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Research Article

Implementation of a Real-Time Wearable Vital Signs Monitoring System for Online Medical Consultation

Aliyu Idris Balarabe*, Alenoghena Caroline Omonatse, Zubair Suleiman and Salawu Nathaniel

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Abstract

Wearable health devices allow acquisition of patients' vital signs and health status monitoring outside conventional medical facilities for remote medical diagnosis and rapid medical attention during emergencies. While attempting to provide real-world online medical services, researchers have developed several Internet of Medical Things (IoMT) telemedicine systems such as the conventional smart wearable health devices for vital signs monitoring readily available from the market. However, optimal exploitation of critical vital signs data acquired from these traditional devices for online medical consultations in real-time has not received adequate attention. In this paper, an IoMT-based wearable Vital Signs Monitoring Network (VIMONET) that employs the widely accepted publish/subscribe lightweight Message Queuing Telemetry Transport (MQTT) communication protocol was developed. The VIMONET comprises of a contactless medical data sensing unit, transmitting unit and an e-clinic platform for real-time medical consultations. The e-clinic platform offers online medical services by utilising vital signs data obtained from wearable hardware for professional consultations in real time. Performance analysis indicates that the wearable VIMONET offers stable high-speed data transfer at an average of 337.9ms, about 12.63% slightly above the benchmark for industrial IoT applications. An average throughput of 1122.58Bps which signifies the data transmitted, read, stored and available for request on the e-clinic server was also achieved.

Keywords: E-clinic platform; Communication protocol; Telemedicine; Vital signs; Wearable device

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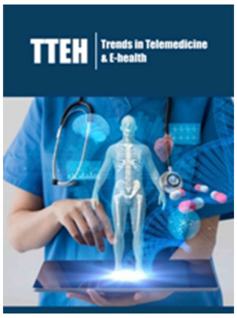

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Introduction

Telemedicine is viewed as the use of ICT for collecting, organising, storing, retrieving and exchanging sensitive data remotely [1]. In a broader term [2] considers telemedicine as the application of computer science and communication systems, sophisticated medical expertise and unconventional medical tools to improve healthcare delivery in hospitals and medical centres by fully utilising the technology and tools in a specific area. One particular application area of computer network technology in health is the application of Internet of Things (IoT) in telemedicine which was conceived by Kevin Ashton in 1999 [3]. IoT is a means of connecting physical objects or Device to Device (D2D) to other network devices or routers for the exchange of data regardless of time and location [4]. Since its evolution, IoT has transformed the healthcare industry enabling various applications for healthcare and the emergence of the Internet of Medical Things (IoMT) [5-9], Healthcare IoT (H-IoT) [10], Internet of Health Things (IoHT) [11-13] and Wearable Internet of Things (WIoT) [14]. Another closely related concept is the integration of telemedicine and virtual software [15] and the combination of

IoT and expert system for telemedicine [16-19]. Other technologies used for IoMT telemedicine include Artificial Intelligence (AI) [20]. Machine Learning (ML) [21-25], Deep Learning (DL) [26], Reinforcement Learning (RL) [26,27], Blockchain [4,28] and Big Data Analytics (BDA) [29,30]. These technologies have been used for avoidance, detection, monitoring, regulation, tracking, disease management, outbreak prediction, data analysis and decision-making procedures [31]. More emerging technologies are highly projected due to the upsurge of IoT devices, ubiquitous computing, sensing and cloud computing for telemedicine.

IoMT is an extension of IoT specifically for healthcare to create a medical platform for remote medication and disease management used by healthcare providers and other stakeholders [32]. The emergence of IoMT has revolutionised healthcare delivery solutions [33]. It is the foundation of smart healthcare or IoHT, made up of healthcare devices and applications linked to a network or Information Technology (IT) through the internet [34-36]. Figure 1 depicts the transformation of IoMT. The combination of telemedicine and IoMT is a foreseeable trend in the growth of modern healthcare delivery. Deploying IoMT in telemedicine could significantly improve the challenges of standardisation in the medical industry caused by regional differences [2]. Implementing a standard IoMT communication protocol with the capability of cross platform interoperability will transform healthcare services into a more personalised system [14]. Economically, IoMT is projected to fund between 1.1 to 2.5 trillion USD yearly financial impact in the health industry by 2025 [6]. Some benefits of using IoMT include a reduction of workload in hospitals, provision of secure medical data transmission, provision of a network for healthcare information sharing and fast healthcare data for emergency medication, etc. [37]. IoMT is majorly for the transmission of medical data between smart objects [38] or "medical things" over the Internet. Other applications of IoMT in telemedicine include the following:

A. Chronic disease management [39].
B. Daily healthcare management in hazardous areas [40].
C. Remote assisted living (Tele-health) [41].
D. Automated seizure detection [35].
E. Remote intervention [42].
F. Preventive care [43].
G. Remote vital signs monitoring [44-46].
H. Infectious disease prediction [47].
I. Improved drug management [48].
J. Smart healthcare delivery [49].
K. Human Activity Recognition (HAR) [50].

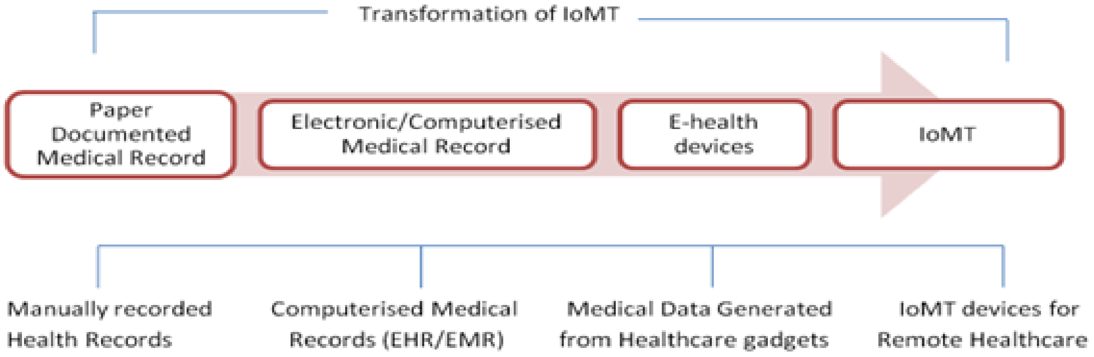


Figure 1: IoMT transformation.

Related Works

Telemedicine is not a plug-and-play technology, it depends on the application scenario subject to different reforms [51]. Different architectures have been adopted utilising available communication protocols best suitable for use case scenarios using several platforms. In order to achieve efficient medical data transmission across all platforms for telemedicine using IoMT, several researchers have tried to implement different kinds of architectures. Most of these works focused on network security [52-54], e-health architectures and security [55], 5G and IoT for e-health [56] and high data rate video streaming [24], factors that impact adoption of telemedicine [15] etc. Issues such as accuracy, security, impersonation and privacy of data in the IoT domain were also highlighted [57,58]. Despite substantial advancements in the deployment of wearable health devices, the devices still have major drawbacks such as poor data representation, lack of user perspective at the design stage, inconsistent readings and the use of unregulated applications that have not been certified by recognised medical and regulatory agencies [59]. Most importantly, wireless medical data transmission using conventional wearable devices is not secured due to a lack of standard regulations [60]. Thus, optimal utilisation of vital signs medical data acquired from conventional devices for online medical consultations and diagnosis in real-time is not guaranteed. Hence the need to provide a reliable network for seamless online healthcare access using secured data transmission network across different platforms and devices.

One major issue limiting the implementation and deployment of telemedicine is the lack of interoperability in communicating medical data from wearable devices to back-end server. To address this issue, [40] introduced Open Mobile Alliance (OMA) LwM2M into a continua architecture that maps BLE profiles into LwM2M. This approach was applied in order to develop a standard protocol that addresses IoT interoperability challenges in wearable health devices for accurate remote health monitoring. The research explored the interoperability standards using different evaluation benchmarks and proposed a management solution for remote personal health device. The operating process phase was validated using two testing scenarios namely: battery level monitoring and firmware update by utilising the Leshan server. The work of uses a single Personal Health Device (PHD) device due to time and lack of other devices. Other PHDs were not considered in the approach. Also, no sufficient work was done to check the security in terms of authentication and authorisation of access for the architecture.

Materials and Method

Three main stages are involved in the system design as shown in Figure 2. This includes the wearable device layer, the network layer and the application layer. These stages represent the electronic unit, the web unit and the mobile nodes respectively.

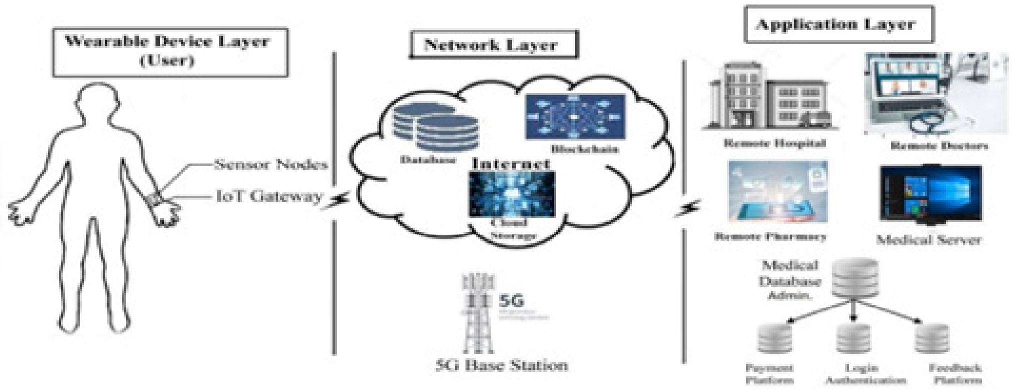


Figure 2: Wearable VIMONET system architecture.

Wearable device layer

The wearable vital signs sensing design consists of the LiPo battery power supply unit and a charging circuit to power the A9G module. 1.8V and 3.3V regulators are used to power the heart rate sensor and the MCU respectively. The system block diagram is shown in Figure 3.

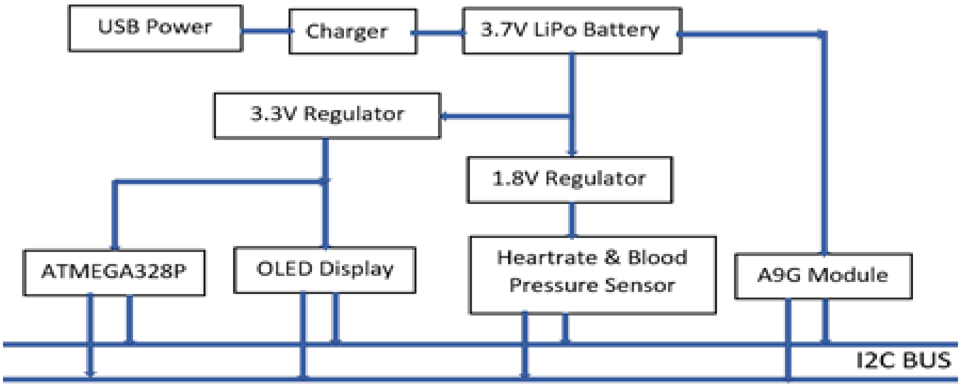


Figure 3: Block diagram of wearable hardware design.

Design components analysis

This section consists of the components used for the implementation and their specifications as follows:

USB power supply: The wearable device is powered through a USB Power source and a Lithium-ion Polymer (LiPo) battery source. A linear low dropout 3.3V regulator is used to supply a stable voltage level for the onboard components.

Battery charger: The MCP73831 linear charge controller was employed to handle the battery charging process. The MCP73811 charge controller consists of a charge status pin for monitoring battery status. This charge status pin is connected to the atmega 328MCU. The USB component is a universal LiPo battery charger that can be connected to any available DC source with a USB port for charging the battery in idle mode and during use. The rechargeable LiPo battery contains a polymer electrolyte instead of a liquid electrolyte. The charging circuit is shown in Figure 4.

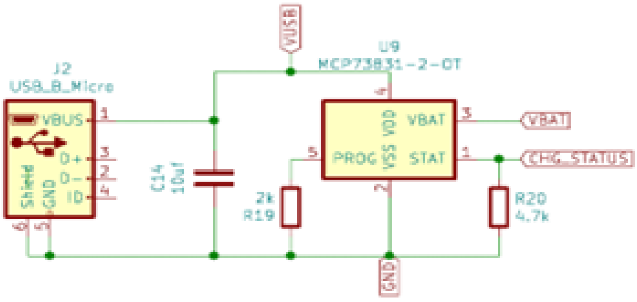


Figure 4: LiPo battery USB charging circuit.

Voltage regulator: The voltage regulator circuit features an LM1117 regulator with a 3 pin configuration that regulates through the pin 3 (output pin) as shown in Figure 5.

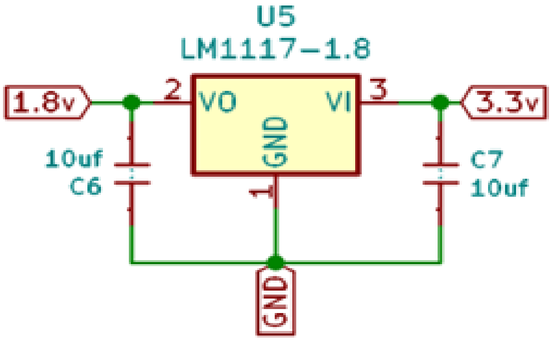


Figure 5: Voltage regulator circuit diagram.

Heartrate and blood pressure sensors: MAX32664D in Figure 6 was used for the heart rate and BP sensing. It is a variation of MAX32664 sensing devices that allow the user to obtain raw vital signs data including the diastolic and systolic BP, SpO2 and heart rate data using finger contact. It could be programmed by connecting the sensing device through the I2C port which is also a means for communicating with the arduino microcontroller unit.

Figure 6: Max30101 HR and BP sensor.

Display: The board can work with any display with an I2C interface. For this project, 0.91-inch (128x32 pixel) OLED is recommended and utilized for this application because of the small form factor, low cost and low power features.

A9G module overview: The LoRa communication protocol for the wearable device was achieved using the A9G module (Figure 7). Surface Mount Device (SMD) module. The A9G was used to interface the Organic Light Emitting Diode (OLED), body temperature, HR and BP sensors through the I2C bus interface. The objective is to read the sensor data process and relay the sensor values to the cloud. The A9G module is a low-power Surface Mount Device (SMD) version with GPRS/GSM/GPS capabilities. It also has the capability of connecting to the GSM and GPRS at a low cost and reduced time. The A9G module that uses low power with GPS support was used as an IoT gateway to serve as a bridge/communication link between IoMT devices within the field, the cloud (VIMONET platform) and the mobile nodes. It uses the Message Queuing Telemetry protocol (MQTT) to send and retrieve data from the MCU. The A9G module sends sensor data to the VIMONET cloud server for monitoring and feedback using API through wearable devices.

Figure 7: A9G module.

The microcontroller unit (MCU): In the Printed Circuit Board (PCB) design using the KiCad 7.0, the Microcontroller Unit (MCU) consists of the atmega328p shown in Figure 8, SMD version used to interface the various on-board peripherals which include the HR and BP sensors, the A9G module and OLED display through I2C bus interface. The board is intended to work with various displays using the I2C interface. 0.91-inch OLED (128 x 64 pixel) was utilised for this design due to its small form factor, low cost and low energy features. The major components for the wearable device are the MCU circuit with the ATMEGA328 and Max 30102 heart rate and temperature sensors readily available from the market. The SMD version of the microcontroller was chosen to reduce circuit complexity. Both circuits for the MCU and the sensors were implemented in the KiCad software. The ATMEGA328p Microcontroller is a low-power, SMD version utilised to interface the various onboard peripherals such as the A9G module, OLED and heart rate sensor via the I2C bus interface. The complete circuit design is shown in Figure 9.

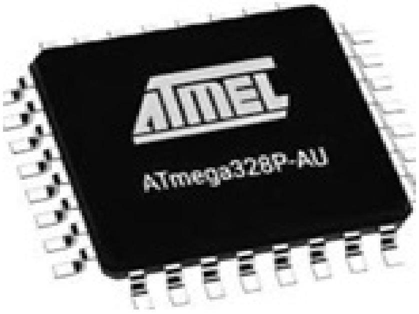
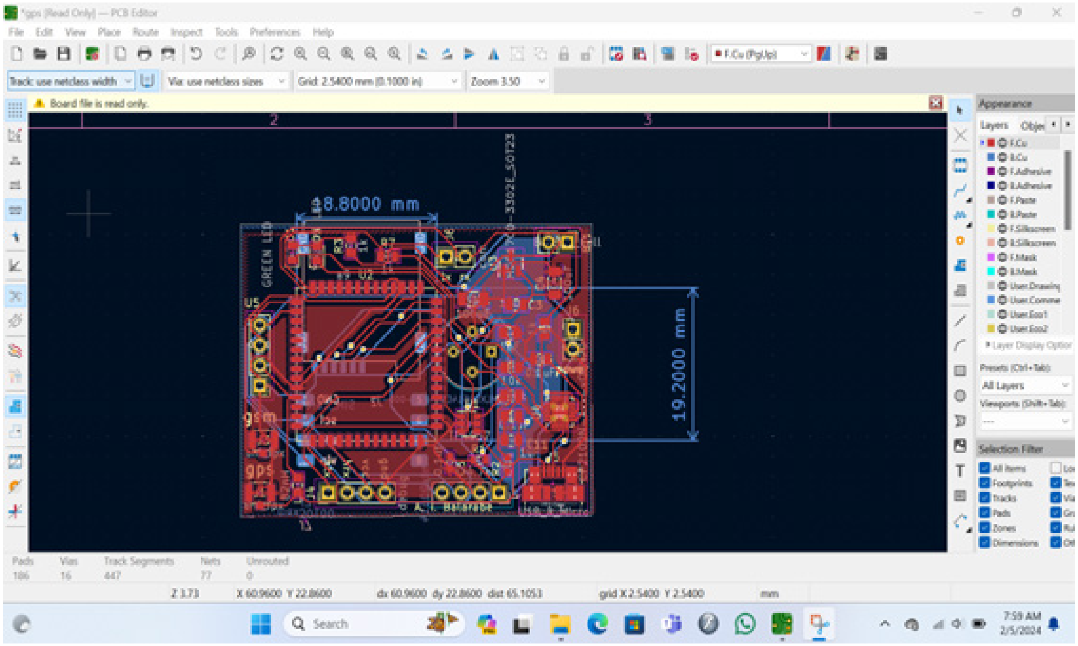


Figure 8: ATMEGA 328p SMD version.



*gps [Read Only] — PCB Editor

Board file is read only.

Figure 9: Circuit design PCB layout.

VIMONET database processing and web platform design

This section consists of the platform design, remote access, software and hardware components used of the e-clinic.

E-clinic platform design: The e-clinic Platform was developed using a client-server architecture as depicted in Figure 10. The client-server is an architecture that allows many clients (remote processors) to request and receive service from a centralized server (host PC). The centralized server holds data and handles the processing of requests from the clients. The clients in the VIMONET e-clinic are the mobile application, the web front-end and wearable devices with sensors. In the platform architecture, the clients will consume the application's API via HTTP requests to the server. Once the server can deliver the client's request, the API returns a response and the resource required translates into mission success. In a situation where the request is not accomplished, then the API will return with an error message. The entire client request flow process is depicted in Figure 11. The VIMONET hardware wearable devices communicate with the database via the API powered by the Hypertext Preprocessor (PHP) framework called Laravel. The developed e-clinic platform's front end uses the API exposed to it from the server. The API sends the request to the application logic layer, where the processing of user data is carried out and stored. The front end was developed using HTML, Chirp Spread Spectrum (CSS) and JavaScript. The web frontend for the VIMONET is everything a user sees from fonts and colours to drop-down menus and sliders when navigating a website/platform via a web browser.

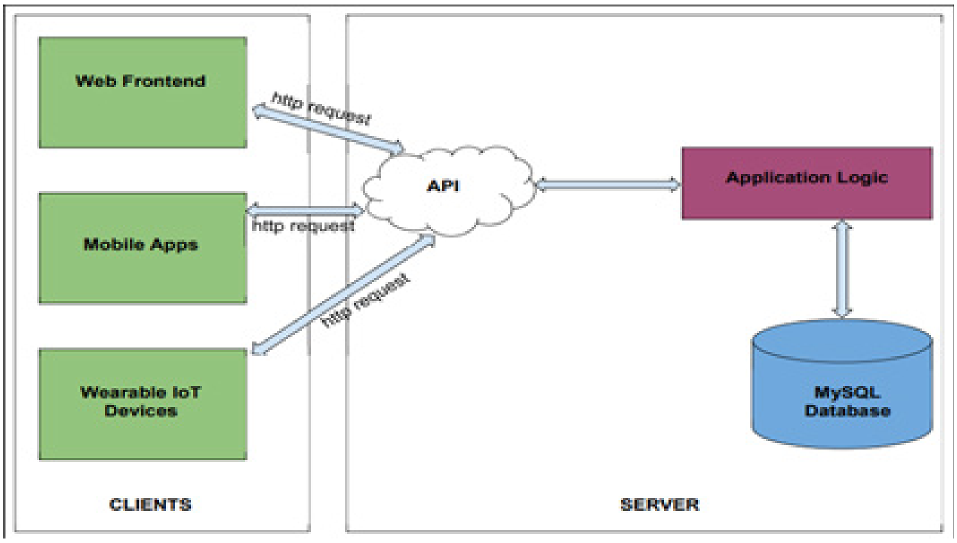


Figure 10: VIMONET e-clinic platform architecture.

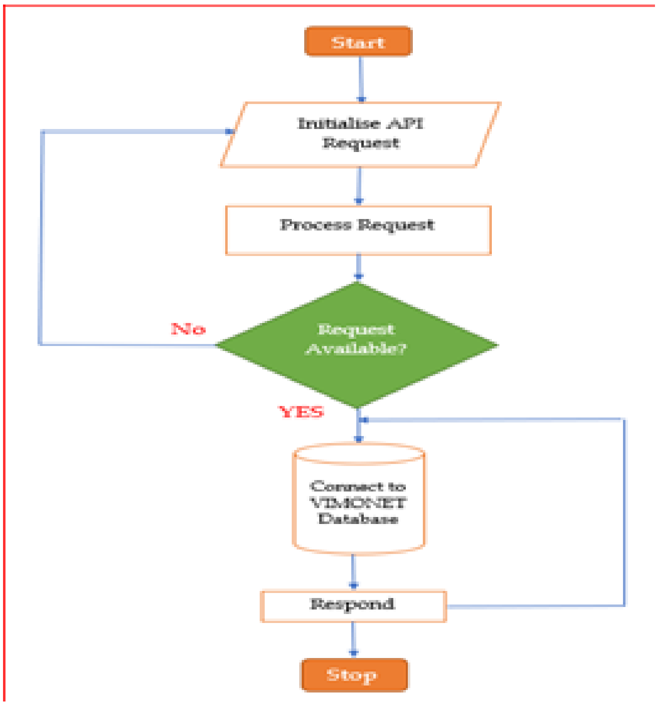


Figure 11: Client request flow process.

VIMONET e-clinic remote access: The developed VIMONET e-clinic platform uses the client-server architecture chosen because of its defector standard in online systems. It allows remote access by using just a web browser: reliable and stable work via the internet without the need for installing additional software on the client side. The overall VIMONET architecture for online consultation and diagnosis is shown in Figure 12. The platform server in Figure 12 uses a Linux, Apache, MySQL and PHP (LAMP) stack server developed to house the e-clinic platform code and database. The wearable devices and other applications connect and reuse codes via the API. This enables clients/ patients to assess the same resources both on the web and on other devices.

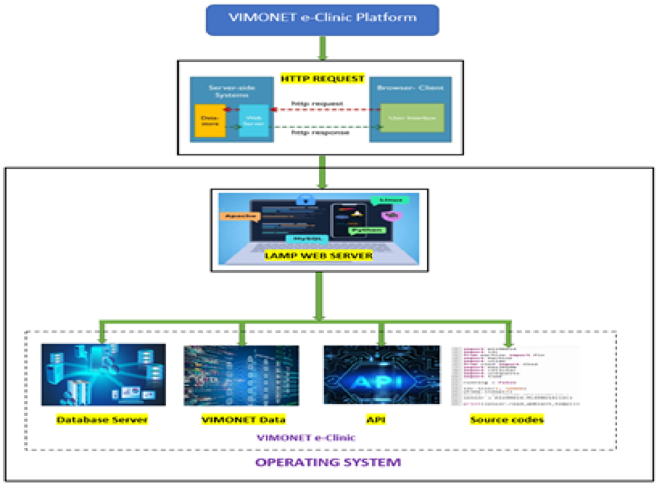


Figure 12: VIMONET e-clinic platform structure.

Components of the VIMONET e-clinic platform: The Major components employed to implement the VIMONET platform include:

a. Virtual web server: It consists of a Linux, Apache, MySQL and PHP (LAMP) stack server which houses the e-clinic platform code via the API.

b. Database: It allows the wearable and other applications to connect and reuse codes.

c. Source codes/API: The Micro python, PHP and reuse codes were used as API's.

d. Hosting service provider: Digital Ocean Inc.: A cloud infrastructure provider in the US.

Hardware and software configuration: The developed server for the platform is a compute-optimized virtual machine with dedicated hyper-threads from genuine Intel CPUs for workloads that rely on CPU more than RAM. The system is designed for CPU-intensive applications like CI/CD, video encoding, machine learning, ad serving, batch processing and active front-end web servers.

User authentication: One major security feature implemented in the VIMONET is user authentication. This is the process of verifying the identity of the wearable device user or client. Authentication on the e-clinic is password-based authentication. A client on the platform has to authenticate using a combination of a registered email address and password set during registration or by an administrator.

VIMONET APIs

APIs are application programming Interfaces that help third-party applications interface or use resources from a web application. APIs were written to enable VIMONET wearables to receive and send data to the e-clinic database. HTTPS is the primary protocol for any kind of web-based communication. This protocol was used to design the web services API that the wearable devices rely on for data transfer. The wearable devices communicate with the database via the APIs, the API itself will be powered by a strong Hypertext Preprocessor (PHP) framework called Laravel.

Vital signs data acquisition and integration into the VIMONET

Telemedicine data requires urgent traffic because it carries critical information concerning the patient's condition. The algorithm must take care of energy efficiency, data security, low latency, high throughput and reasonable QoS. Data collection is achieved by measuring patients' physical parameters using the medical sensor (max 30102) that is connected to the Microcontroller Unit (MCU). The MCU is responsible for collecting sensor data and uploading it over the VIMONET network. The sensor transmits data in real-time to the network continuously based on the implemented algorithm. The flow diagram of the deployed VIMONET algorithm is depicted in Figure 13.

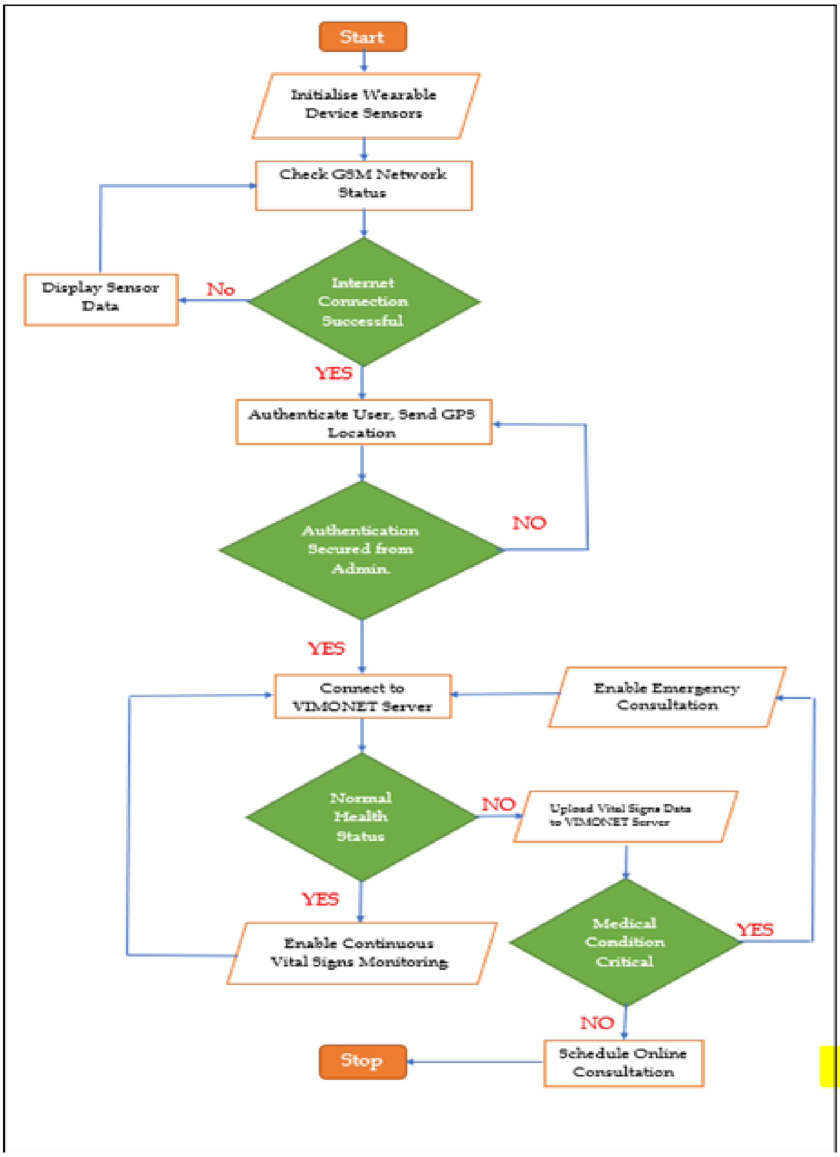
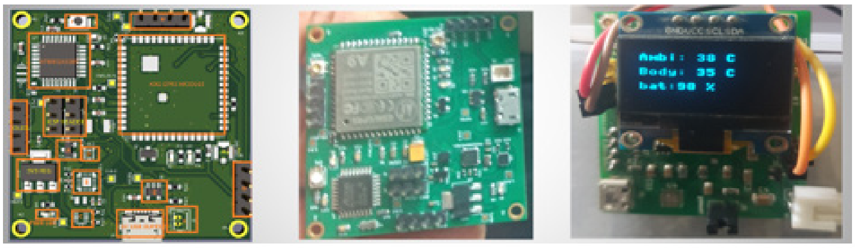


Figure 13: Flow diagram for wearable health device.

Testing and Results

Board testing/troubleshooting procedure

The fabricated PCB is shown in Figure 14. It is recommended to test the board to ensure it works based on the specifications. The PCB design consists of test terminals placed at critical points of interest to make testing easy. The test points are for power testing. The following procedure describes how the test was conducted on the board after production.



(a) Prototype design (b) Functional PCB (c) Implemented device

Figure 14: Wearable device implementation.

Power testing

By connecting a 5V USB power supply to the board, the power indicator turns on at this point. If not, use a voltmeter to test the voltage at the VUSB test point and the 3.3V test points to see if they are supplying the correct voltage level (5V and 3.3V respectively). The power LED is connected to the 3.3V regulator output. Using a voltmeter test all the power test points for each of the peripherals to ensure they are receiving the correct voltage level. The square yellow points in Figure 10 show where the test points are onboard.

Sensor testing

After ensuring that the sensors are receiving the adequate voltage level for normal operation proceed to write some codes to read their values and display them on LCD. The following endpoints have been created on the VIMONET platform.

A. Update window: To update user vitals (temperature, blood pressure and heart rate) information on the database.

B. Data retrieval: To retrieve user vitals and information from the database.

Alpha (usability) test

Alpha test was conducted on the developed VIMONET e-clinic platform to determine if the system conforms to features specified on the software requirements. This test was specifically carried out to ensure the following:

a) The VIMONET e-clinic platform contains all the functions specified

b) Functionality of all features it was intended to perform

c) Proper handling of exception conditions

d) Complete and correct output delivery

e) System performance within design specifications

f) Insignificant errors in the entire system to enable user experience test

The Procedure for the Alpha test includes:

A. Client/user test script which shows step-by-step instructions to be followed by the to assess the platform.

B. Cheat sheet guiding the user on the information and hints on how the system works.

C. Error template showing an organised step for documenting issues noticed during the test.

System performance

The VIMONET wearable device monitors rapidly changing health conditions in real-time. For effective system performance, therefore, there is a need for high throughput showing the amount of data received and written to the server, data read from the wearable device and returned to the requesting system in Bytes Per Second (Bps). Also, the latency should be as low as possible to avoid transmission delay in the cloud environment, while enabling large data transfer at high speed. Also known as one-way delay, latency shows the time for the wearable data to move from the device to the VIMONET server. The throughput and latency results obtained from the web server while uploading data are presented in Table 1.

Table 1: Latency and throughput test results.

Number of Runs	Latency (milliseconds)	Throughput (Bps)	Data Transferred (bytes)
1	362	1033.15	374
2	308	1214.29	374
3	315	1187.30	374
4	307	1218.24	374
5	328	1139.02	374
6	297	1259.60	374
7	308	1214.29	374
8	323	1157.59	374
9	412	907.77	374
10	419	892.60	374
Average values	**337.9**	**1122.58**	**374**

Discussion of results

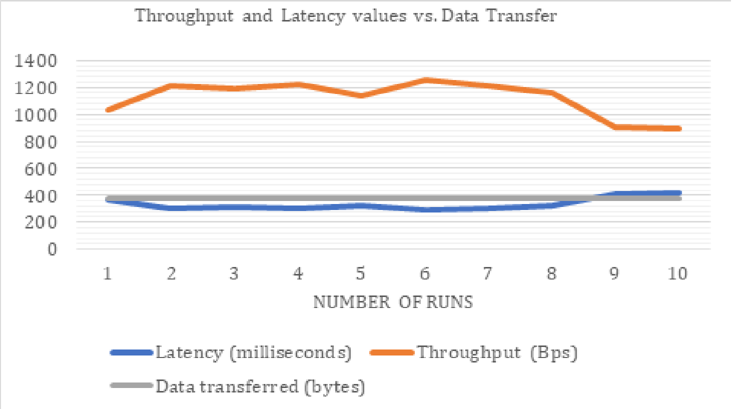


Figure 15: Latency and throughput test results.

The results obtained from this research show how measured vital signs data could be accessed from the web by providing the required fields pre-defined by the web server agent. The developed wearable device measures body temperature and heart rate and uploads the same in real-time to the VIMONET server with user location for online diagnosis and consultations. The alpha test and system performance also show that the system is feasible in real time providing a low latency with high data transfer and throughput as shown in Figure 15.

Conclusion

This paper presents the implementation of a real-time wireless heart rate, Body Temperature and Blood pressure monitoring device for online medical diagnosis and consultation. An electronic real-time wearable device was implemented to read the vital signs using contactless heart rate, blood pressure and temperature sensors connected to a microcontroller for data processing. The system uses an approach that employs the MQTT communication protocol through the A9G module between the medical sensors and the IoMT gateway. The vital signs monitoring system consists of a network that transmits medical data to an e-clinic platform for diagnosis and consultation in real time. The client interface is provided through an API in the web platform to access web-based health professionals in remote locations. Results obtained from this research show how measured vital signs data could be accessed from the web by providing the required fields pre-defined by the web server agent. The developed wearable device measures body temperature and heart rate and uploads same in real-time to the VIMONET server with user location for online diagnosis and consultations.

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