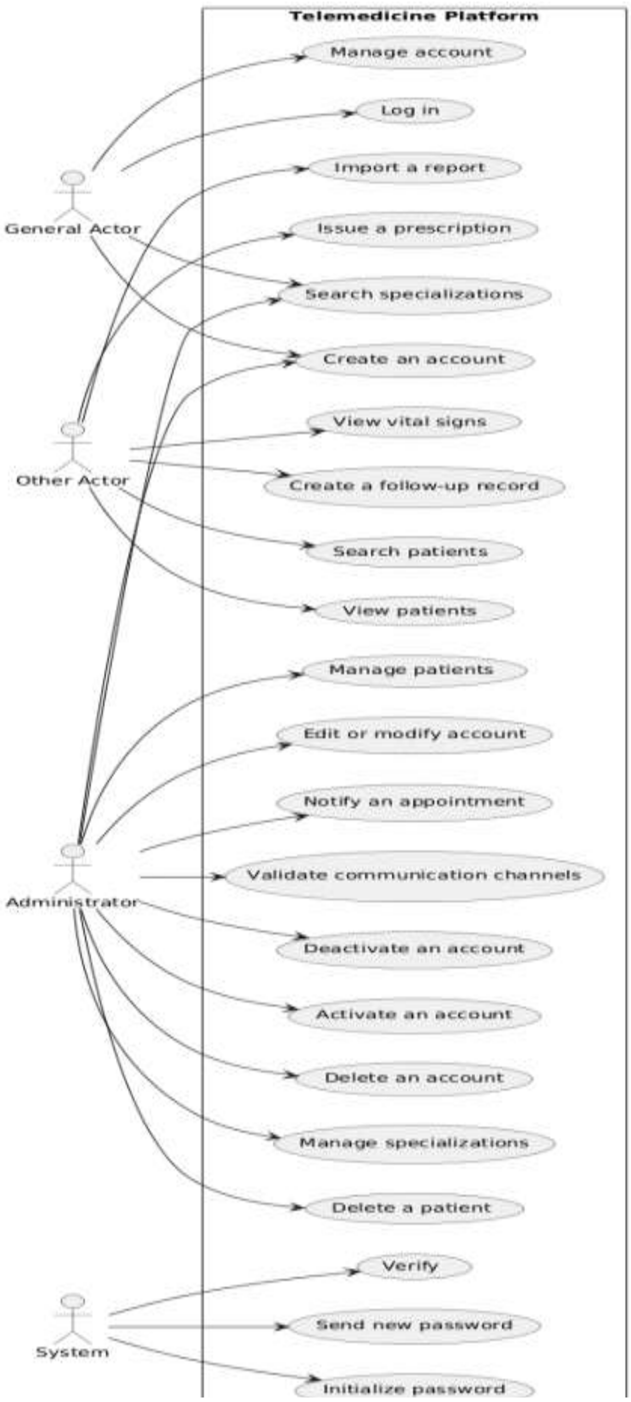

Figure 30: Use Case Diagrams

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b. Class Diagrams

This diagram outlines the software structure by modeling its classes, attributes, operations, and relationships between objects.

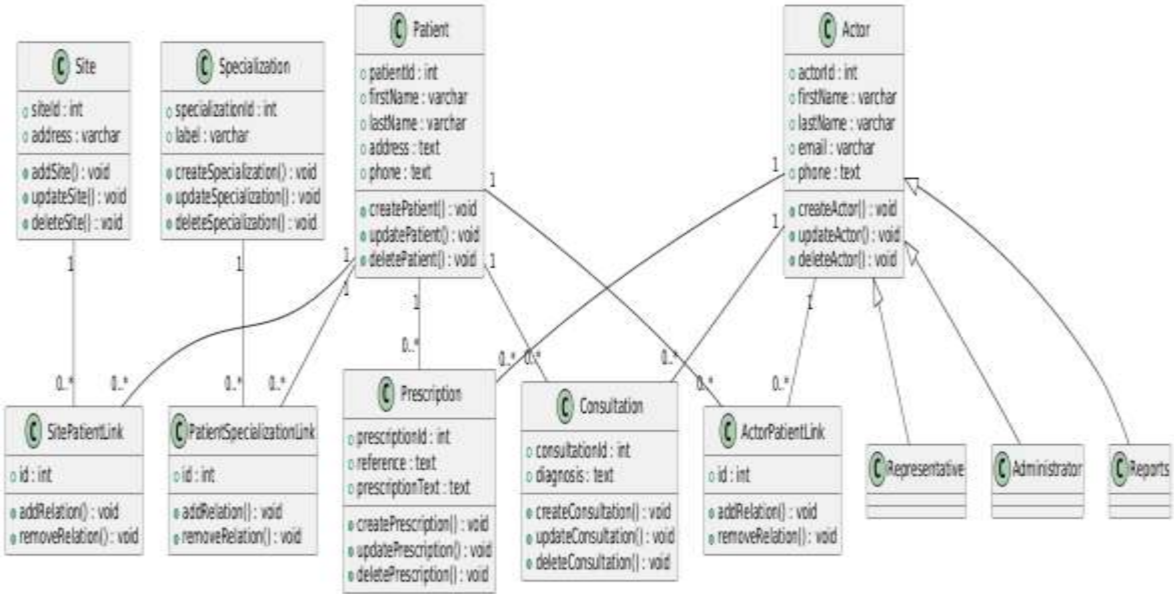

Figure 31: Class Diagrams

c. Sequence Diagrams

This diagram graphically represents interactions between actors and the system in chronological order for the following scenarios: account creation, authentication, and teleconsultation.

- **Account Creation**

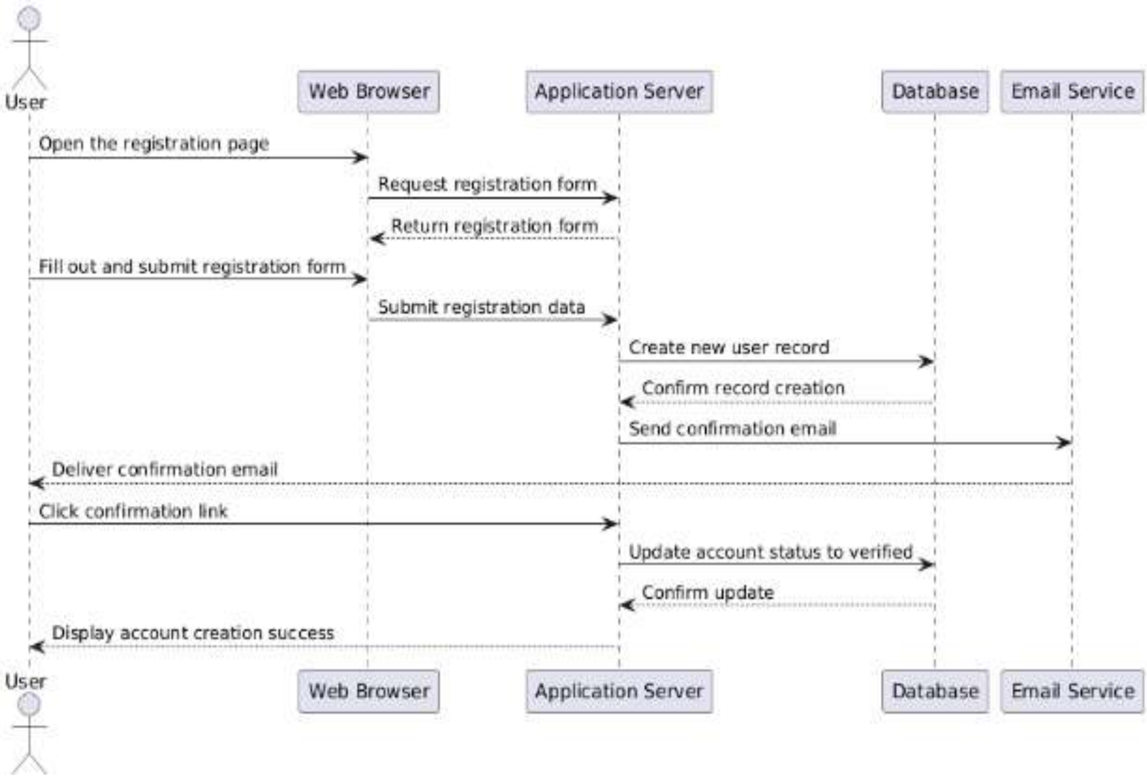

Figure 32: Account Creation Sequence Diagram

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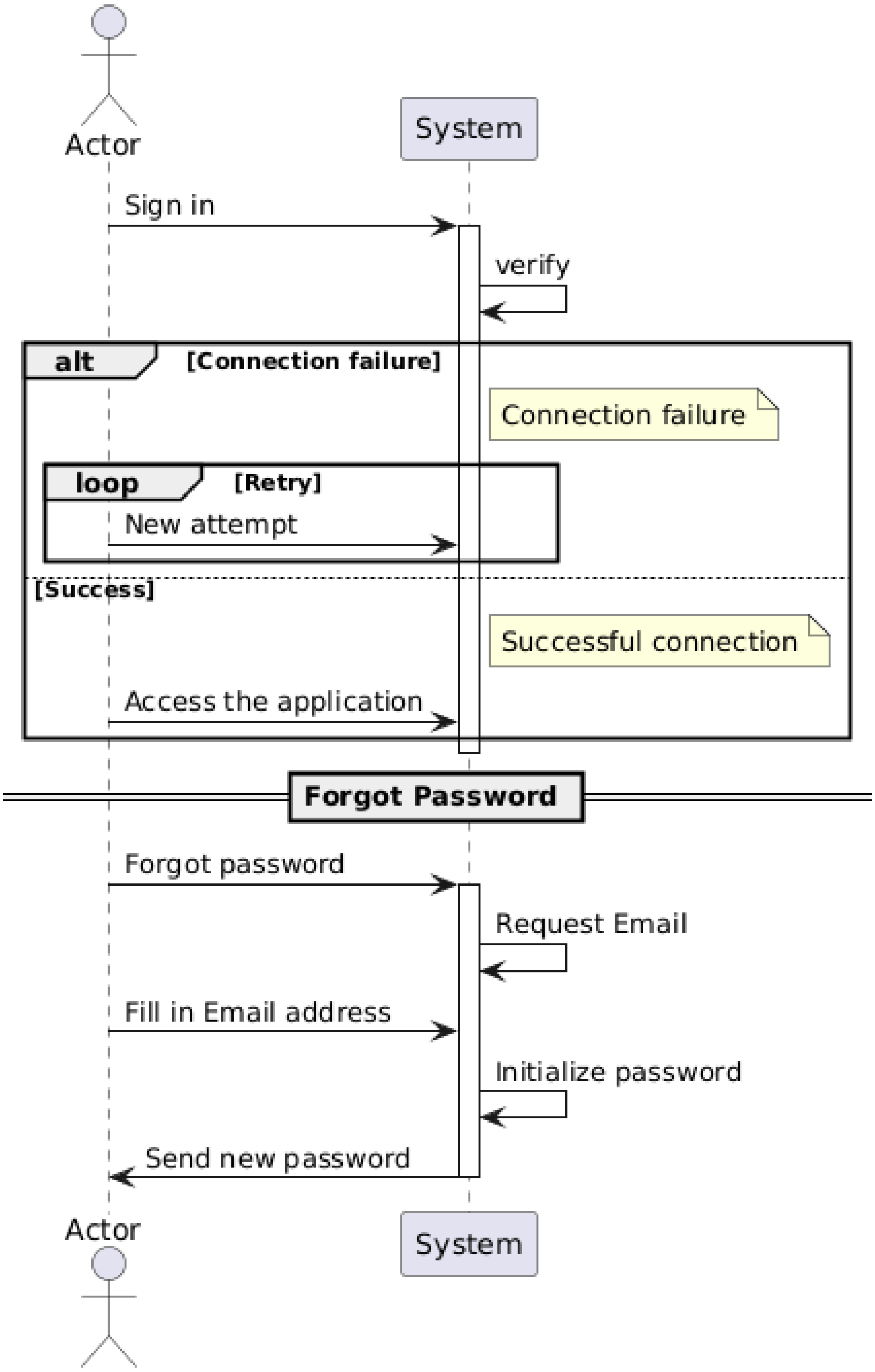

Figure 33: Authentication Sequence Diagram

- Teleconsultation

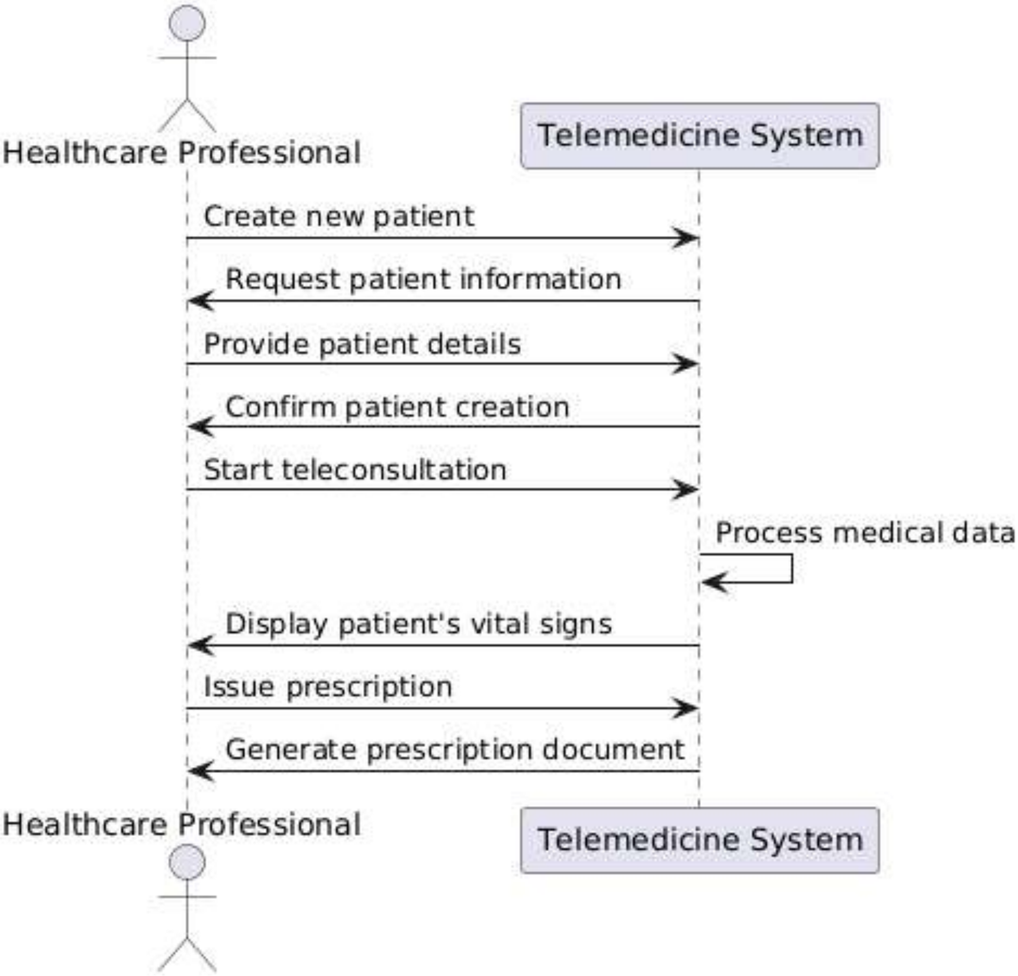

Figure 34: Teleconsultation Sequence Diagram

3.7.2 Platform for Managing Actors and Patients

This software manages information for all stakeholders in the system. With a simple click, users can access information about doctors and healthcare professionals, based on their specialization and location. Similarly, actors can search for patients based on name, district, or required specialization. They can communicate via video calls for assistance or medical expertise. User access rights for viewing, reading, or writing information may vary depending on their role, ensuring data confidentiality and providing only necessary information to maximize efficiency. Only the administrator has full privileges to access all features and settings of the application.

Upon startup, the platform prompts users to authenticate with a login and password. The authentication is successful if both data exist and match in the database. These elements are crucial as they determine the user's access level to different sections of the software.

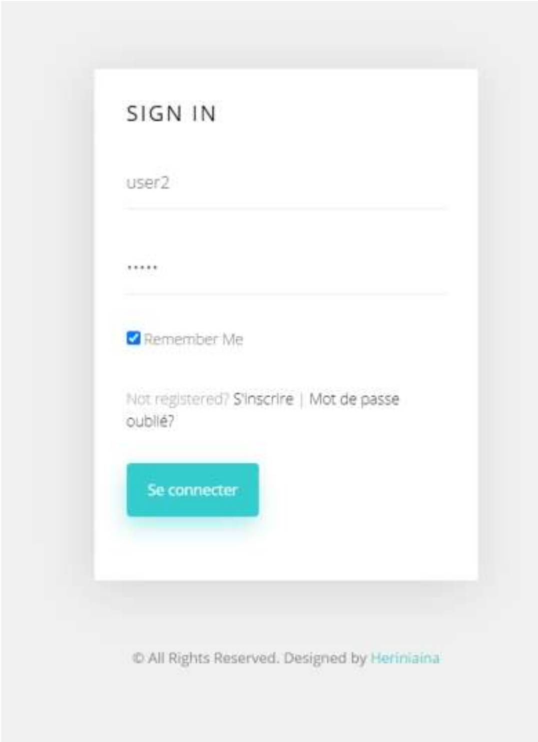

Figure 35: Login Form

If the user does not have an account, they must register by filling in the following information:

- Image
- Login
- First Name
- Last Name
- Email
- Password
- Confirm Password
- Specialization
- Location
- Gender
- Role

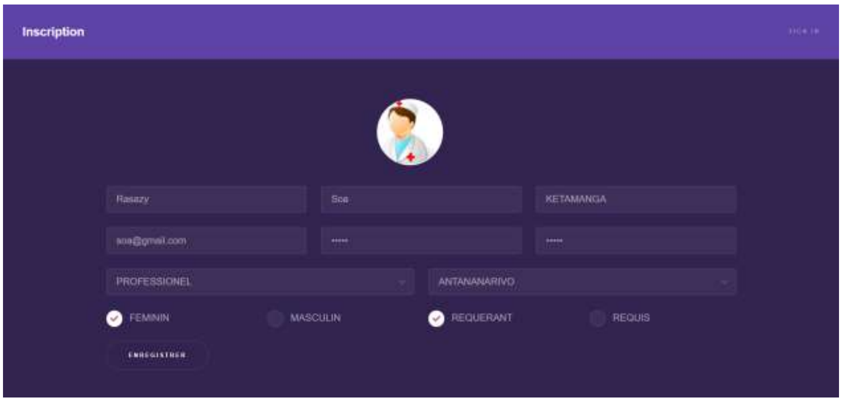

Figure 36: Registration Form

Once the account is created, it remains inactive until the administrator approves and activates it. The email address serves as the user's identifier.

In case of a forgotten password, the account owner can request a reset via the recovery email, and the system will send a new password for re-access.

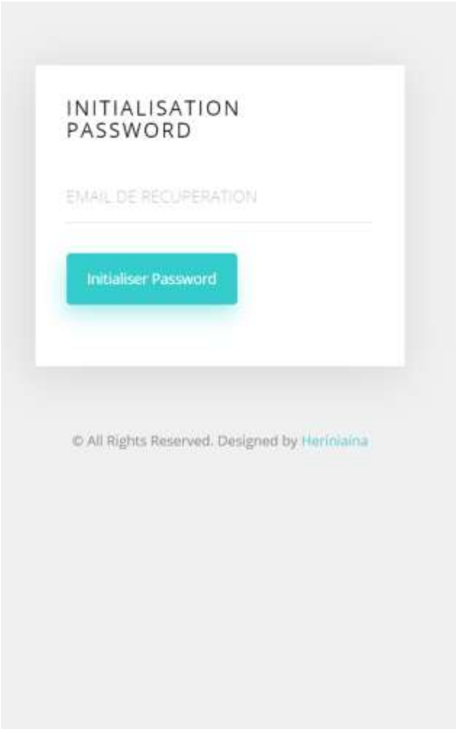

Figure 37: Password Reset Form

The homepage is displayed immediately after a successful login. It greets the user with a welcome message and introduces the platform. On the left, user account information and the menu bar allow access to different application functions.

Figure 38: Homepage

The "SPECIALIZATION" menu presents descriptions of available specializations within the system. Users can consult them easily with a keyword search. Only the administrator has the privilege to add, modify, or delete them.

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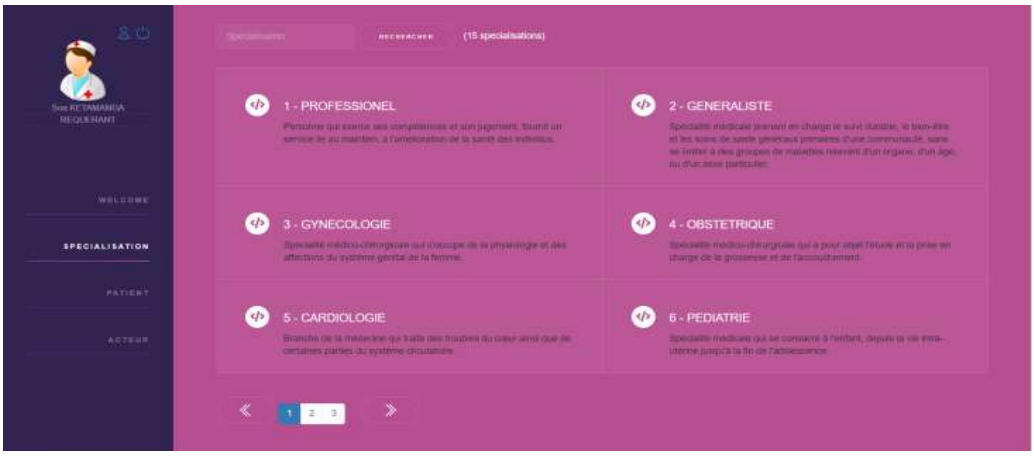

Figure 39: Specialization Section

Through the "PATIENT" menu, actors can access patient information. The application generates a QR code, which serves as the patient's identifier. There are also buttons to insert or modify this information, as well as to create and download a medical prescription in PDF format.

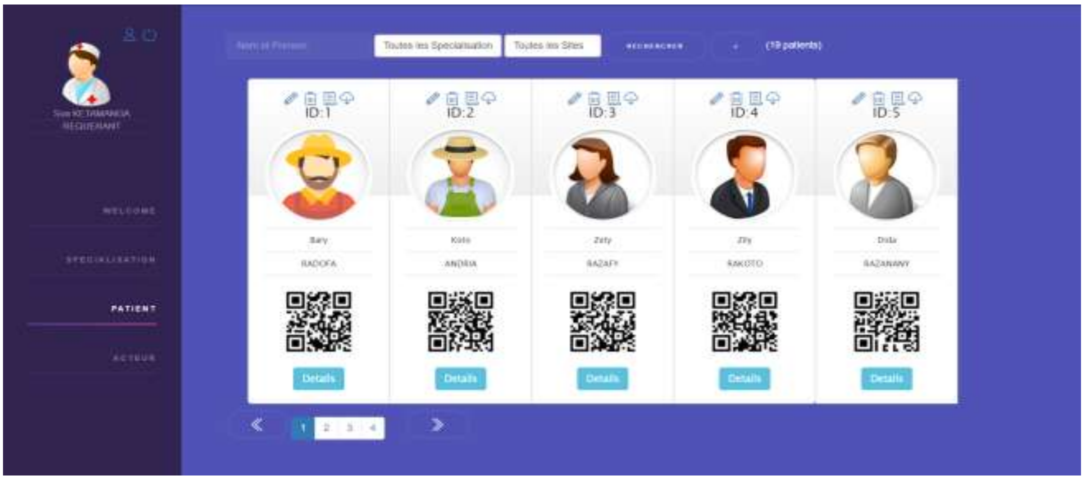

Figure 40: Patient Section

The "ACTOR" menu is a directory of the required professionals, doctors, and the administrator. They can communicate with each other via video calls.

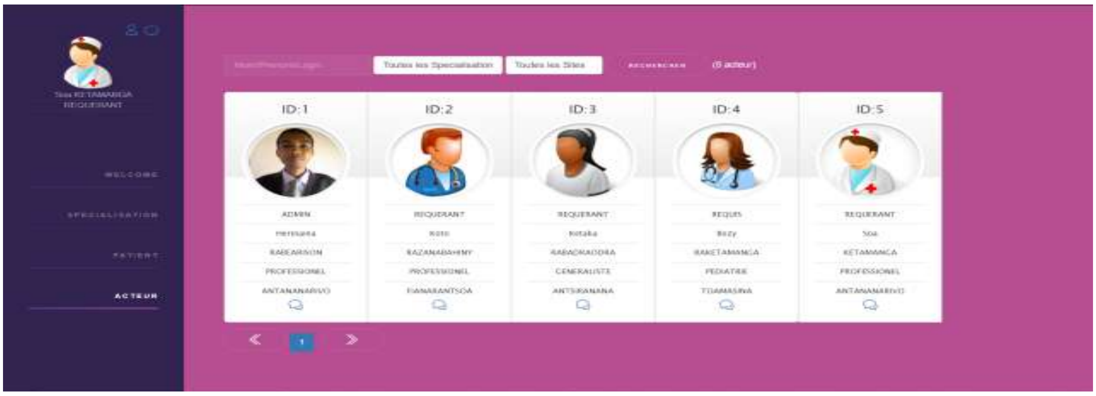

Figure 41: Actor Section

Only the administrator can block, unblock, modify, or delete accounts that they do not own.

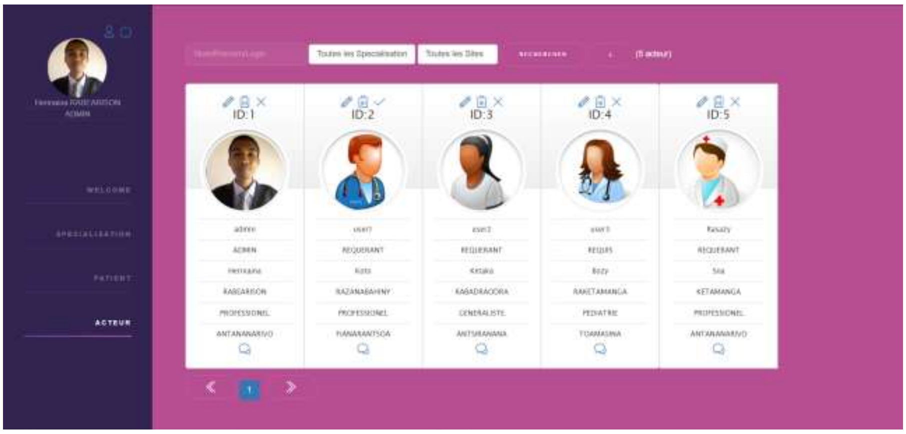

Figure 42: Administrator Interface

3.7.3 Real-Time Data Visualization

Before conducting the teleconsultation, the requesting staff enters the new patient's information into the system. They then select the treating physician based on the required specialization.


Figure 43: Patient Information Preview

Next, the various sensors are connected to the patient, and their vital signs are visualized. The interface displays data from the electrocardiogram, auscultation, temperature, heart rate, pulse oximeter, and blood pressure, as shown below.

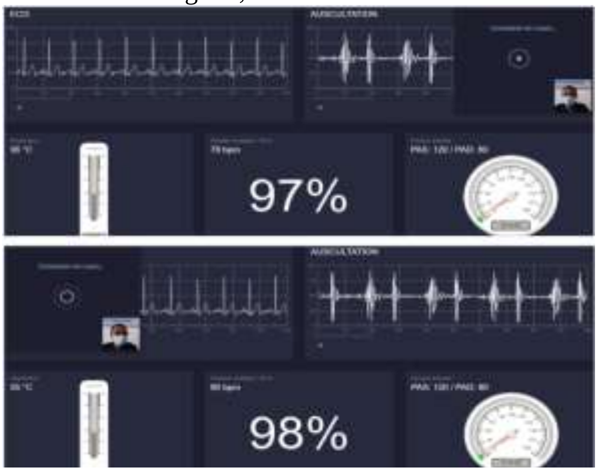

Figure 44: Real-Time Vital Sign Visualization Interface

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3.7.4 Prescription

After the teleconsultation, the consulting physician provides a medical prescription. This document includes the patient's information, the prescribing doctor's details, observations, and prescribed medications. The QR code lists the medications and recommendations, which will help combat self-medication and the illegal purchase of drugs in illicit markets.

ORDONNANCE

Patient ID : 1
Nom et Prénom : BARY RADOFA
Adresse : LOT36BIS15

DIAGNOSTIC - OBSERVATIONS

-maux de gorge
-diarrhée
-conjonctivite
-maux de tête

PRESCRIPTIONS

-Azithromycine
-MAGNE B6
-ACE Sélénium Zinc
-Vitamine C
-CVO +
-Mivavaka tsara

Consultation du 16/04/2021
Par Dr. Bozy RAKETAMANGA

Figure 45: Medical Prescription Model

3.8 COST ESTIMATION, STRATEGIC PROJECT ANALYSIS, AND RESULTS DISCUSSION

3.8.1 Project cost estimation

The initial investment includes preliminary studies, the provision and implementation of the solution (infrastructure, hardware, software, associated services like installation and training), and project management. The goal of cost estimation is to generate information for budgeting, depending on the project's progress. Estimation methods vary depending on the project's phase. At this stage, we are in the initial study phase, focusing on estimating the design cost of the device based on each module's cost.

Table 5: Device Cost Estimation

Component	Estimated Cost
Data Acquisition Unit	
Stethoscope module	$8
ECG module + accessories	$31
Pulse Oximeter module	$8
Blood Pressure module	$18
Data Processing Unit	

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Microcontroller + accessories	$17
Data Transmission Unit	
Module + accessories	$14
TOTAL ESTIMATED COST	$96

3.8.2 Swot analysis of the project

Figure II-15 presents the SWOT matrix, identifying the Strengths, Weaknesses, Opportunities, and Threats of the project.

S (Strengths)	**O (Opportunities)**
• Quality innovative products • Strong brand reputation • Skilled workforce Recognized expertise	• Controls in development process and imple-mentation • Significant investment in R&D • Specialized products with high added value • Development of technology Large-scale projects
W (Weaknesses)	**T (Threats)**
• Absence of a structured IT system • Dependence on the base component • Significant price for customers Poor communication	• Arrival of new technologies • Changing customer behavior • Heavily guarded sector by trends/competition Reactive to new technological adaptations

Figure 46: SWOT Analysis of the Project

The matrix reveals that deploying the telemedicine project offers numerous advantages, particularly in addressing medical deserts. It can assist people in isolated regions lacking sufficient healthcare professionals, meeting a fundamental population need. This field is expanding due to digital technology development and can branch out into other healthcare sectors like robotic surgery and telecardiology. However, every new technology introduces new risks, some of which may not be identified at the project's start. These risks include challenges with actors (training, adapting to new technologies, responsibility shifts, resistance to change), hardware (IT networks, basic components for device manufacturing), and dependence on suppliers for component imports, especially in developing countries

CONCLUSION

This project aimed to develop an innovative telemedicine system for remote healthcare services, focusing on creating a comprehensive, interoperable platform for patient monitoring and consultation. The system integrates various sensors for acquiring real-time health data, such as ECG, pulse oximetry, blood pressure, and stethoscope measurements, with an Ethernet Shield for data transmission and processing.

Through detailed analysis and design, we have established a clear architecture for the telemedicine system, including modules for data acquisition, processing, and transmission. The use of UML modeling, with case diagrams, class diagrams, and sequence diagrams, has allowed for effective software development, facilitating the creation of a user-friendly interface for doctors, patients, and administrators. Additionally, the platform supports real-time data visualization, enabling healthcare professionals to monitor and provide consultations remotely.

The project also explored the cost estimation and strategic analysis of deploying such a system. The estimated costs, including the necessary components, microcontroller, and software development, were outlined. Moreover, the SWOT analysis revealed that while the project holds immense potential in bridging the healthcare gap, especially in underserved areas, it also faces challenges related to technological adaptation, training, and dependency on suppliers.

Ultimately, this project demonstrates the viability of telemedicine in improving access to healthcare, offering a scalable solution for remote consultations, monitoring, and medical assistance. The results pave the way for further research and development, including the integration of emerging technologies like robotic surgery and telecardiology, to enhance healthcare services in isolated or underserved regions. By leveraging advancements in digital technology, this telemedicine solution offers a promising future for healthcare delivery.

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