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Exploring Healthcare Applications of the Internet of Things: A Comprehensive Survey

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ABSTRACT: The Internet of Things (IoT) is transforming healthcare by revolutionizing patient care through enhanced diagnostics, real-time examinations, and preventive as well as actual treatments. IoT in healthcare involves smart devices equipped with sensors that accurately collect data for further analysis and action. These devices leverage real-time data to enable monitoring, tracking, and management, thereby improving healthcare outcomes. The efficiency of IoT leads to better decision-making and reduces the risk of errors. Additionally, IoT can be used to prevent machine failures, improving the reliability and quality of patient supply chain responsiveness. This paper provides a comparative survey of IoT applications in the healthcare system.

KEYWORDS: Internet of Things, Wireless Body Area Network, Wireless Sensor Networks, Wearable Sensors, Healthcare System.

I. INTRODUCTION

The Internet of Things (IoT) represents a form of wireless connectivity that links objects and people across healthcare ecosystems to obtain, combine, and analyze data that was previously inaccessible. In healthcare, IoT commonly involves connecting people. By tracking each patient, managing proper equipment, and providing drugs efficiently and safely, IoT extends care beyond the hospital walls and promotes wellbeing by aiding people in making healthy choices. This capability has led many healthcare companies to assert that IoT is driving the creation of new business models, bringing the future of healthcare closer than we think. Thus, IoT is transforming the healthcare system.

The Internet is no longer just about connecting people, known as the Internet of People (IoP); it now connects objects, hence the term Internet of Things (IoT). The two crucial keywords are "Internet" and "Things." The Internet is a network of networks, a medium through which devices connect, and the "things" can be any object equipped with the intelligence to connect to the Internet, such as software- or electronics-embedded objects. These things extend beyond PCs, laptops, and smartphones to include items like air conditioners, coffee machines, cars, or even entire cities. Thus, IoT provides a junction where various devices connect to the Internet to communicate, combine, and exchange data with one another.

II. A MODEL FOR INTERNET OF THINGS HEALTHCARE SYSTEMS

The Internet of Things (IoT) represents the next evolution of the Internet, where machines communicate with each other and take actions autonomously. This capability significantly transforms healthcare by automating information exchange and action-taking processes. Previously, the healthcare system was inefficient as information had to be manually transferred, and patients had to visit hospitals to obtain reports. IoT automates these processes, making the healthcare system more efficient and cost-effective.

IoT revolutionizes care delivery by enabling autonomous, aware, and actionable devices. For instance, a diabetic person might use an insulin pump that automatically adjusts based on real-time blood sugar levels. IoT can collect thousands of data points per second for each patient, leading to more accurate and immediate decision-making. It allows for early disease prediction by analyzing incoming patient data, providing insights into risk factors based on environmental and genetic information, and enabling better medical practices.

Key applications of IoT in healthcare include:

- **Organs on Chips:** This innovation uses IoT to create human organ models on chips, allowing detailed study of organ functions and increasing the efficiency of medications through personalized treatment based on real-time analysis.
- **Telemedicine:** Telemedicine has become crucial in global healthcare, significantly aiding pre-operative and post-operative care by enabling remote consultations and monitoring.
- **3-D Prescription Printed Bills:** IoT enables the printing of personalized medication doses at home using wearable gadgets and sensors that send instructions to a 3-D printer.
- **Automatic Wheelchairs:** Designed with wireless networks and multiple sensors, automatic wheelchairs monitor patients' vital signs and locations, enhancing safety and independence for individuals with disabilities.
- **Wearable:** IoT wearable monitor physiological conditions like pulse, blood pressure, temperature, and oxygen levels. Sensor nodes collect and transmit data to central nodes, which can then be acted upon and forwarded to third parties, reducing human fatigue in healthcare monitoring. Detailed descriptions of wearable healthcare systems forming Wireless Body Area Networks (WBAN) are provided in the subsequent subsection.

III. WEARABLE HEALTHCARE SYSTEM

The primary benefit of the Internet of Things (IoT) in the healthcare sector is the ability to monitor, control, and assist patients remotely, necessitating the support of Wireless Body Area Networks (WBAN). This system focuses on non-obtrusive and non-invasive sensors, excluding implantable sensors. These sensors are designed to track and monitor fundamental human body parameters. Out of five basic sensors, three are dedicated to tracking breathing/respiratory rate, body temperature, and pulse rate. The remaining two sensors are used for measuring blood oxygen and blood pressure, as described below:

3.1 Pulse Sensors

Pulse monitoring is often a critical factor in detecting potentially fatal situations. Pulse readings can be obtained from various parts of the human body. Fingertip or earlobe readings provide very accurate results but are typically non-wearable. Conversely, chest-worn systems are considered wearable, but for long-term use, wrist sensors are more comfortable. Numerous fitness tracking devices with pulse measurement capabilities are available, such as HRM-Tri by Garmin, H7 by Polar, FitBit PurePulse, and TomTom Spark Cardio.

Photoplethysmogram sensors (PPG sensors) are wearable wrist sensors used to determine pulse rate and blood oxygen levels. These sensors detect pulse movements, although high motion can interfere with pulse rate recording. The reduction of motion artifacts has significantly improved signal quality. Researchers have developed highly-sensitive and flexible sensors for pulse rate detection, showing promising results. PPG sensors are often combined with pressure sensors to create a pulse sensor that reads pulse rate from multiple points on the wrist, providing clear and accurate values that aid in successful diagnostics. Consequently, PPG sensors are effective devices for accurately reading pulse rate with reduced signal noise.

3.2 Breathing/Respiratory Rate Sensors

Previous research has highlighted several significant methods for designing sensors to measure breathing/respiratory rate. One commonly used sensor is the thermistor, which functions as a nasal sensor. Another method involves using Echocardiogram (ECG) signals to measure respiratory rate, known as ECG Derived Respiration (EDR). This technique estimates breathing patterns and identifies apnea events, providing reliable respiration rate data and is wearable. However, prolonged contact with ECG devices can irritate the skin, and since they are non-reusable, they must be replaced periodically.

In another approach, microphones have been utilized to detect respiration and measure respiratory rate, focusing on identifying wheezing, a common asthma symptom. Nevertheless, microphones are not ideal for wearable devices due to their susceptibility to external noise.

3.3 Body Temperature Sensors

Body temperature is a crucial parameter for diagnosing conditions such as hypothermia, heat stroke, and fevers, making it an important aspect of wearable healthcare systems. Thermistor-type sensors are commonly used to measure body temperature. For instance, Negative-Temperature-Coefficient (NTC) sensors have been utilized for this purpose, as noted in studies [10, 11], while Positive-Temperature-Coefficient (PTC) sensors have been employed in other research

[12, 13]. However, the accuracy of body temperature measurements heavily depends on the precise placement of these sensors on the human body.

3.4 Blood Pressure

Blood Pressure (BP) is a vital sign frequently monitored alongside other health metrics. Hypertension, a major risk factor for cardiovascular diseases such as heart attacks, underscores the importance of integrating BP monitoring with Wireless Body Area Networks (WBAN) for healthcare purposes. However, designing a wearable sensor that can continuously and non-invasively monitor BP remains challenging. Further research is needed to develop a device that can accurately and comfortably measure blood pressure, as no such device currently exists.

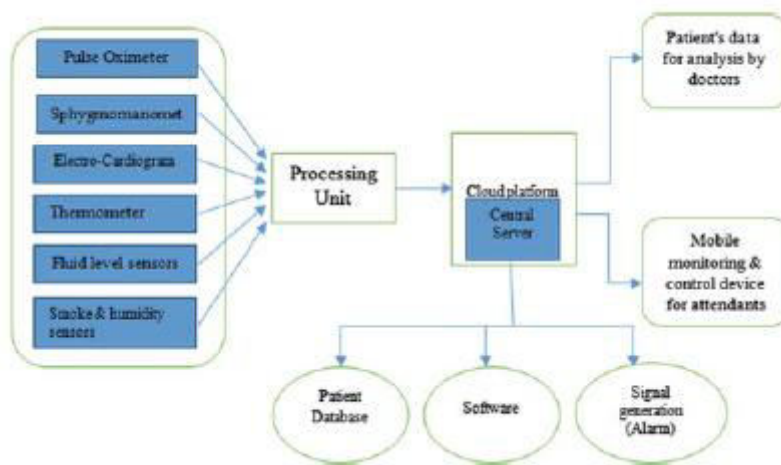


Fig. 1 Block diagram of IoT based healthcare system

3.5 Pulse Oximetry Sensors

Pulse oximetry sensors measure the oxygen level in the blood by generating Photoplethysmogram (PPG) signals. Typically, two LEDs—one red and one infrared—are used to transmit light through the skin. Initially, pulse oximeters were worn as finger clips, but recent studies have aimed to develop more portable devices. To enhance wearability, these pulse oximeters have been designed to operate on low power. In extreme conditions, such as shock or hypothermia, an in-ear reflective pulse oximeter can accurately detect blood oxygen levels. Figure 1 illustrates an IoT-based healthcare system, summarized below.

Product Infrastructure:

- **Hardware:** Includes amplifiers for sensor signals and a dedicated device for displaying data.
- **Software:** Comprises control algorithms.

Sensors:

- Pulse Oximeter
- Sphygmomanometer (Blood Pressure)
- Electro-Cardiogram
- Thermometer
- Fluid Level Sensor
- Humidity and Smoke Sensor.

Connectivity:

- Bluetooth (From sensor to Microcontroller)
- Wi-Fi (Microcontroller to Server and Server to Device).

Analytics:

- Analyze sensor data and correlate to determine patient's health parameters.

- Alert attendant for assistance required by the patient.
- Predict degradation/up-gradation of patient health using continuous data learning (Machine Learning).
- Identify and predict cases of incorrect medication and generate alerts for medication-related body changes.
- Generate and update dose schedules and timely alerts for attendants.

Application Platform:

- Allow doctors access to patient information on their computers, including all details.
- Provide dedicated monitoring devices for attendants.

Additional IoT Applications in Healthcare:

- Sensor-enabled pills: Pills that provide information about drug intake.
- Monitoring of cardiac activity.
- Medication dispensation, such as smart, connected insulin pumps.
- Real-time data collection from the human body, including fitness trackers and sleep trackers.
- Remote diagnostics and patient monitoring.
- Collection of physiological information from patients during critical conditions.
- Living space monitoring.
- Monitoring of stock levels for medical supplies.

IV. IOT BENEFITS IN HEALTHCARE SERVICES

Some of the advantages of IoT in healthcare are depicted in Figure 2. One of the primary benefits of an IoT healthcare system is the reduction of healthcare costs. Currently, healthcare costs are a major concern for everyone. The issue is not just the amount of money spent on healthcare; the more significant problem is that healthcare is reactive. Reactive healthcare means people react to a disease only when symptoms arise. This approach involves responding to adverse situations or conditions of any disease. However, investing more in preventive healthcare, or proactive healthcare, is essential. Proactive healthcare involves taking actions before symptoms appear, rather than waiting for symptoms to manifest.

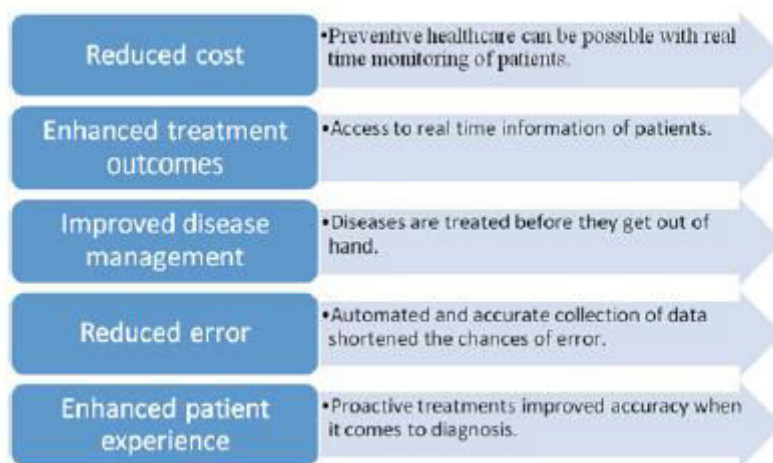


Fig. 2 Importance of IoT healthcare services

Continuing to invest in reactive healthcare leads to growing healthcare costs. With IoT, healthcare costs can be reduced because data is immediately available to doctors or individuals, enabling appropriate actions to be taken. Additionally, IoT enables better treatment outcomes because doctors have real-time information and access to everything they need. IoT can reduce healthcare and management costs and better monitor patients' health conditions. It also reduces disease management complexity and the chances of medical errors.

Recent medical research reveals that medical errors are the third leading cause of death, surpassing deaths from aviation accidents or road traffic accidents. Incidents such as patients receiving the wrong medication, surgeons operating on the wrong body part, medication overdoses, and other medical mistakes are more common than realized. The scientific study of patient safety recognizes that people don't just die from bacteria and cancer; they also die from incorrect medical treatment. IoT reduces such medical errors by providing real-time patient information.

Furthermore, IoT enhances patient care delivery because information is available everywhere. Patients can easily verify and track their health information on their television, refrigerator, or any other connected device.

V. REVIEW OF LITERATURE

Several literature surveys on IoT in healthcare applications are listed in this section. Health monitoring using IoT is a recent research area. Niranjana [14] introduced an intelligent home-based healthcare IoT system utilizing a Medical Box (iMedBox) and a gateway called iGATE. The iMedBox and iGATE were used for home healthcare IoT systems and gateways, respectively. Wearable sensors were integrated with intelligent medicine packaging (iMedPack) using a wireless networking system. Radio Frequency Identification (RFID) was used to couple iMedPack with iMedBox, enabling users to receive real-time healthcare prescriptions. Alharbe et al. [15] also presented the application of ZigBee and RFID technologies in healthcare in conjunction with the Internet of Things.

Yvette and Gelogo [16, 17] presented the IoT U-healthcare system. In their work, mobile devices were used to communicate data to doctors or medical stations. Body sensors were mounted on patients' bodies to gather data and transmit it for examination at surveillance centers.

Castillejo et al. [18] presented a Wireless Sensor Network (WSN)-based IoT for E-health monitoring. They proposed incorporating wearable devices in WSN. Their work focused mainly on raising alarming alerts in hazardous situations. This E-health monitoring system using IoT was designed to generate an alarm signal when a person reaches a hazardous level of activity. This real-time monitoring system aimed to prevent individuals from engaging in further strenuous activity when an alarming signal is triggered. The proposed work provided a well-tested real-time monitoring in E-health using IoT; however, the accuracy and efficiency are still significant concerns.

He et al. [19] discussed security concerns for WBAN using emerging technologies with IoT. The efficiency of healthcare using IoT with WBAN improved the modern medical system by enabling real-time data collection from different sensors incorporated using WBAN directly from the patient's body anytime, anywhere. They focused on several security and confidentiality issues of IoT-based healthcare monitoring. Different schemes in this regard have been proposed; however, security remains a major concern and a challenging issue.

Zhang et al. proposed a method to improve the lifetime of WBAN to increase the duration of real-time data gathering by sensor networks in IoT-based healthcare systems [20]. In IoT-based healthcare using WBAN, sensors play a major role in collecting and transmitting real-time data. Their energy depletion makes healthcare data collection less reliable. As sensors are battery-dependent, improper management can lead to energy depletion, degrading the overall network lifetime. The authors proposed a power game-based approach for effective management of power control in WBAN, thus improving social interaction.

Arcadius et al. surveyed IoT-based healthcare applications and challenges [21]. As IoT applications are growing and will be a prerequisite along with several digital technologies in the future, the focus is on introducing new Internet Protocol addressing that can satisfy any node in the network.

Dhanvijay et al. [22] surveyed enabling technologies in healthcare and their applications. The authors examined various healthcare applications and WBAN-based IoT healthcare technologies. IoT healthcare network devices and sensors have limited battery power, so the requirement for power-efficient sensors for e-healthcare using IoT is emphasized.

Authors in [23] discussed the objectives of IoT and how it has revolutionized the concept of the Internet by connecting not only humans but also Machine-to-Machine (M2M) connections. This paper addressed the basic IoT architecture, focusing on its importance compared to regular information networks. Different challenges arising from technical, economic, and application aspects are also discussed in the paper. Despite its several challenges, IoT has found applications in daily life, starting from smart home, smart city, smart healthcare systems, supply chain management,

smart agriculture, etc. Supporting the benefits of IoT, the authors also presented case studies on Multi-Robot systems where interaction and data transmission are done between robots to execute missions against terrorism. Another application of IoT is seen in hospital emergency sections where RFID tags are used to provide urgent medical treatments to critical patients. The paper concludes by highlighting the three visions of IoT: things-oriented vision, Internet-oriented vision, and semantic-oriented vision.

Authors in [24] discussed different technological evolutions of IoT, mentioning various research trends. The paper also presented the service-oriented architecture of IoT, mentioning different layers and their functionalities. The authors identified different emerging technologies where IoT can be implemented, including several benefits and challenging issues. Applications of IoT are found in diversified fields, including healthcare, social networks, business, and industry applications.

Considering the demand for low-cost smart hospitals, authors in [25] proposed a new technological invention that is cheaper and beneficial for developing smart hospitals. The proposed framework helps in remotely monitoring patients and providing alerts during critical health conditions. The use of sensors in wearable devices helps in monitoring patients' health conditions from remote locations. Sensors attached to patient beds record each vital sign for better medical treatment and analysis. The use of IoT helps in reducing the cost of the proposed architecture. A huge amount of data is collected, stored in the cloud, and analyzed using big data techniques. Thus, the proposed system is effective for better medical treatment with low cost and improved quality.

In healthcare applications, Wireless Body Area Network (WBAN) is becoming more important because of the implantation of wearable devices in the human body. Authors in [26] proposed an autonomous WBAN with three features: a solar panel for solar energy harvesting with MPPT circuit, Bluetooth energy transmission with wearable sensor node, and a smartphone for visualizing data and giving notifications in case of emergencies. Different wearable sensors can be placed on the human body to measure body temperature, heartbeat, and other parameters, which can be monitored using a smartphone. The use of a solar energy harvester acts as a power supply, extending the lifetime of the sensor nodes. Moreover, the wearable devices are also built keeping in mind usability and ease-of-use features from the user's perspective.

Authors in [27] conducted a qualitative study on the adoption of WSN-based smart home healthcare systems (WSN-SHHS), addressing facilitators and barriers by indicating cognitive, socio-technical, and socio-economic factors. The literature survey of WSN-SHHS focused on its technological aspects, giving less observation on the patient's issues for adoption and use. Thus, the authors presented a mixed method for providing great insights into patients' perceptions of WSN-SHSS systems using both quantitative and qualitative research methods. The quantitative method uses a survey technique based on certain questionnaires prepared from hypotheses designed by the authors, while the qualitative method uses an interview technique. The result analysis focuses on certain findings and guidance that need to be followed for the design and development of WSN-SHSS. However, the research study also finds certain limitations and scope for future work.

Authors in [28] presented a model for the implementation of WBAN in a healthcare system, highlighting the design features that need to be incorporated into a WBAN system. The proposed model targets multi-patient monitoring in medical centers, focusing on individual use, use in one room, and one floor. The paper described the hardware implementation of the model using sensor nodes and CCU. The data collected from the model is transmitted to remote locations using multi-hopping techniques that use MAC protocols. This system helps in monitoring patients' physiological parameters remotely. The proposed system is different from the traditional system in that it can monitor many patients' physiological signals to simulate a real hospital environment.

Authors in [29] proposed a cooperative IoT model for monitoring and controlling the health of rural people. The system provides effective Quality-of-Service (QoS) because of the cooperation technique. The result analysis shows the trade-offs of energy, latency, and throughput using NS-2 simulation tool. The proposed model proves to be reliable for continuous health monitoring. In the future, the authors propose to expand the model by adding authentication and authorization features in the cooperative IoT system.

Pantelopoulous et al. [30] presented a survey on wearable sensor-based systems for health monitoring and prognosis, where Wearable Health Monitoring Systems (WHMS) have the potential to revolutionize healthcare by providing low-cost, early detection, and better treatment of chronic diseases.

Pervez et al. [31] discussed the medical applications of wireless body area networks in smart healthcare systems, including epileptic seizure warning, glucose monitoring, and cancer detection, proving that WSN and WBAN in medicine can be further expanded to improve the quality of life.

Huang et al. [32] presented a healthcare monitoring architecture coupled with wearable sensor systems and an environmental sensor network for monitoring elderly or chronic patients in their residence.

VI. SYSTEM ARCHITECTURE AND ANALYTICAL MODEL OF IOT BASED HEALTHCARE SYSTEM

After reviewing a wide variety of IoT-based healthcare systems, the need for designing such systems becomes apparent. In healthcare systems utilizing IoT architecture, data gathered from sensors, prescriptions, and previous medical data are used for descriptive, diagnostic, predictive, and event-based actions, as shown in Fig. 3. Each paper focuses on using sensors to monitor the patient's current health condition. Authors in [37, 38] suggest deploying home sensors based on characteristics gathered from environmental vision. However, this restricts the use of the IoT system to a specific location. Therefore, it is suggested to deploy all sensors to be portable with wearable nodes fixed externally. This would enable monitoring of patients' health wherever they go, providing non-intrusive, safe, and restful solutions. Patients would be more responsive, as they would be continuously monitored based on their health. Repairing and replacing externally wearable nodes would be much simpler compared to sensors fixed at one specific location.

The use of Bluetooth, a short-range communication system, is preferred in the current state of the art for sending data from sensors to a smartphone, which requires further processing. LTE, a long-range communication system, can be deployed to transfer the processed information gathered via SMS or the Internet to the healthcare provider from the patient. However, smartphones have limited battery life and require periodic recharging. So, a patient with a discharged battery would be disconnected from all healthcare centers. In such scenarios, the use of low-powered nodes is recommended. These nodes should be specially designed for gathering and managing information from the healthcare system.

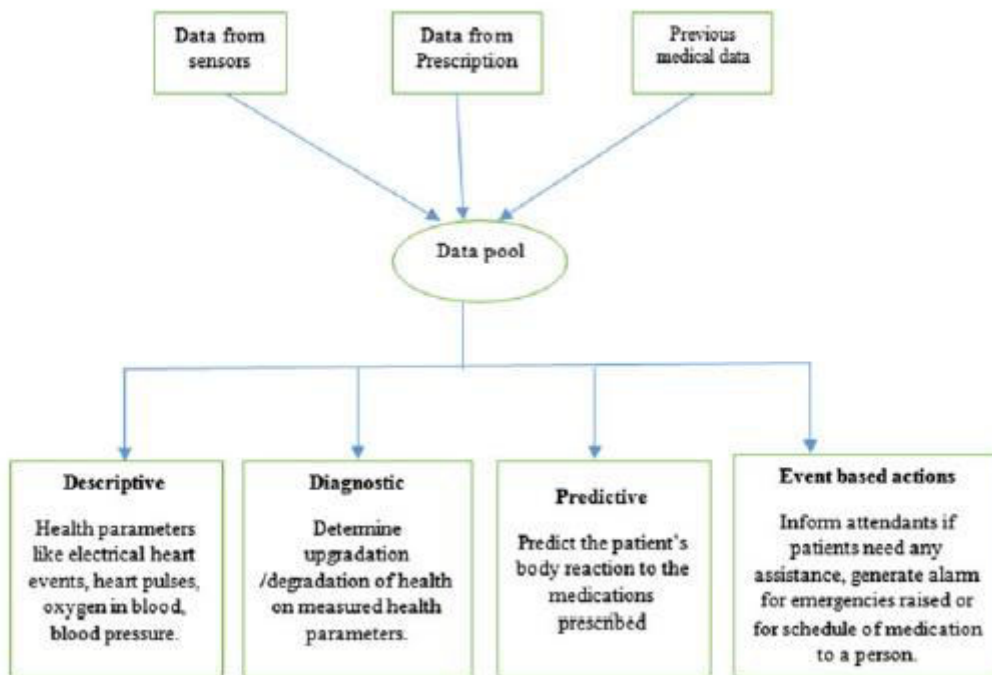


Fig. 3 Analytics data model of IoT healthcare system

Storing high volumes of medical data requires cloud storage, as mentioned in research works related to the healthcare system [39, 40]. Based on the recurring trends in the literature to date, the following will support the development of future Internet of Things in healthcare systems:

I. For short-range communications in healthcare IoT systems, it's crucial to choose a technology that allows sensors to interact with the central node without impacting humans. Factors such as security, latency, and interference need to be considered. The chosen method should incorporate strong security mechanisms to protect patient data. Low latency is also important for time-critical systems, such as those that track critical health and call an ambulance if necessary.

II. Long-range communications are essential for forwarding raw data from the central node to a central hub for processing by a caretaker or doctor. Similar to short-range systems, long-range communication standards must be chosen carefully, considering factors like security, error correction capabilities, dynamicity against interference, and low latency. These systems must also be readily available to ensure continuous delivery of patient information, regardless of the patient's geographical location. While critical in terms of timing, long-range communication systems are suitable for a variety of applications.

III. Secure cloud storage architecture is crucial for storing patients' medical data for further use. It's important to have a large database storing all patient information available to doctors. Storing this information in the cloud has been shown to be reliable and secure. Researchers developing healthcare IoT systems should focus on providing professionals with secure access to the required data. Additionally, while machine learning has been recognized as a technique for enhancing IoT-based healthcare systems, it has not been fully developed yet. Machine learning can help identify trends in medical data for better treatment planning, diagnostics, and patient-specific suggestions.

VII. CLOUD BASED IOT HEALTHCARE SYSTEMS

The utilization of cloud storage for processing and analyzing big data has made cloud computing a highly researched field. Numerous previous works have been extensively reviewed to design systems supporting healthcare based on cloud computing frameworks.

Some of the benefits provided by cloud technologies in healthcare include:

- Software as a Service (SaaS): With SaaS, healthcare providers can work with relevant data and perform other useful tasks.
- Platform as a Service (PaaS): PaaS provides users with tools and techniques for network management, database management, and virtualization.
- Infrastructure as a Service (IaaS): IaaS offers physical infrastructure for storage and server purposes.

These services can be utilized for a variety of tasks, but two of the most significant uses can be easily identified.

i. Big Data Management: Big data management involves handling data based on the 5 V's: volume, velocity, variety, veracity, and value. Volume refers to the amount of data obtained and generated, while velocity is the speed at which data is generated. Variety refers to the different types of data, and veracity is the uncertainty of future data additions. Value is the information gained from the dataset. The main challenge of big data management is the inability to tailor a system to specific features of a big data set. For emergency healthcare IoT systems requiring large volumes and varieties of data, a data storage model can be designed to easily access heterogeneous physiological data during emergencies. Cloud technologies offer benefits for big data management, such as tremendous storage space, easy accessibility for both patients and doctors, and enabling doctors to provide accurate treatment without meeting the patient in person.

ii. Data Processing and Analytics: Cloud-based IoT systems offer various data processing technologies, including computational offloading and machine learning. Computational offloading uses the cloud to process data beyond the resources of wearable devices with limited capacities. Machine learning facilitates the collection of information from large datasets and can establish meaningful links between symptoms and diseases. This enables accurate predictions of possible diagnoses based on previous cases, helping to develop patient-specific treatment plans based on successful past treatments for similar illnesses.

VIII. SECURITY AND PRIVACY ISSUES IN IOT HEALTHCARE

Security and privacy are critical issues in the healthcare industry, especially with the advent of IoT. Connected devices inherit the same security threats as computers and smartphones, making endpoint security crucial. Healthcare organizations are prime targets for ransomware attacks due to the reliance on private data records for healthcare delivery. Educating employees about security threats can help minimize such risks, as insiders are often responsible for security breaches.

In healthcare, privacy is particularly sensitive. Real-time data availability is a challenge, as medical research often relies on residual data from examinations. IoT can address this by providing access to vast amounts of real-time data for analysis and testing. Lack of smart care devices is another challenge, but IoT can empower healthcare professionals and improve care quality while reducing costs. For example, smart care devices can monitor certain parameters and alert caregivers if any parameter is breached, allowing for remote patient monitoring and quick interventions.

Cloud security is essential in healthcare systems based on cloud technology. Access to patient health information must be easy for relevant parties while keeping sensitive data private. Some research has focused on developing dynamic security protocols for healthcare practices. For instance, an access control scheme called "Safe-Protect" allows patients to control access to their health records by creating access policies for healthcare providers, ensuring the encryption and secure storage of individual patient data in the cloud.

XI. CONCLUSION

The future of healthcare is being shaped by the Internet of Things (IoT), particularly Wireless Body Area Networks (WBAN). With increased patient data and real-time tracking, there is a greater potential for disease prevention and treatment. IoT devices are revolutionizing traditional healthcare approaches, making healthcare products more user-friendly. This paper has explored the applications of IoT in healthcare and highlighted areas needing further research, such as security, privacy, and power resource management, to enhance the robustness, reliability, and scalability of healthcare systems. The integration of WBAN and IoT technologies is making home health services more effective, indicating a significant future for IoT in healthcare research and development.

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